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Alternative modelling of brittle structures in a sub-area of the SKB candidate area at Forsmark, eastern Sweden

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Geosigma AB, Uppsala.
Date: November 2008

Background

A reasonable understanding of the character of the bedrock hosting a deep geological repository, i.e. the natural barrier, is an important component in the safety assessment of the deep geological repository for spent nuclear fuel. The structures in the rock, together with the regional stress field, affect the mechanical stability of the bedrock and the ground water transport within the bedrock. The rock types, the alteration of the bedrock and the character of the infilling material in fractures affect the groundwater chemistry. Together, these factors have influence on the environment within which transport of substances may occur, both in the near- and the far-field of the geological repository.

The Swedish Nuclear Fuel and Waste Management Co (SKB) has, in accordance to their initial and complete site investigation programmes, concluded the surface-based site investigations at two sites, the Forsmark and Laxemar candidate areas, located in the eastern and southeastern part of Sweden, respectively. Based on the site investigations SKB has presented geological models for the candidate areas.

The Swedish Radiation Safety Authority (SSM) will use the present study in their technical review of SKB's site investigation programme for potential repository sites.

Modelling

In the present study, an alternative brittle deformation model of a selected part of the Forsmark candidate area is constructed based on cluster analysed of geophysical borehole logs in combination with geological core logs and PFL-logs.

Purpose

Construct an independent alternative model to test what structural information can be extracted and to test the existing SKB model (stage 2.2).

Results

The cluster analysis of fracture data from Forsmark may identify what can be minor deformation zones (MDZ) that could lie within the repository volume and which have the potential to be mapped deterministically during construction. The study mainly confirms SKB model of local deformation zones.

Effects on SSM supervisory and regulatory task

The study has generated an alternative structural model of a small part of the Forsmark site that may translate into a different assessment of groundwater flow within the repository rock volume compared to the SKB model.

Project information

SSM reference: SSM 2008/147
Responsible at SSM has been Öivind Toverud

Abstract

One way to test the confidence of a presented model is to construct an alternative model. Such work is cognitive process of skill acquisition and also a process of understanding data in the sense of sorting and classifying data. This is of particular interest for the Swedish Radiation Safety Authority (SSM) in their technical review of SKB's on-going site investigation programme for potential repository sites.

In this study, an alternative brittle deformation model of a selected part of the SKB candidate area in eastern Sweden was constructed. The input data set was obtained from SKB's database SICADA and is a selected set of data from five cored boreholes drilled from two drill-sites and comprises geophysical borehole logs, geological core-logs, hydrological logs (PFL; Posiva Flow Log) and borehole deviation measurements.

Statistical cluster analysis applied on the geophysical borehole data were used to obtain the locations of bedrock with contrasting physical characteristics similar to those of brittle deformation zones. The cluster analysis is an objective procedure, contrasting with SKB's more subjective approach to the single-hole interpretation. Thus some differences are expected which could illustrate the effect of methodology that includes subjective "expert judgement." and indicate the possibility of alternative interpretations.

The information about brittle structures in the geological boreholes logs was sorted and classification was made according to character of the structures (all fractures, open fractures, partly open fractures, frequency, orientate on/identification of fracture sets, sections of crush rock, and alteration). A separate study was performed to relate rock alteration with structures. The resolution applied in the fracture statistics is one metre, i.e. all studied entities were expressed per metre borehole length.

All clusters were structurally characterized by the fractures inside the clusters (orientation and density of fractures) and compared with the structural character of the adjacent rock. The resolution in the cluster analysis is less than half a metre.

The classified fracture data, results from the cluster analysis and borehole deviation data comprise the input data in the structural modelling performed in a fully three-dimensional space. PFL logs (hydrological data) were used to test the model.

The constructed model (EW oriented: 900 by 550m and 850m deep) contains seventy-six brittle deformation zones: sixteen from correlated data in three to five boreholes, sixteen structures from correlated data in two boreholes and forty-four are indicated in one borehole.

The alternative model agrees with the SKB site descriptive model. However, the structures in the SKB model are relatively wide compared with the structures in the alternative model and the SKB model may disregard finer structures, especially if they intersect the SKB structures. Deviations in the models are the frequency of NS/vertical structures and a sub-horizontal structure in the deeper part of the model.

Some general observation related to safety assessment issues are that relatively thin structures may have a minimum extension of several hundreds of metres, which may question the assumption of a correlation of structure width to extent and might also be of importance for the choice of canister positions. Further, the pattern of connected fractures has changed during the geological history and the characterization of the disturbed/transitional zone around

regional structures with a long geologic history may be intricate. The geometrical configuration of boreholes gives a borehole orientation bias and also gives space for structures, e.g. parallel the dominant regional structures, to pass unnoticed between the boreholes. Finally, indicated existence of gently inclined brittle deformation zones at depth may affect the layout of a repository.

Keywords: Structural geology, fracture, fracture zone, classification, cluster analysis, alternative model, model comparison, safety analysis.

Sammanfattning

En test på tillförlitligheten hos en geologisk modell av en plats är att bygga upp en alternativ modell. Detta arbete är en lärande process och ger ökad förståelse för data, förutsättningarna för att sortera och klassa data och speciellt ökar det förståelsen av platsen. Svensk Kärnbränslehantering AB (SKB) har bedrivit undersökningar för att ta fram potentiella platser för förvar för använt kärnbränsle. Strålsäkerhetsmyndigheten (www.ssm.se) har inom sitt ansvarsområde att utföra teknisk granskning av SKB:s platsundersökningar och kommande ansökning avseende plats för ett slutförvar. Alternativ modellering är en del av detta granskningsarbete.

I föreliggande arbete har en alternativ modell beskrivande berggrundens mönster av spröda deformationszoner/sprickzoner inom en del av SKB:s kandidatområde i Forsmark framtagits. Basen för studien är geoinformation från fem kärnborrade borrhål. Underlagsdata har erhållits från SKB och hämtats från deras databas SICADA. De data som använts är geofysiska borrhålsloggar, geologiska borrkärneloggar, en hydrologisk log som benämns PFL (Posiva Flow Log) och data på borrhålens tredimensionella lägen i berggrunden.

En typ av statistisk verktyg som benämns klusteranalys har använts för att finna lägen i berggrunden (kluster) som har en fysiskt avvikande karaktär vilken liknar den som spröda deformationszoner/sprickzoner har. Klusteranalys är en objektiv metod att identifiera delmängder såsom deformerade delar av berget och denna metod skiljer sig från SKB:s mer subjektiva geologiska borrhålsutvärdering som till stor del baseras på erfarenhet. Vissa skillnader i resultat vid användande av de två metoderna kan förväntas och dessa skillnader belyser möjligheten till alternativa tolkningar.

Den sprödtektoniska (sprickor) informationen i de geologiska borrhålsloggarna sorterades och klassificerades i enlighet med deras karaktär (alla sprickor, öppna sprickor, delvis öppna sprickor, sprickfrekvenser, sprickorientering/identifiering av sprickgrupper, sektioner med krossat berg, och omvandlingar i/vittring av sprickor). I samband med studie av omvandlingar i sprickor utfördes även en studie av omvandlingar i själva berget. Upplösningen i dessa studier är mindre än en meter (antal strukturer per meter borrkärna).

Antalet kluster funna i de fem kärnborrhålen var 121. Dessa kluster har strukturgeologiskt beskrivits med avseende på de sprickor som klustren innehåller (sprickors orientering, antal sprickor/spricktäthet och identifiering av sprickgrupper) och denna information jämfördes med sprickbilden i berget som omger klustren. Upplösningen i klusteranalysen är mindre än en halv meter.

Klassade sprickdata, resultat från klusteranalysen tillsammans med data på borrhålens rumsliga lägenn var ingångsdata som användes vid upprättandet av en alternativ tredimensionell sprödtektonisk modell. Hydrologiska data (PFL) användes för att testa modellen.

Den alternativa modellen innehåller sjuttiosex strukturer och av dessa är sexton korrelerade mellan tre till fem borrhål, sexton strukturer är korrelerade mellan två borrhål och fyrtiofyra är enkla borrhålstolkningar, dvs. har ej kunnat korreleras mellan borrhål. Modellen är orienterad i öst-väst och är 900*550m och 850m djup. Borrhålskonfigurationen i det modellerade området ger en viss skevhet i provtagning av strukturer och borrhålens lägen medger att strukturer, t.ex. strukturer parallella med de regionala strukturer som avgränsar Forsmarksområdet, kan passera obemärkta mellan borrhålen.

Den alternativa modellen överensstämmer i stort med SKB:s platsbeskrivande modell för spröda deformationszoner. Emellertid är strukturerna i SKB:s modell relativt breda i jämförelse med dem i den alternativa modellen. Detta gör att SKB-modellen kan förbise tunna strukturer, speciellt där de eventuellt korsar SKB-strukturerna. Att enkelt korrelera strukturers längd med deras bredd kan ifrågasättas. Skillnaden i modellerna är att SKB-modellen har färre vertikala NS-strukturer samt har ej med en flack, djupt belägen struktur.

I studien har framkommit några iakttagelser som är relevanta för säkerhetsanalysen av området om det föreslås som lämplig plats för ett geologiskt slutförvar. Dessa iakttagelser är:

- Att modellerade tunna strukturer kan ha en utsträckning överstigande ett flertal hundra meter (relevant för val av läge avseende deponeringshål för kapslarna).
- Att mönstret av sammanbundna sprickor utmed vilka vatten kan ha transporterats i berget tycks ha förändrats under områdets geologiska utveckling (relevant för reaktivering av uthålliga strukturer, bildandet av ”nya” transportvägar för vatten).
- Karakteriseringen och avgränsning av den så kallade övergångszonen/störda zonen som omsluter sprödtektoniska zoner (den bergvolym inom vilket en zon sidledes har påverkat berget) kan vara svårbedömd. Det senare kan gälla om den störda zonen tillhör en struktur som har haft en lång tektonisk historia. Bestämning av övergångszonens storlek är relevant vid bestämning av det så kallade respektavståndet, dvs. det avstånd som av säkerhetsskäl skall hållas till större strukturer vid planeringen av ett förvars layout och speciellt kapselpositioner.

Table of content

1. Introduction

1.1 General

The objective of the present study is to construct an alternative deterministic structural model of a selected part of the SKB Forsmark site. The model is based on structural and geophysical data from five cored boreholes. Deterministic modelling is a cognitive process of skill acquisition and also a process of understanding data in the sense of sorting and classifying data.

"*Alternative conceptual models (ACMs) are alternative SDMs* (Site Descriptive Models), *that are consistent with all or most of the available data, and there is no basis to prefer one to another. In this sense, ACMs are no different from the SDM, except that they may not have equal probability of reality. Sometimes, an ACM (or SDM) is not consistent with all the data, in which case the data in question should be clearly identified and evaluated, and perhaps additional measurements made to confirm the data*" (INSITE 2003).

The base data for this study were kindly provided by the Swedish Nuclear Fuel and Waste Management Co (SKB), and comprise QA checked data from the SKB database SICADA.

Forsmark and Laxemar are the two candidate areas within which SKB has performed surface-based site investigations (SKB 2001). The results from the investigations form the basis for the on-going SKB safety-assessment study, SR-Site, which purpose is to show that a safe repository for nuclear waste can be built.

The present study is a part of the Swedish Radiation Safety Authority (SSM) technical review of SKB's on-going site investigation programme for potential repository sites.

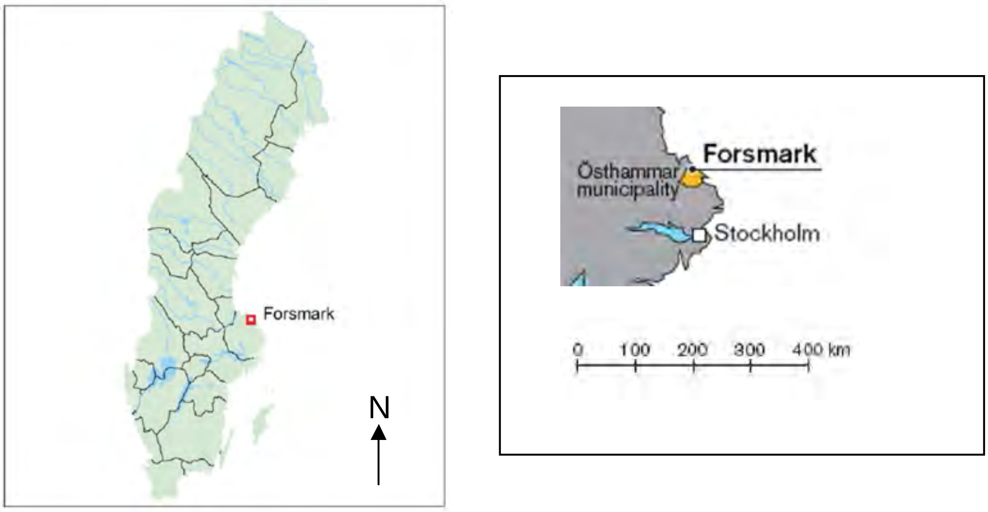


Figure 1-1: Location of the Forsmark area.

1.2 Figures and data treatment

Orientation of structures is presented in rose diagrams and stereograms (Schmidt net, lower hemisphere projection). If nothing else is stated, the outer circle in the rose diagrams represents 10% of the plotted population and in the stereogram the contouring is 1,2,3,5 and 7%. Corrections of sampling biases of structural information are not performed; the primary data are visualized and the full set of data is used in the deterministic modelling.

1.3 Previous investigations

The SKB surface-based site investigation in the Forsmark candidate area was conducted during six years and ended in March 2007.

The results of the geological investigation are summarized in a succession of reports:

SKB, 2002: Forsmark – site descriptive model version 0. Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, report SKB R-02-32.

SKB, 2004: Preliminary site description Forsmark area – version 1.1 Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, report SKB R-04-15.

SKB, 2003: Preliminary site description Forsmark area – version 1.2. Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, report SKB R-05-18.

SKB, 2006: Site descriptive modelling Forsmark Stage 2.1. Feedback from completion of the site investigation including input from safety assessment and repository engineering. Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, report SKB R-06-38.

Stephens, M. B., Fox, A., La Pointe, P., Simeonov, A., Isaksson, H., Hermanson, J., and Öhman, J., 2007: Geology Forsmark. Site descriptive modelling Forsmark stage 2.2. Swedish Nuclear Fuel and Waste Management Co (SKB), Stockholm, report SKB R-07-45, 224 + 17 appendices.

There are also numerous supporting reports available (cf. www.skb.se, R and P reports).

1.4 Brief description of site geology

Forsmark candidate area is a flat, low altitude area and the percentage of outcrops is relatively low and they are heterogeneously distributed (Sohlenius et al. 2004). Approximately 75% of the ground surface is covered by till and 5% consists of outcrops (about 3% at the power plants). Subordinate soil types are sand together with boulders, clay, gyttja clay, peat and glaciofluvial sediments. The amount of artificial fill is relatively large adjacent to the power plants (comprising about 4% of the candidate area). In the central northern part of the Forsmark candidate area (Figure 1-2) is a lake, Bolundsfjärden, and there is a bay, Asphällsfjärden (the percentage of the water-covered parts of the candidate area, e.g. lakes and the sea, is not given).

The bedrock comprises foliated and lineated Precambrian rocks. The selected area of the present study is located in the western part of a large-scale fold closing northwards, Figure 1-2. The deformation (foliation) in the rock becomes more intense when going westwards as the western limb of the fold lines up with a regional NW-trending shear zone, the Eckarfjärden shear zone, that dips steeply westwards. Other regional shear zones that form important constituents in the large-scale deformation pattern are the extensive WNW-trending shear zones; the Forsmark deformation zone to the south and the Singö deformation zone just north of the candidate area.

The regional Eckarfjärden deformation zone is actually an accentuated brittle deformation zone located in an approximately one kilometre wide ductile deformation zone. The structure penetrated by borehole KFM09A is not the actual Eckarfjärden deformation zone, but a brittle deformation zone located at the eastern rim of the wide ductile deformation and it is denoted in SKB 2.2 Geological Model zone ZFMNW1200. This eastern zone intersects borehole KFM09A at a borehole length of 723 to 790m (Stephens et al. 2007). In this study, the zone drilled by borehole KFM09A is, for convenience, denoted the regional western border zone of the Forsmark candidate area, or in short “the western border zone”.

1.5 Selection of boreholes for the present study

The fracturing in the shallow parts of the bedrock is enhanced and dominated by sub-horizontal fractures, some filled with Quaternary sediments. The sub-horizontal fracturing may be the cause of the difficulties SKB has with the correlation of lineaments with the observations of brittle tectonic structures in boreholes. Considering this, the approach of the present study is to put the main efforts on the modelling of subsurface data sampled below the shallow section of fractured rock (at least below the upper 100 m). This can most efficiently be performed in areas where the separation of boreholes is relatively small.

The site has a high environment value and natural reserves are located close the candidate area. Therefore, SKB had to minimize the number of drill-sites and therefore some boreholes were divergently drilled from each drill-site in order to sample the rock volume of interest. Boreholes from two drill-sites (DS 7 and DS 9, Figures 1-2 and 1-3) in the northwestern part of the candidate area were selected (3+2 boreholes) for the following reasons:

1. The drill-sites are comparably closely located to each other and the boreholes cover a relatively large volume (model volume=4.2075 $10^8 m^3$, area=4.95 $10^5 m^2$, dimensions are 900*550m and 850m deep, the longer side of the model is oriented EW, cf. below size of modelled volume).
2. The drill-sites are located in the so called prioritized area, which is the potential site area for a repository.
3. The location gives an opportunity to study brittle deformation in the vicinity of a higher order deformation zone, i.e. it will give information about the disturbed zone in the vicinity of a regional structure.

A drawback of selecting boreholes KFM07A,B,C and KFM09A,B is that the boreholes are located in an area where the surface investigations are hindered by buildings and minor roads. Another drawback is that the sampling of the rock volume may be biased as three of the boreholes have similar trends and relatively similar dips (55, 55 and 85°southeastwards).

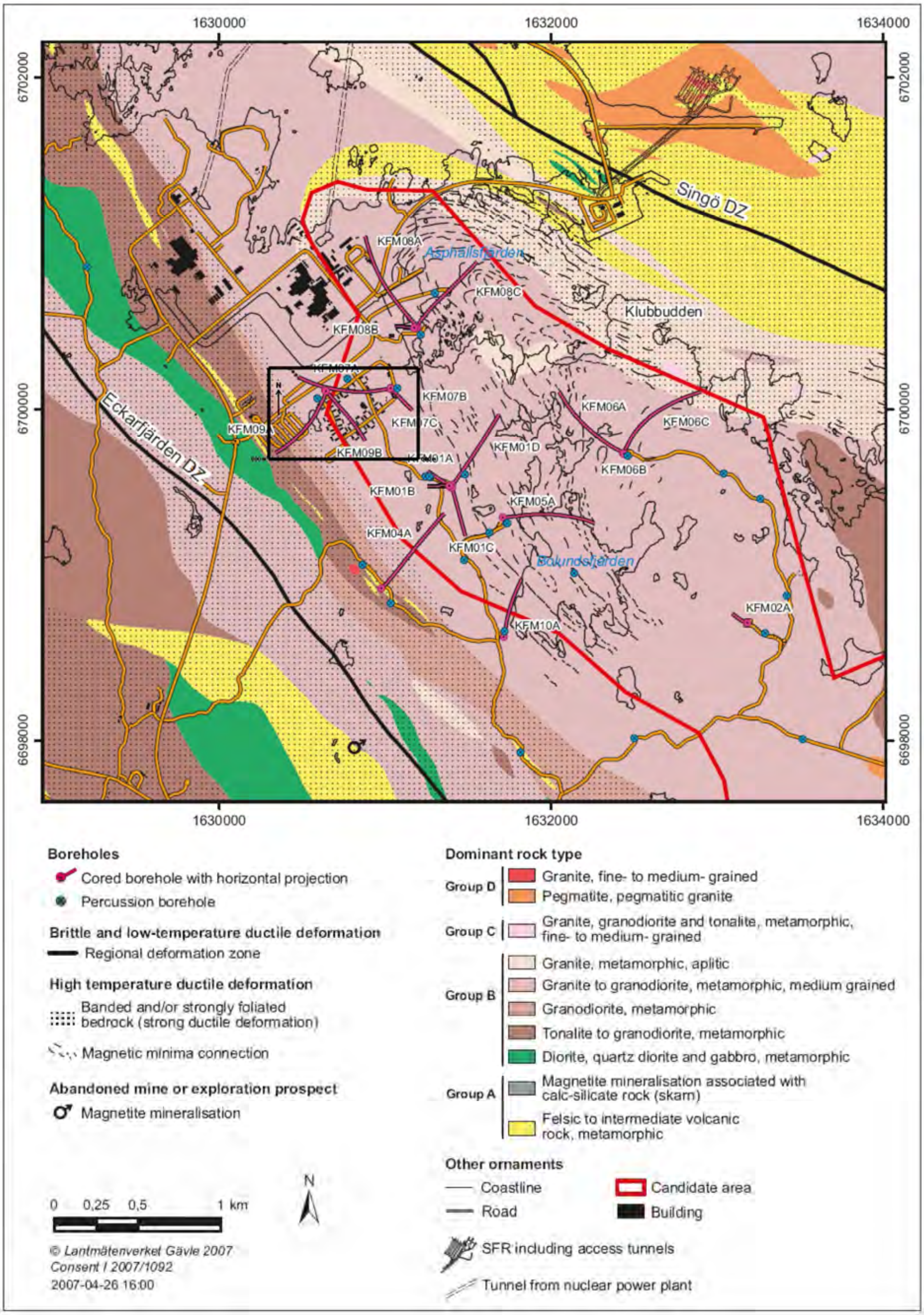
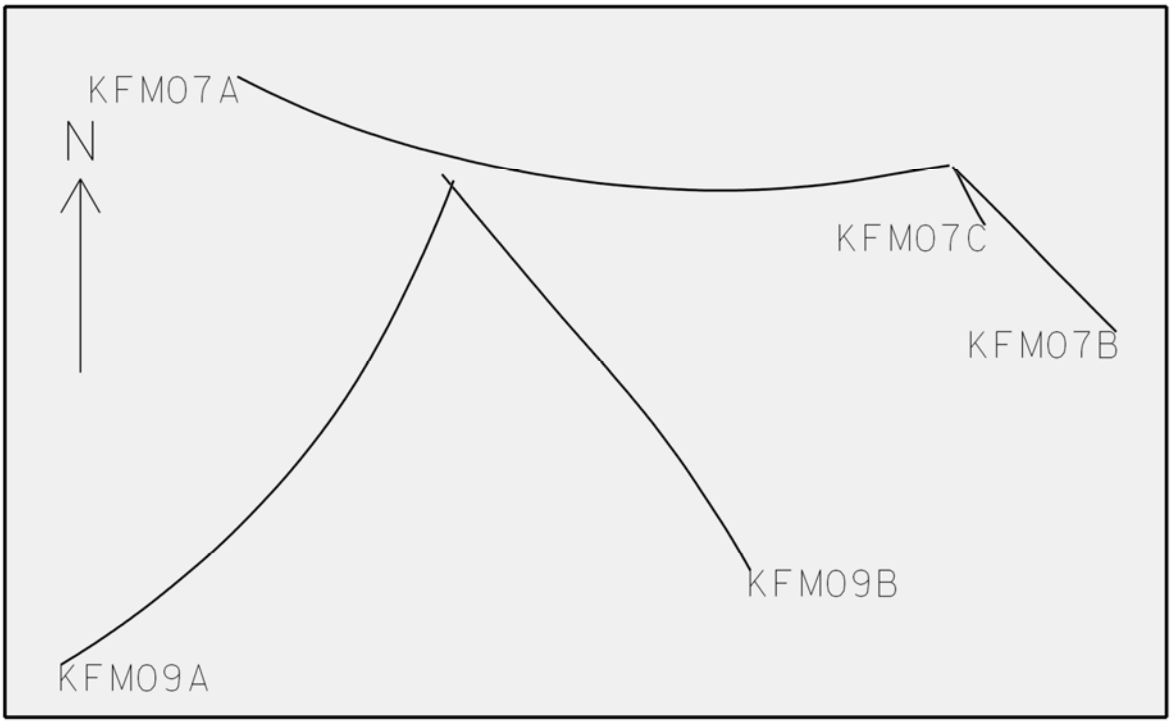
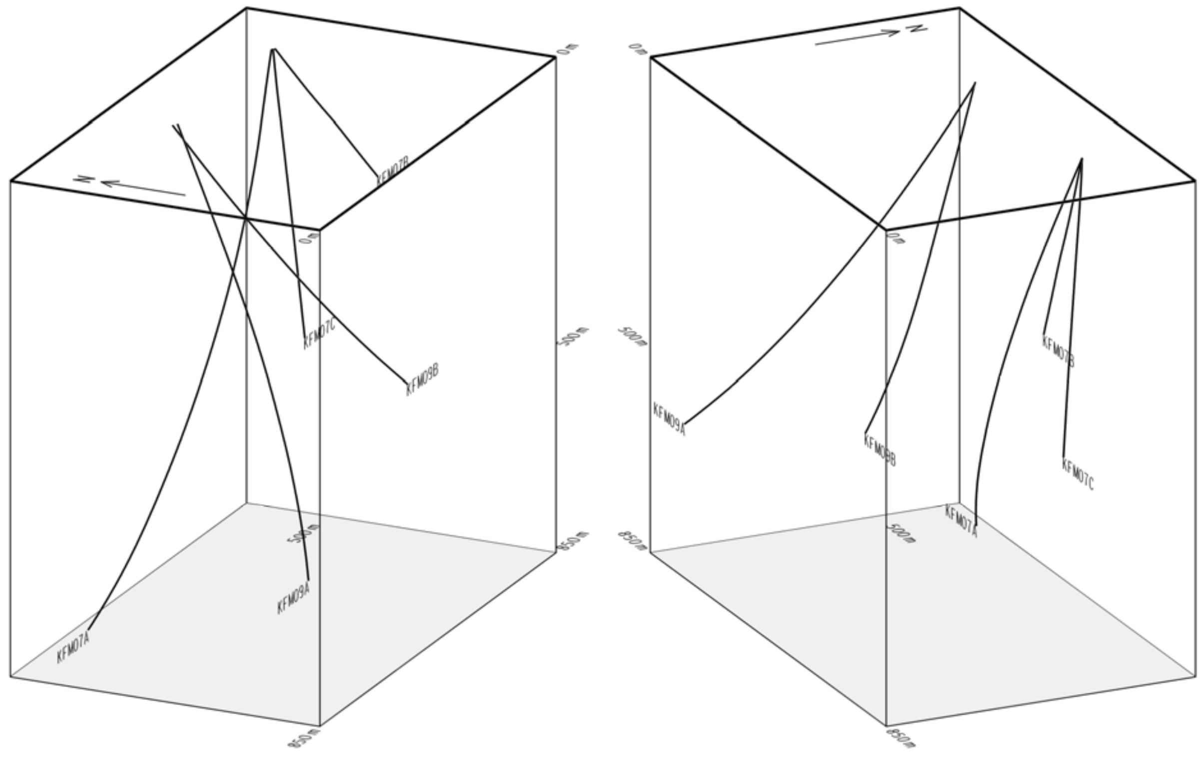


Figure 1-2: Geological map of the Forsmark area. The sub-area modelled in this study is represented by a rectangle in the central part of the map. The area comprises drill-site DR7 and 8 and cored boreholes KFM07A,B,C and KFM09A,B.



a.



b. c.

Figure 1-3: Location of drill-sites and borehole configuration in the alternative structural model presented in this report. The size of the model is 550 by 900m by 850m deep; a. top view, b. viewed from SW and c. viewed from SE. Location of the model volume is given in Figure 1-2.

1.6 Size of modelled volume

The size of a modelled volume can be established from the dimensions of the volume encompassing the boreholes. The distances between drill-sites (DS) and bottoms of boreholes are given in Table 1.1. The actual size of the modelled volume is given in the previous section.

Table 1.1: Measured distances within the modelled sub-area in Forsmark (DS =drill-site, KFM0YZ are cored boreholes).

From	To	Distance (m)
DS7	DS 9	390
DS7	Bottom KFM09A	1000
DS7	Bottom KFM09B	580
DS9	Bottom KFM07A	840
DS9	Bottom KFM07B	580
DS9	Bottom KFM07C	640
Bottom KFM07A	Bottom KFM07B	920
Bottom KFM07A	Bottom KFM07C	675
Bottom KFM07A	Bottom KFM09A	515
Bottom KFM07A	Bottom KFM09B	650
Bottom KFM07B	Bottom KFM07C	310
Bottom KFM07B	Bottom KFM09A	410
Bottom KFM07B	Bottom KFM09B	410
Bottom KFM07C	Bottom KFM09A	800
Bottom KFM07C	Bottom KFM09B	320
Bottom KFM09A	Bottom KFM09B	560
Bottom KFM07A	Ground surface	820

2. Modelling approach

The applied approach consists of:

1. General statistical treatment of fracture data followed by sorting and classifying the data according to fracture sets/families and fracture density, see Section 3. The section contains also a study of alteration of fractures, wall rock alteration (oxidation) and the general alteration of the bedrock.
2. Application of cluster analysis to geophysical borehole data in order to identify brittle deformation zones (fracture zones); see Section 4.
3. Characterization of each cluster with respect to orientation and to density of the fracture population within, above and below each identified cluster; see Section 5.
4. Identification of fracture sets within each cluster (potential brittle fracture zone); this serves as input data to the three-dimensional modelling of fracture zones. All fractures are sorted into classes according to their orientation; each group contains fractures with a range of 10 degrees in strikes and dips; see Section 5.
5. The use of three-dimensional CAD technique (MicroStation©) to visualize selected fracture data sets representing potential brittle deformation zones (clusters); see Section 6.

Use of oriented data (borehole radar) in the modelling was tested but the success of this was limited.

3 Structures mapped in boreholes

The recording and data storage of structural borehole data are described in following method-descriptive documents:

SKB MD 143.006 (approved 2002-09-19): Metodbeskrivning för BOREMAP-kartering. Swedish Nuclear Fuel and Waste Management Co (SKB) (in Swedish).

SKB MD 143.008 (approved 2004-07-05): Nomenklatur vid BOREMAP-kartering. Swedish Nuclear Fuel and Waste Management Co (SKB) (in Swedish).

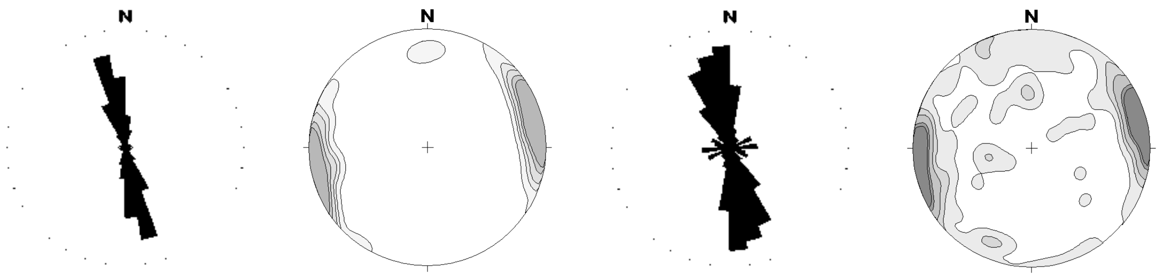
Depths given in this section refers to metres below sea level (m b.s.l.) if nothing else is stated.

3.1 Ductile to semi-ductile structures and rock contacts

In the figures below, the data on lithological contacts are obtained from the SICADA-files KFMXXY-p_rock.xls (XX is a number and Y is a letter or not included) and structural features such a foliation, ductile shear zones and brittle-ductile shears zones are obtained from SICADA-file KFMXXY-_rock_struct_feat.xls.

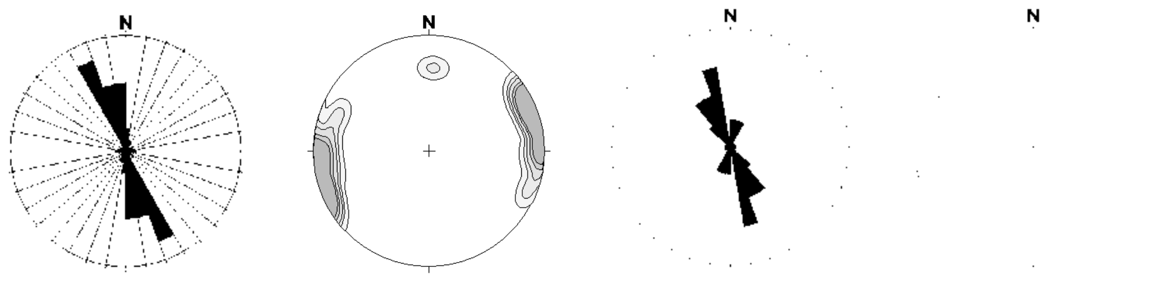
Lithologies in the boreholes are described within two SICADA-files (KFMXXY-p_rock.xls and KFMXXY-p_rock_occur.xls). The difference in content between the two files is that one (..-rock.xls) describes rock sections with a borehole length of one metre or more while the other (..-rock_occur.xls) considers rocks that occur in shorter sections. In this text, data for the latter are added when contributing with additive information.

The foliation in the rock shows a consistent orientation in the five boreholes and the lithological contacts parallels the foliation, Figures 3-1 to 3-5.



KFM07A, foliation, N=101

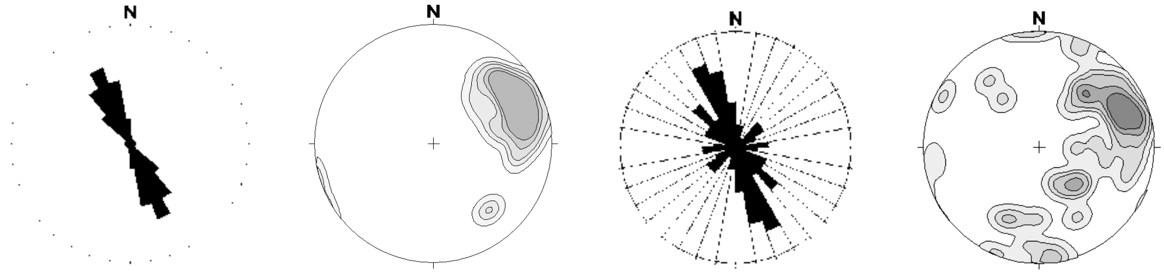
KFM07A, rock contacts, N=150



KFM07A, ductile shear zones, N=51

KFM07A, brittle-ductile shear zones, N=11

Figure 3-1: Foliation, rock contacts and shear zones in the cored borehole KFM07A (Length of borehole: 1002 m; Depth: 815m b.s.l.; Orientation (trend/plunge):261/59).

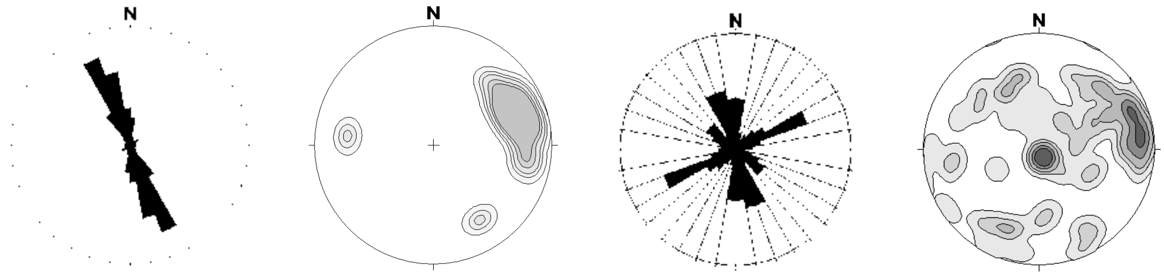


KFM07B, foliation, N= 70

KFM07B, rock contacts, N=53

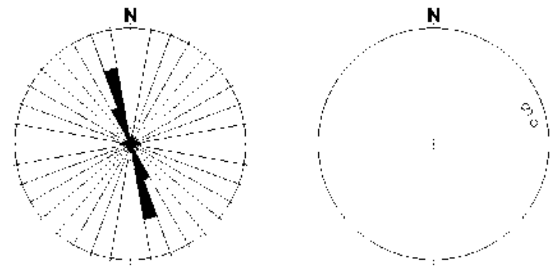
No ductile and brittle-ductile shear zones recorded in KFM07B

Figure 3-2: Foliation and rock contacts in the cored borehole KFM07B (Length of borehole: 299 m; Depth: 237m b.s.l.; Orientation (trend/plunge): 134/55).



KFM07C, foliation, N=32

KFM07C, rock contacts, N=68



KFM07C, ductile shears, N=3

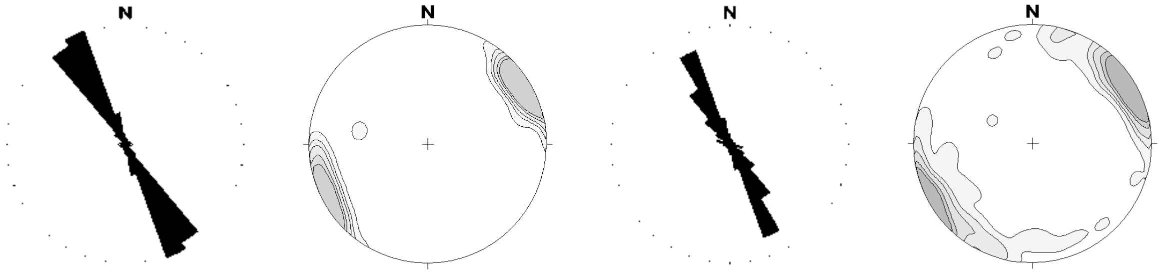
No brittle-ductile shear zones recorded.

Figure 3-3: Foliation, rock contacts and ductile shear zones in the cored borehole KFM07C (Length of borehole: 500 m; Depth: 815m b.s.l.; Orientation (trend/plunge):143/85).

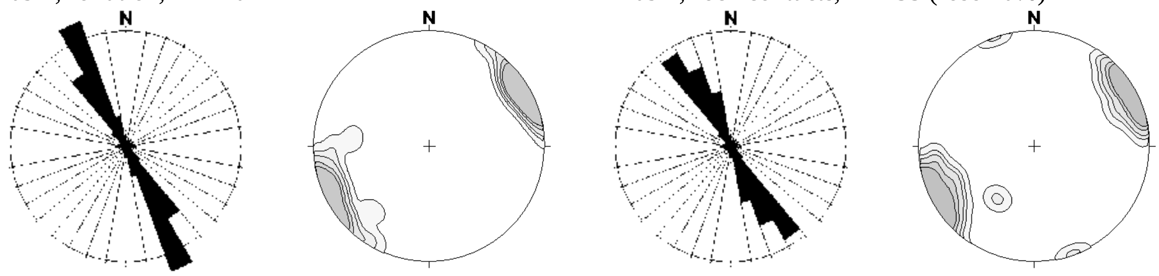
In borehole KFM07A (Figure 3-1), the contacts of thinner aplites and fine to medium granites deviate from the general NNW to NS orientation. Aplites trend NE while the granites are more EW-trending. Three sub-horizontal thin veins of granitic composition occur at depth of about 220, 490 and 580m, respectively.

In KFM07B (Figure 3-2), a spread in orientation of rock contacts is found for metamorphic granodiorites and it is even more pronounced for thin pegmatite veins. This holds also for the contacts of other thin rock units. Just one sub-horizontal pegmatite dyke is fond, at a depth of 90m.

The trend of the foliation in boreholes KFM07C and KFM09A (Figures 3-3 and 3-4) and is slightly more to the NW compared with other boreholes. Thin pegmatites are frequent in borehole KFM07C and have a great spread in orientation with two clusters in NNW/steep W and NE/moderate SE. Amphibolites and felsic rocks are steeply dipping and the trend is mainly NS.

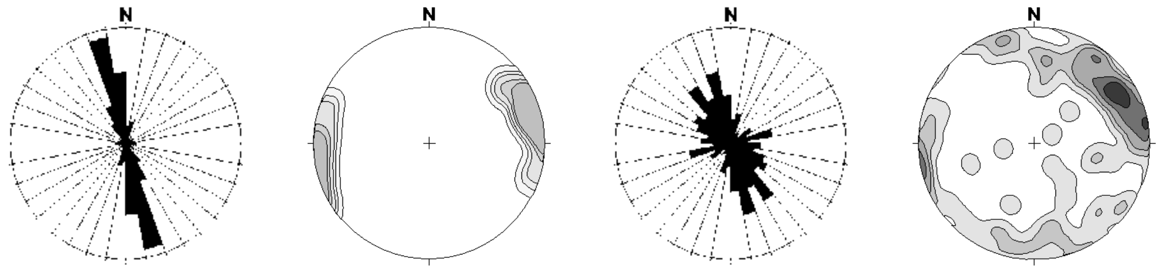


KF09A, foliation, N=120 | KFM09A, rock contacts, N=155 (rose 20%)

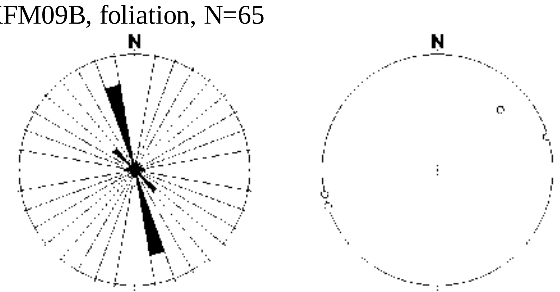


KFM09A ductile shear zones, N=76 | KFM09A brittle-ductile shear zones, N=51

Figure 3-4: Foliation, rock contacts and shear zones in the cored borehole KFM09A (Length of borehole: 800m; Depth: 618m b.s.l.; Orientation (trend/plunge):200/60).



KFM09B, foliation, N=65 | KFM09B, rock contacts, N=96



KFM09B, ductile shear zones, N=3 | No brittle-ductile shear zones recorded

Figure 3-5: Foliation, rock contacts and ductile shear zones in cored borehole KFM09B (Length of borehole: 616 m; Depth: 462m b.s.l.; Orientation (trend/plunge):140/55).

The orientation of rock contacts in KFM07C also differs from the other boreholes because of the more frequent occurrence of gently dipping contacts. The contacts are uniform in orientation (237-245/6-7) and located at depths of about 100m (most frequent), 200m, 410m and 495m.

The intensity in the structural imprint in the rock in borehole KFM09A (Figure 3-4) is revealed by the conformity of the orientation of rock contacts, the foliation and ductile to semi-ductile structures in the rock. The number of mapped shear zones is anomalous high compared to other boreholes. Except for the pegmatites, only two rock contacts deviate in orientation: a tonalite (WNW/subvert) and a diorite (ENE/subvert). A few thin sub-horizontal rock bands, mainly quarts veins, occur at depth of c. 75, 135, 215 and 450m

The distribution of orientations of rock contacts and the uniform orientation of the foliation in borehole KFM09B (Figure 3-5) to some degree resemble that in KFM07C. In borehole KFM09B, 14 steeply dipping ENE-trending breccias are mapped. Most of the breccias have a width of the order of one centimetre; the most extreme one has a length of three decimetres along the borehole. Eight of the breccias are found in a depth interval of 410 to 423m (borehole lengths 528 to 546m) and only one is found at a shallow level (28m). Three sub-horizontal thin bands of granite and pegmatite are found at depths of about 40, 150 and 285m, respectively.

Summing up and general conclusions

The ductile to semi-ductile structures in the rock are relatively uniform with a dominant NNW to NS trend, oblique (approximately 30°) to the northwest trending western border zone located just to the south. The foliation, shear zones and rock contacts are parallel, which reflects the penetrative ductile deformation of the rock. The shears are reactivated in a ductile-brittle state. Of special interest is that foliated and metamorphosed medium-grained granitoids and veins locally have sub-horizontal rock contacts.

3.2 Fractures in boreholes

Fractures in the bedrock exhibit a pseudo-orthogonal symmetry (Figures 3-6 to 3-10), which is somewhat surprising as the area is characterized to be located in an area with major anastomosing shears with large-scale WNW-ESE trending shear lenses.

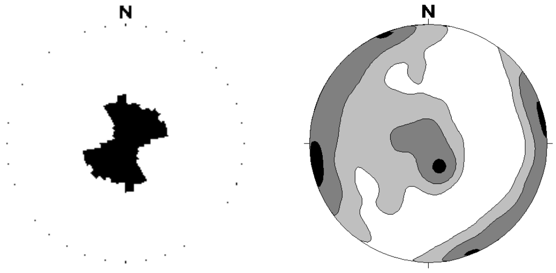
Orientation of all fractures (mapped as open, partly open and sealed) are presented is Section 2.2.1. Open fractures are presented in Section 2.2.2, altered fractures in Section 2.2.4 and fractures with altered wall rock in Section 2.2.6.

Description of fracture frequency and the relative percentage of open fractures are given in Section 2.2.3 and similar data for altered fractures are given in Section 2.2.5. Identification of fracture families and sorting of fracture data to support the modelling is described in Sections 2.2.6 and 2.2.7, respectively.

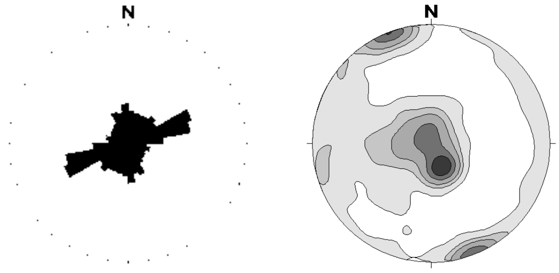
3.2.1 All fractures

In the overview of fracture orientations in boreholes the fracture population is presented for each borehole as, 1) all fractures in the entire borehole 2) all fractures in the depth intervals of 0-300m 3) 300-600m, and 4) below 600m. The depth intervals are chosen to distinguish fractures at possible deposition depth from fractures at shallower or deeper levels.

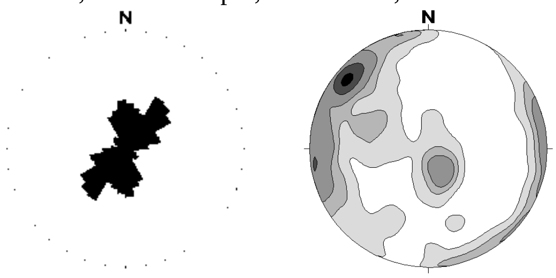
From the borehole data it is obvious that the five boreholes do not have identical fracture patterns, Figures 3-6 to 3-10.



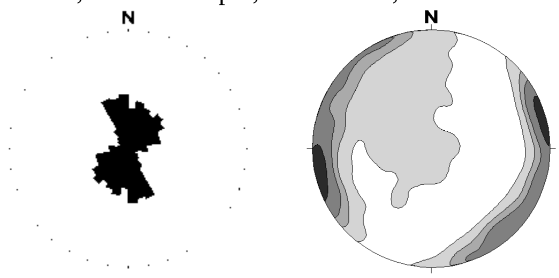
KFM07A, 85-815m depth, all fractures, N=3172



KFM07A, 85-300m depth, all fractures, N=976

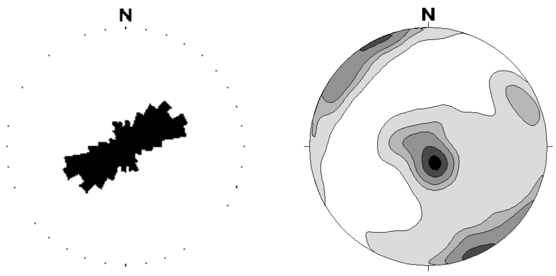


KFM07A, 300-600m depth, all fractures, N=728



KFM07A, 600-815m depth, all fractures 9A, N=1568

Figure 3-6: Fractures in the cored borehole KFM07A (Length of borehole: 1002m; Depth: 815m b.s.l.; Orientation (trend/plunge):261/59).



KFM07B, 1-237m depth, all fractures, N=1706

Figure 3-7: Fractures in the cored borehole KFM07B (Length of borehole: 299m; Depth: 237m b.s.l.; Orientation (trend/plunge): 134/55).

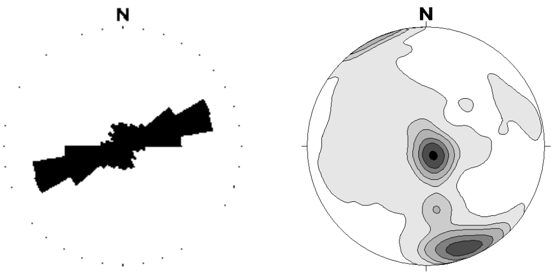
The impression of a pseudo-orthogonal fracture system, when looking at all fractures in the borehole KFM07A (Figure 3-6), is false. At shallow levels, 0-300m, the fracture density is high compared to the middle part of the borehole; ENE/vertical fractures and sub-horizontal fractures dominate. These fractures occur at a large high angle to the foliation (about 80°). At intermediate depths, 300-600m, the fracture intensity decreases and the sub-vertical fracture set dips SE and the subdominant fracture sets dip gently NW and steeply NNE. At depth, borehole KFM07A approaches the regional western border zone and the fracture density increases; the vertical NNW-trending fracture set dominates and is sub-parallel to the foliation, rock contacts and ductile/ductile-brittle shear zones. Steeply dipping NE-trending fractures are sub-dominant.

The cored borehole KFM07B (Figure 3-7) is a shallow borehole and the fracture pattern resemble the pattern in the shallow part of borehole KFM07A, cf. Figure 3-6, dominated by vertical ENE-trending and sub-horizontal fractures dipping NW. The two fracture sets are at a large angle to the foliation, while the subdominant fracture set, oriented NW/steeply SW, is sub-parallel to the foliation. The orientation of the boreholes KFM07B and KFM07C suppresses observations of NW-trending fractures.

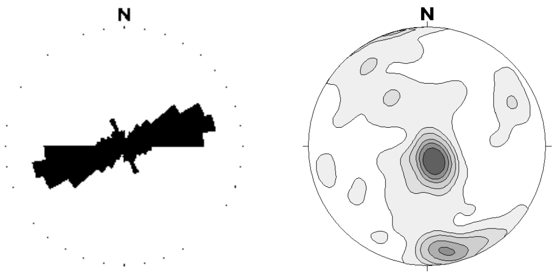
The orientation of fractures in borehole KFM07C (Figure 3-8) is relatively consistent with depth and conforms to fractures in the shallow parts of boreholes KFM07A and B, i.e. fractures at a large to the foliation. In KFM07C, the trend of the sub-vertical fractures shift from EW to ENE with increasing depth. The sub-horizontal fractures conforms to one set of rock contacts, while the correlation between rock contacts and steeply dipping to vertical fractures is weak.

The fracture system in borehole KFM09A (Figure 3-9) is orthogonal and fairly uniform along the length of the borehole. However, there is a increase in the frequency of vertical fractures trending NW and a decrease in NE-trends with depth. The NW-trending fractures are sub-parallel to the foliation and are slightly oblique to the orientation of the regional western border zone.

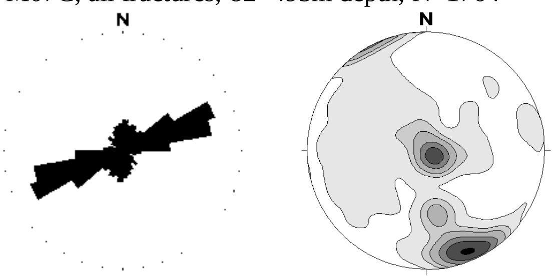
The fracturing in borehole KFM09B (Figure 3-10) is similar to that in the upper part of boreholes KFM07A, KFM07B and KFM07C. One difference, however, is the relatively low frequency of sub-horizontal fractures below 300m depth. The lack of NW-trending fractures in KFM09B is most likely an effect of sampling bias as the orientation of the borehole is SE. Fractures parallel to the foliation are almost absent and this may reflect the sampling bias as the foliation trend is NNW-SSE and is vertical. The fracture pattern is oblique to the orientation of rock contacts in borehole KFM9B.



KFM07C, all fractures, 82- 493m depth, N=1764

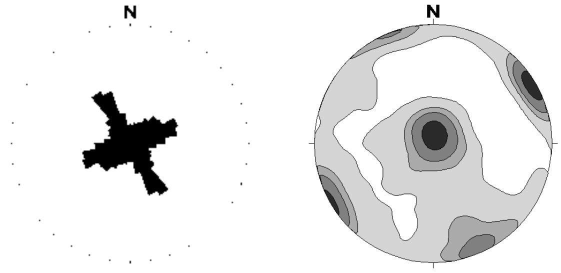


KFM07C, 82-300m depth, all fractures 0-300m, N=593

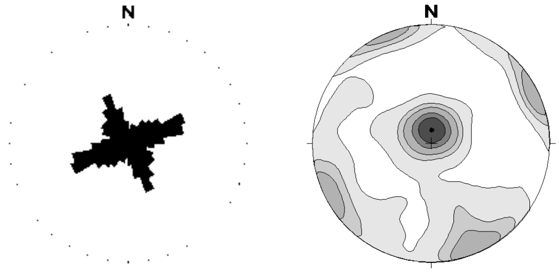


KFM07C, 300-493m depth, all fractures, N=1171

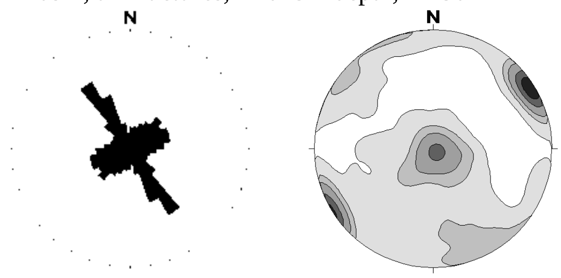
Figure 3-8: Fractures in the cored borehole KFM07C (Length of borehole: 500m; Depth: 815m b.s.l.; Orientation (trend/plunge):143/85).



KFM09A, all fractures, 2- 618m depth, N=5017

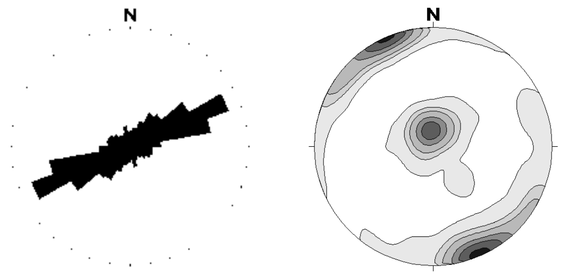


KFM09A, 2-300m depth, all fractures, N=2373

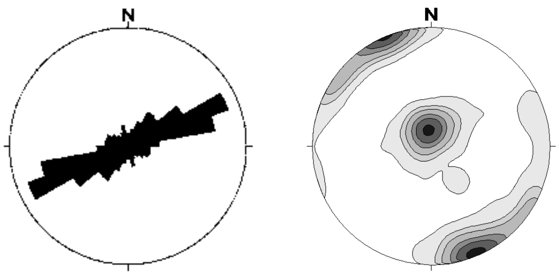


KFM09A, 300-618m depth, all fractures, N=2644

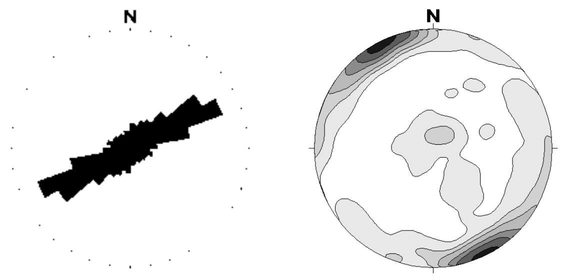
Figure 3-9: Fractures in the cored borehole KFM09A (Length of borehole: 800m; Depth: 618m b.s.l.; Orientation (trend/plunge):200/60).



KFM09B, all fractures, 3-462m depth, N=3491



KFM09B, 3-300m depth, all fractures, N=2645



KFM09B, 300-462m depth, all fractures, N=846

Figure 3-10: Fractures in the cored borehole KFM09B (Length of borehole: 616m; Depth: 462m b.s.l.; Orientation (trend/plunge):140/55).

<u>*Summing up and general conclusions*</u>

The fracture pattern in the bedrock at drill-sites 7 and 9 consists of three dominant sets of fractures: two sets are sub-vertical and trend NW to NNW and ENE to NE, respectively, and the third set is sub-horizontal dipping either SE or NW. The northwesterly trend of boreholes KFM07B,C and KFM09B suppresses observations of steeply dipping fractures trending NW, i.e. structures sub-parallel to the regional system of deformation zones.

3.2.2 Open and partly open fractures

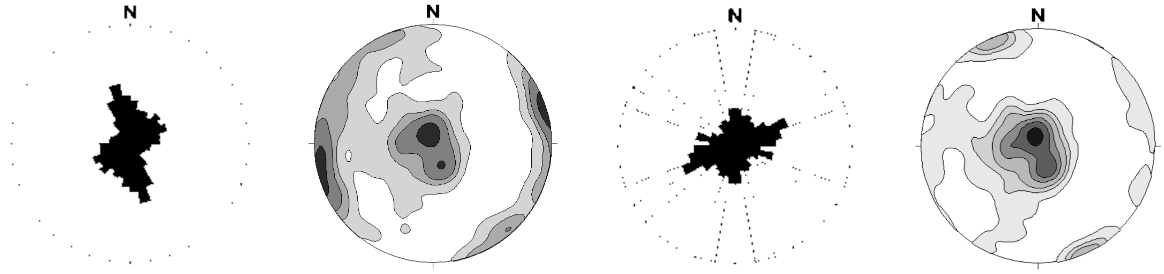
An open fracture, according the SKB Method Description for nomenclature used in Boremap mapping of drill cores (SKB MD 143.008 vers. 1, approved 2004-07-05), is defined as ”a natural fracture in the bedrock filled with gas, water or unconsolidated rock material” (translated by the authors). Partly open fractures (*delvis öppna sprickor)* are described as “fractures mapped as unbroken with channels but interpreted as open”. In this section (cf. figures below) open fractures include all fractures in SICADA (files KFMXX-p_fract_core.xls) that have the attributes “open” or “partly open”. The percentage of “partly open fractures” included in the total number of open fractures for each borehole is given in Table *3-1*. The table also gives the relation between open and partly open fractures in relation to all mapped fractures. Orientation of open fractures are given in Figures 3-11 to 3-15.

Table 3-1: Percentage of fractures mapped as “partly open fractures” in relation to all “open fractures” (open and partly open fractures) in boreholes KFM07A, B, C and FM09A, B (SICADA-files KFMXXY-p_fract_core.xls).

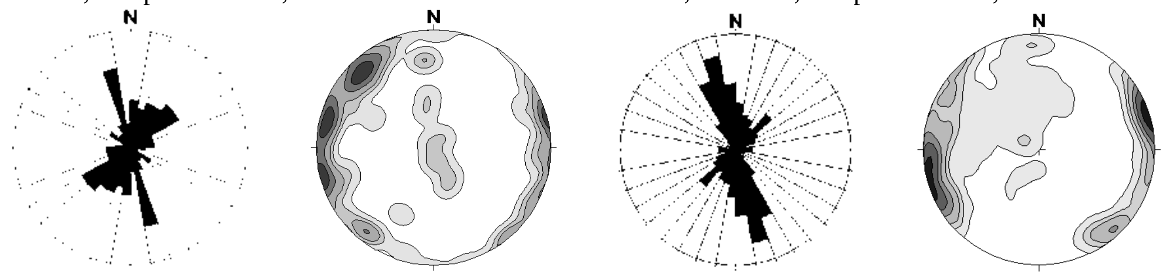
	Borehole				
Parameter	**KFM07A**	**KFM07B**	**KFM07C**	**KFM09A**	**KFM09B**
Percentage of partly open fractures in relation to all open fractures (%)	9.1	9.6	15.3	7.8	10.9
Percentage of all open fractures in relation to all mapped fractures (%)	19.5	35.4	18.4	23.9	22.8

The percentage of “partly open” fractures in relation to all open fractures is rather uniform, about 10%, except for borehole KFM07C (Table 3-1). Borehole KFM07C has the steepest plunge compared with all other boreholes in this study (sub-vertical; plunging 85° SE) and the dominant part of the “partly open” fractures intersected by the borehole is dipping sub-vertically NNW, i.e. they are slightly oblique to the borehole. However, the percentage of all open fractures (open and partly open) in relation to all mapped fractures varies by a factor of two, from 18 to 35 %. The shallow borehole KFM07B has the highest percentage of open fractures, while the boreholes that are deeper and more centrally located in the target area have the lowest average proportion of open fractures and the more westerly located boreholes display higher average values (Table 3-1).

In the cored borehole KFM07A (Figure 3-11) the orientation of open fractures at shallow levels, 0-300m, is dominated by sub-horizontal southward-dipping fractures and vertical fractures trending ENE-WSW. At intermediate depth, 300-600m, the proportion of open sub-horizontal fractures decreases markedly while three other sets of fractures dominate: sub-vertical fractures dipping SE, and vertical fractures trending NNE and NNW. At still deeper levels, 300-815m, the number of open fractures per metre borehole increases markedly. Most frequent are vertical fractures trending NNW-SSE. These open fractures are sub-parallel to the foliation and rock contacts.

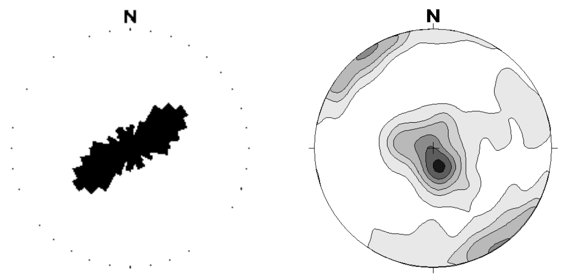


KFM07A, all open fractures, N=617 KFM07A, 85-300m, all open fractures, N=300



KFM07A, 300-600m, all open fractures, N=73 KFM07A, 600-815m, all open fractures, N=244

Figure 3-11: Open fractures in the cored borehole KFM07A (Length of borehole: 1002m; Depth: 815m b.s.l.; Orientation (trend/plunge):261/59).

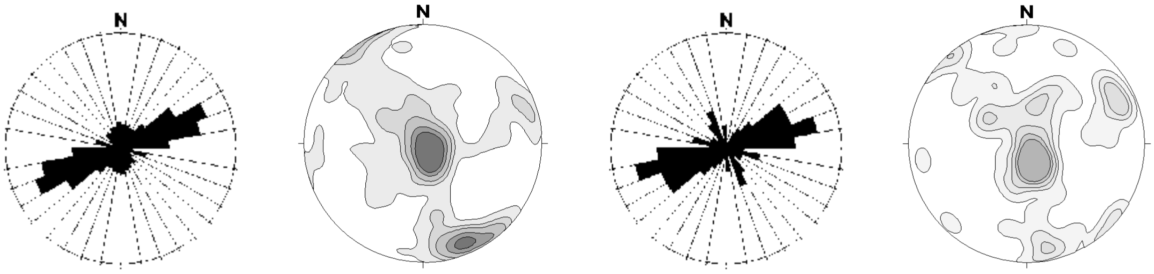


KFM07B, 1-237m, all open fractures, N=575

Figure 3-12: Open fractures in the cored borehole KFM07B (Length of borehole: 299m; Depth: 237m b.s.l.; Orientation (trend/plunge): 134/55; mapped by another team of geologists).

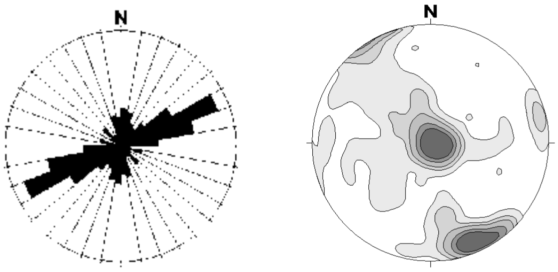
The open fractures in the cored borehole KFM07B (Figure 3-12) consist of sub-horizontal NW-dipping and vertical fractures trending NE-SW. There is also a sub-dominant set of open fractures dipping steeply SW.

In the cored borehole KFM07C (Figure 3-13) sub-horizontal fractures dipping NW are frequently occurring together with sub-vertical fractures dipping SW. At intermediate levels, 300-493m, the number of open fractures increases and the orientation of fractures are horizontal and steeply dipping NW.



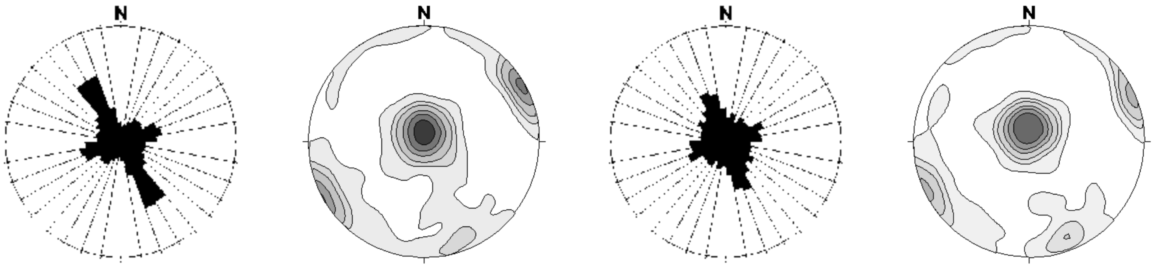
KFM07C, all open fractures, N=285

KFM07C, 82-300m, all open fractures, N=100



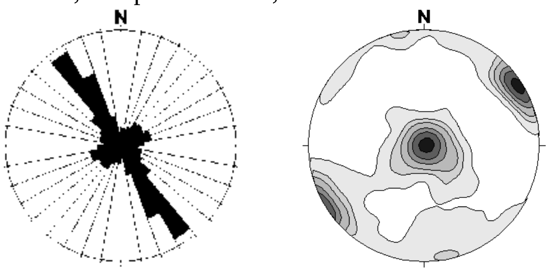
KFM07C, 300-493m, all open, N=185

Figure 3-13: Open fractures in the cored borehole KFM07C (Length of borehole: 500m; Depth: 493m b.s.l.; Orientation (trend/plunge):143/85).



KFM09A, all open fractures, N=1190m

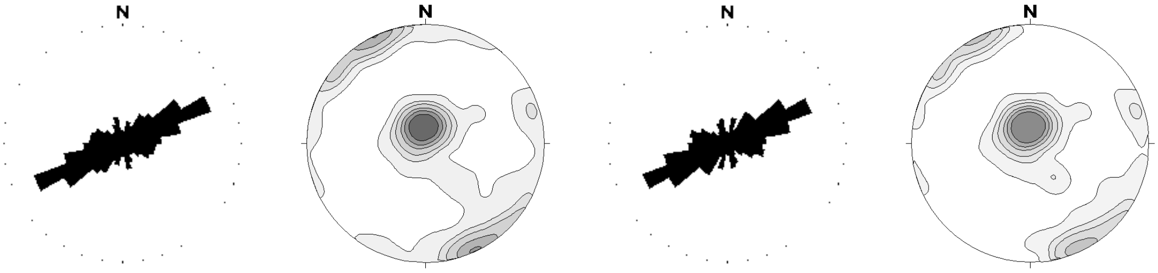
KFM09A, 2-300m, all open, N=675



KFM09A, 300-618m, all open fractures, N=515

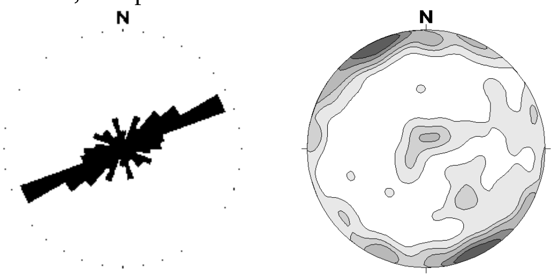
Figure 3-14: Open fractures in the cored borehole KFM09A (Length of borehole: 800m; Depth: 618m b.s.l.; Orientation (trend/plunge):200/60).

The upper 300m and the lower part of the borehole KFM09A (Figure 3-14) have similar fracture patterns. There are some minor differences in the orientation of fractures: at depth sub-horizontal fractures become horizontal and the vertical fractures shift trend from NNW-SSE to be more NW-SE. There is a slight decrease in the fracture density (number of fracture per metre borehole) in the deeper parts of the borehole. The open NW-SE trending fractures show increasing relative occurrence with depth and are sub-parallel to the foliation and to the regional western border zone.



KFM09B, all open fractures N=761

KFM09B, 3-300m, all open fractures N=592



KFM09B, 300-462m, all open fractures N=169

Figure 3-15: Open fractures in the cored borehole KFM09B (Length of borehole: 616m; Depth: 462m b.s.l.; Orientation (trend/plunge):140/55).

ENE-trending fractures, both sub-horizontal and vertical, dominate in the cored borehole KFM09B (Figure 3-15, cf. KFM07C). The frequency of sub-horizontal fractures decreases with depth. The sampling of fractures parallel to the foliation, i.e. NW-SE/vertical fractures, is strongly biased in this borehole because the borehole is sub-parallel to the foliation.

<u>*Summing up and general conclusions*</u>:

Open sub-horizontal fractures occur in the shallow sections (0-300m depth) in all boreholes. The deepest borehole KFM07A show a strong decrease in sub-horizontal fractures with increasing depth and below 600m depth there are very few fracures. A similar decrease is also displayed in borehole KFM09B, while boreholes KFM07C and KFM09A display open sub-horizontal fractures at depths greater than 300m. At shallow levels, open vertical fractures trending NE-SW occur in all boreholes except for borehole KFM09A where NNW/vertical fractures are frequent. With increasing depth the orientation of the open vertical fractures may shift. In borehole KFM07A the dominant trend of open vertical fractures at depth is NNW-SSE and in KFM07C the trend is ENE-WSW. In borehole KFM07C, vertical ENE-WSW trending fractures become more dominant with increasing depth. In borehole KFM09B the open vertical fractures have a constant trend, ENE-WSW, along the entire borehole. In short, fractures outside the regional western border zone are discordant to the orientation of the zone, which implies that they may form transport paths for groundwater from the interior part of the model volume into the regional zone, if the extension of the fractures are long enough or the fractures are connected. The relative occurrence of open fractures in boreholes may indicate both structural inhomogeneity and sampling biases.

3.2.3 Fracture frequencies and percentage of open fractures

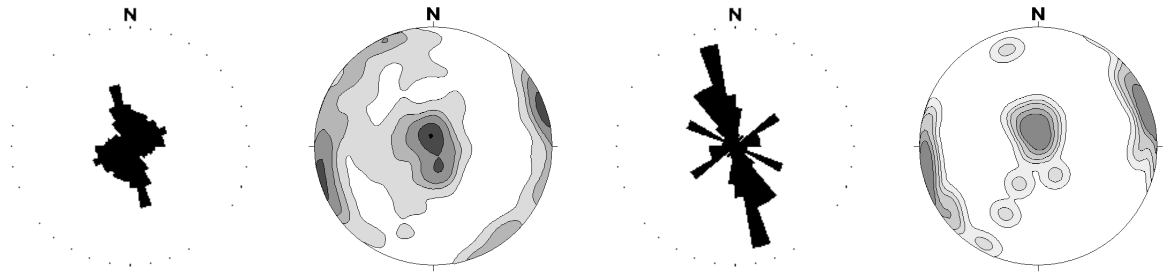
The spread in fracture frequency and proportion of open fractures relative to all fractures in the boreholes is large, Table 3-2. In general, the fracture frequency and the relative proportion of open fractures are greatest in the shallower parts of the bedrock. The variability may reflect the inhomogeneous deformation in the area; the closeness to the regional western border zone in the west but also due to the occurrence of local deformation zones. The fracturing in borehole KFM07 shows the lowest intensity in all boreholes at intermediate depth and the fracturing increases again in the most western and deepest parts of the borehole, i.e. when approaching the regional western border zone. The intense fracturing in the lower parts of KFM07C may reflect the effects of local heterogeneous deformation. Presumably, there is also pronounced sampling bias, e.g. in borehole KFM09B. The separation between open fractures at intermediate depth (repository level) varies from 5m to 0.8m.

Table 3-2: Fractures in cored boreholes KFM07A,B,C and KFM09A,B (bold text – potential repository level). Fracture frequencies are given as number of fractures per metre along boreholes.

	Sections			**Parameters**				
Borehole	**Section secup (m b.s.l.)**	**Section seclow (m b.s.l.)**	**Interval width (borehole length; m)**	**Number of all fractures**	**Number of open fractures**	**All fractures (fr/m)**	**Open fractures (fr/m)**	**Open/all fractures (%)**
KFM07A	85	815	892	3172	617	3.6	0.7	19.5
KFM07A	85	300	253	976	300	3.9	1.2	30.7
KFM07A	**300**	**600**	**363**	**728**	**73**	**2.0**	**0.2**	**10.0**
KFM07A	600	815	276	1568	244	5.7	0.9	15.6
KFM07B	1	237	294	1677	575	5.7	2.0	34.3
KFM07C	82	493	414	1764	285	4.3	0.7	16.2
KFM07C	82	300	219	593	100	2.7	0.5	16.9
KFM07C	**300**	**493**	**195**	**1171**	**185**	**6.0**	**0.9**	**15.8**
KFM09A	2	618	613	5017	1160	8.2	1.9	23.1
KFM09A	2	300	357	2373	675	6.6	1.9	28.5
KFM09A	**300**	**618**	**429**	**2644**	**515**	**6.2**	**1.2**	**19.5**
KFM09B	3	462	591	3491	761	5.9	1.3	21.8
KFM09B	3	300	371	2645	592	7.1	1.6	22.4
KFM09B	**300**	**462**	**220**	**846**	**167**	**3.8**	**0.8**	**19.7**

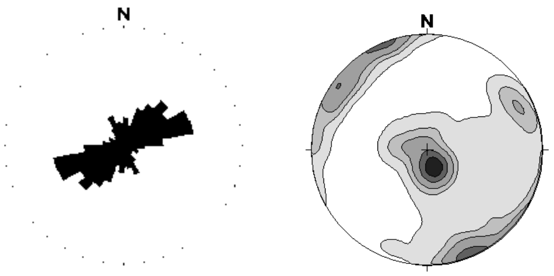
3.2.4 Altered fractures

Two codes describing alteration of fractures are included in BOREMAP: frac_alter_code and joint_alteration. The former describes the alteration of the actual fracture plane and the fracture coating while the second is a rock-mechanical code (not used in this study). However, the alteration of the fracture wall is described together with the fracture minerals in BOREMAP. Further, there is a code that describes the alteration of the rock independently of the location of tectonic structures (rock_alter). However, bedrock alterations occur preferentially as halos along structures, ductile and brittle, and all rock_alter-data are given with orientations.



KFM07A, all altered fractures, N=512 KFM07A, moderately to highly altered fractures, N=46

Figure 3-15: Altered fractures in the cored borehole KFM07A (Length of borehole: 1002m; Depth: 815m b.s.l.; Orientation (trend/plunge):261/59).



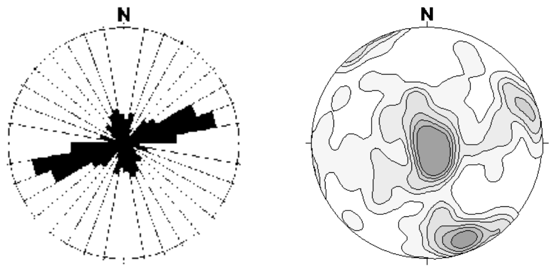
KFM07B, all altered fractures, slightly to moderately, N=1237 (3 moderately altered)

Figure 3-16: Altered fractures in the cored borehole KFM07B (Length of borehole: 299m; Depth: 237m b.s.l.; Orientation (trend/plunge): 134/55; the borehole is mapped by another mapping team of geologists).

The actual mapping of alteration attributes is not described in the method descriptions “Nomenclature applied in Boremap” - core logging (SKB MD 143.008) or the Method Description of BOREMAP – core logging (SKB MD 143.006). The fract_alter_code/fract_alteration is listed in SICADA in files denoted KFMXXY-p_fract_core.xls, wall rock alterations are listed in the same file in columns labelled Min1 to Min5 and the bedrock alteration is listed in KFMXXY-p_rock_alter.xls files. The wall rock alteration and the rock alteration are described in sections 2.2.6 and 2.2.7, respectively.

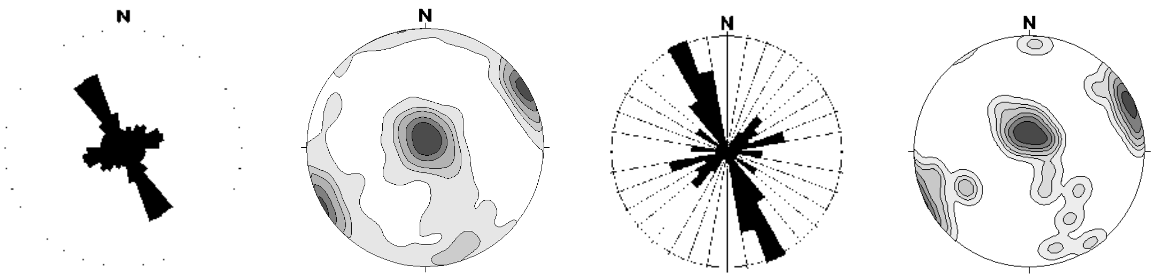
The frequency of altered fractures in borehole KFM07A (Figure 3-15) decreases from the ground surface to a depth of approximately 300m and displays a minor increase below 800m depth. However, in the intermediate depth interval there is an alteration peak at 420m borehole length (slightly to intermediately altered fractures, at c. 355m depth) along vertical NNW-trending fractures. Highly altered fractures (six fractures) are vertical and trending NS to WNW. Slightly altered (466 fractures) fractures show the same pattern as all of the mapped fractures (Figure 3-6), i.e. dominated by NNW/sub-vertical and horizontal fractures.

The number of fractures denoted as slightly altered in SICADA is extreme in borehole KFM07B (Figure 3-16; note that this borehole is mapped by another mapping team). The fractures have an ENE-trend and are either sub-horizontal or vertical. Moderately altered fractures (3) in borehole KFM07B are moderately to gently inclined. No highly altered fractures are found.



KFM07C, all altered fractures, slightly to moderately, N=185 (10 moderately altered)

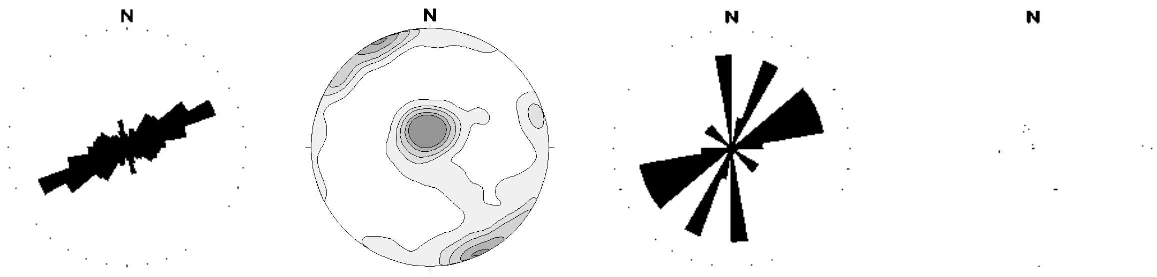
Figure 3-17: Altered fractures in the cored borehole KFM07C (Length of borehole: 500m; Depth: 493m b.s.l.; Orientation (trend/plunge):143/85).



KFM09A, all altered fractures, N=826

KFM09A, all moderately to highly altered fractures, N=49 (3 highly)

Figure 3-18: Altered fractures in the cored borehole KFM09A (Length of borehole: 800m; Depth: 618m b.s.l.; Orientation (trend/plunge):200/60).



KFM09B, all altered fractures, N=577

KFM09B, all moderately altered fractures 9B, N=19

Figure 3-19: Altered fractures in the cored borehole KFM09B (Length of borehole: 616m; Depth: 462m b.s.l.; Orientation (trend/plunge):140/55).

Open fractures in borehole KFM07C (Figure 3-17) exhibit the same pattern as in KFM07B. The moderately altered fractures (10) are sub-horizontal or dip steeply WNW.

In borehole KFM09A (Figure 3-19) moderately (46) to highly altered (3) fractures show the same pattern as the slightly altered fractures, i.e. NNW/vertical and sub-horizontal. The orientation of moderately altered fractures agrees with the orientation of slightly altered fractures. The frequency of altered fractures is somewhat irregular along the borehole and there is an increase toward the end of the borehole. The pattern of altered fractures in the borehole reflects its closeness to the NW-trending regional Eckarfjärden deformation zone.

In borehole KFM09B the altered fractures are oriented ENE/vertical and sub-vertical. The moderately altered fractures (highly altered fractures are not found) show a greater relative dispersion in orientation compared to all altered fractures and gently inclined fractures are dominant.

Summing-up and general results

The system of altered fractures closely resembles that of the open fractures. In all boreholes altered sub-horizontal fractures make up a high proportion of all altered fractures. The distribution of the altered fractures differs somewhat from borehole to borehole. The shallow borehole KFM07B is extreme in the sense that the number of altered fractures is more than two times higher than the number of open fractures. The frequencies of all and open fractures in the borehole KFM07B are higher compared to shallow sections in neighbouring boreholes KFM07A,C (Table 3-2) and similar to comparable sections in boreholes KFM09A,B. The high number of altered fractures in borehole KFM07B may not be fully explained by the borehole being shallower than other boreholes but is due to the fact that the borehole was mapped by a second team of geologists (a matter of inconsistency in the use of nomenclature).

Table 3-3: Altered fractures in cored boreholes KFM07A,B,C and KFM09A,B. Fracture frequencies are given as number of fractures per metre along boreholes.

	Mapped borehole sections			**Parameters**		
Borehole	**Section secup (m bh.l.)**	**Section seclow (m bh.l.)**	**Interval width (m bh.l.)**	**All altered fractures**	**Frequency of altered fractures (fr/m)**	**Altered /all fractures (%)**
KFM07A	85	815	730	512	0.7	16.1
KFM07B	1	237	236	1237	5.2[1]	73.8
KFM07C	82	493	411	185	0.5	10.5
KFM09A	2	618	616	826	1.3	16.5
KFM09B	3	462	459	577	1.3	16.5

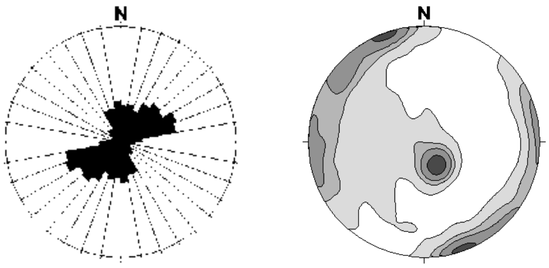
[1] Borehole KFM07B is mapped by another mapping team than KFM07A,C and KFM09A,B.

3.2.5 Fracture frequencies and percentage of altered fractures

The proportion of altered fractures in relation to all fractures (Table 3-3) is relatively constant in most of the boreholes (c. 10-17%); borehole KFM07B is an extreme exception (74%). However, KFM07B is a shallow borehole and mapped by another team of geologists. The frequency of altered fractures in the other borehole is similar to the frequency of open fractures.

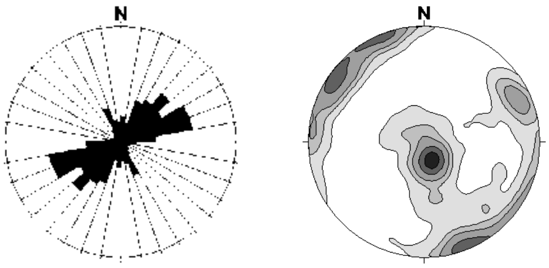
3.2.6 Oxidizes wall rock

The only type of alteration of the rock adjacent and related to a fracture noted in BOREMAP is “oxidized wall” (SICADA files KFMXXY-p_fract_core.xls parameters MIN1 to MIN4). The oxidized wall has a typical red colour and the fractures with such characteristics are oriented in ENE/vertical (dominant) or are gently dipping (Figures 3-20 to 3-25). In KFM07B there are also fractures oriented in NNW/steep SW with oxidized wall rock.



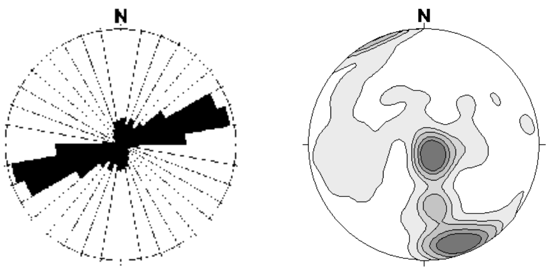
KFM07A, oxidized wall, N=1493

Figure 3-20: Oxidized wall rock in the cored borehole KFM07A (Length of borehole: 1002 m; Depth: 815m b.s.l.; Orientation (trend/plunge):261/59).



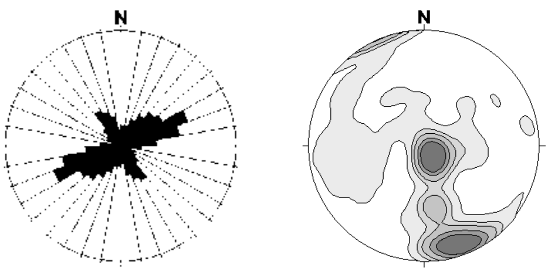
KFM07B, oxidized wall, N=871

Figure 3-21: Oxidized wall rock in cored borehole KFM07B (Length of borehole: 299 m; Depth: 237m b.s.l.; Orientation (trend/plunge): 134/55; the borehole is mapped by another team).



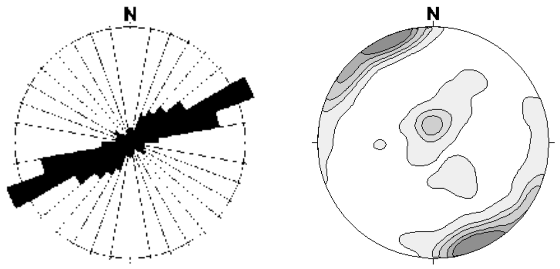
KFM07C, oxidized wall, N=1002

Figure 3-22: Oxidized wall rock in the cored borehole KFM07C (Length of borehole: 500 m; Depth: 815m b.s.l.; Orientation (trend/plunge):143/85).



KFM09A, oxidized wall, N=1789

Figure 3-23: Oxidized wall rock in the cored borehole KFM09A (Length of borehole: 800m; Depth: 618m b.s.l.; Orientation (trend/plunge):200/60).



KFM09B, oxidized wall, N=1336

Figure 3-24: Oxidized wall rock in cored borehole KFM09B (Length of borehole: 616 m; Depth: 462m b.s.l.; Orientation (trend/plunge):140/55).

Table 3-4: Fractures with oxidized wall rock.

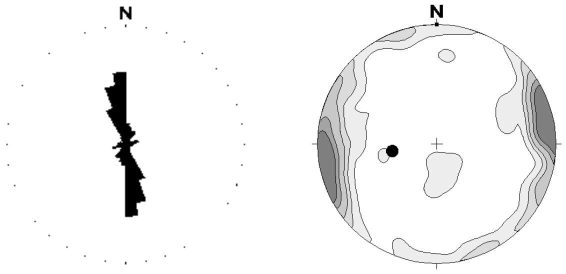
	Borehole				
Fractures	**KFM07A**	**KFM07B**	**KFM07C**	**KFM09A**	**KFM09B**
Proportion of fractures with oxidized wall rock in relation to all fractures in borehole (%)	47.1	45.7	53.7	35.5	38.2
Proportion of fresh fractures amongst fractures with oxidized wall (%)	93.6	2.4[1]	92.6	95.2	93.0

[1] Borehole KFM07B is mapped by another mapping team. The reason for this strong deviation in value is due to an inconsistent use of the nomenclature (see text above).

The proportion of fractures characterized by oxidized wall rock, red coloured, in relation to all mapped fractures in the five drill cores KFM07A,B,C and KFM09A,B, vary from about thirty-five to nearly fifty-five percent (Table 3-4). However, the relative occurrence of fresh fractures among the fractures with oxidized wall rock is uniform and high, about ninety -three percent. Close to all fractures mapped as fresh are sealed, i.e. are tight.

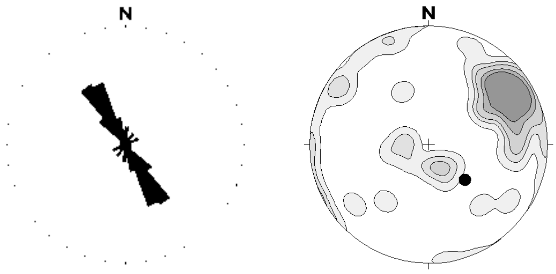
3.2.7 Rock alteration

The orientation of the boundary of rock alteration may be transitional or it may be difficult to determine the orientation. However, all of the altered sections (all but 2 out of 853 readings in boreholes KFM07A,B,C and KFM09A,B) in the host rock are apparently given by the orientation of structures along which the alteration occur. What is sampled appears to be primarily wall rock alteration rather than a general alteration in bedrock. In the figures below, the orientations of the boreholes are displayed as a reference orientation since the orientations perpendicular to the borehole axis may be over-represented. The relative occurrence of different types of rock alterations is given as percentages of borehole lengths.



KFM07A, boundaries of rock alteration, N=262 (rose 20%)

Figure 3-25: Altered rock in the cored borehole KFM07A (Length of borehole: 1002m; Depth: 815m b.s.l.; Orientation (trend/plunge):261/59; black dot).



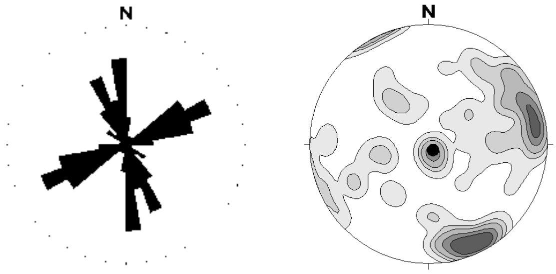
KFM07B, rock alteration, N=85 (rose 20%)

Figure 3-26: Altered rock in the cored borehole KFM07B (Length of borehole: 299m; Depth: 237m b.s.l.; Orientation (trend/plunge): 134/55; black dot).

The boundaries of the alteration in rocks penetrated by the cored borehole KFN07A are vertical and the dominant trend NNW (Figure 3-25). The three most frequent types of alteration of fractures (in percentage of total number of altered fractures) are: Oxidation (10%), albitization (3%), chloritization (1%) and sericitization (1%). The alteration of the rock occurs at all levels. However, oxidation show an increase below 675 m b.s.l., albitization is more common below 515 m b.s.l., and chloritization is frequent below 675m b.s.l.

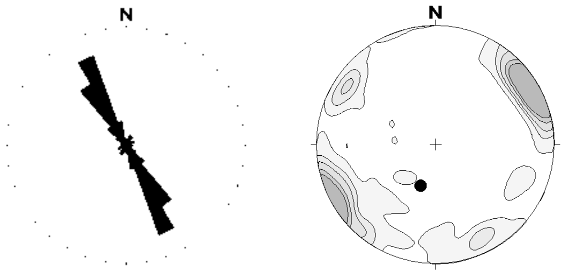
The dominant orientation of domains with altered rocks in boreholes KFM07B (Figure 3-26) is NW/steeply SW. Dominant types of alterations are oxidation (8%) and albitization (2%).

The dominant orientations of domains with alteration in borehole KFM07C (Figure 3-27) are almost parallel to the borehole and trending NNW and ENE, respectively, and there is also a subdominant set of alteration boundaries at right angle to the borehole, i.e. sub-horizontal, similar to what is seen in the pattern of open fractures. The most common types or alteration of the bedrock are: Oxidation (10%), chloritization (1%) and albitization (1%). Oxidation and chloritization are most common below 300m b.s.l., while albitization is more evenly distributed along the borehole.



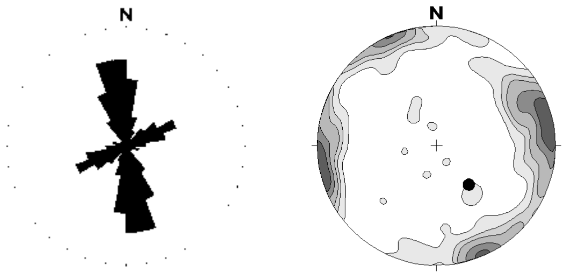
KFM07C, rock alteration, N=132

Figure 3-27: Altered rock in the cored borehole KFM07C (Length of borehole: 500m; Depth: 493m b.s.l.; Orientation (trend/plunge):143/85; black dot).



KFM09A, altered rock, N=195

Figure 3-28: Altered rock in the cored borehole KFM09A (Length of borehole: 800m; Depth: 618m b.s.l.; Orientation (trend/plunge):200/60; black dot).



KFM09B, altered rock, N=178

Figure 3-29: Altered rock in the cored borehole KFM09B (Length of borehole: 616m; Depth: 462m b.s.l.; Orientation (trend/plunge):140/55; black dot).

The dominant orientations of alterations are vertical, trending NW-SE, which is one of the dominant orientations of open and altered fractures in borehole KFM09A (Figure 3-28; cf. Figures 3-14 and 3-18). The most common types of alterations are: Oxidation (10%), albitization (1%) and quartz dissolution (1%). Oxidation is more common below depths of 480m b.s.l. Albitization is most common at depth deeper than 500m. The sections with quartz dissolution occur at a depth of about 415 m b.s.l.

The dominant orientation of boundaries of altered rocks in borehole KFM09B (Figure 3-29) is NNW/vertical; subdominant boundaries are oriented ENE-WSW/vertical. The latter is parallel to open vertical fractures in the borehole, while there are no observed open fractures trending

NNW-SSE. The dominant types of alteration of fractures are: Albitization (12%) and oxidation (9%). Albitization is more pronounced below 200m b.s.l., while oxidation is more frequent at shallow levels (above 100m b.s.l.).

Summing up and general results

In all boreholes there are boundaries of alteration trending NNW-SSE to NNW-SE that are vertical to steeply dipping SW. Sub-vertical boundaries of alteration trending ENE-WSW are conspicuous in two of the boreholes (KFM07C and KFM09B). Sub-horizontal boundaries of alteration are most pronounced in one borehole, KFM07C and occur in boreholes KFM07A,B. Remarkable is that contacts of alteration that are slightly oblique to the borehole axis are easily identified in several boreholes. Furthermore, sub-horizontal sections with altered rock are relatively rare except in borehole KFM07C, in which there exist sub-horizontal lithological contacts.

A pattern seems to appear when comparing the dominant vertical set for the total population of fractures (all fractures), total number of open fractures (open and partly open fractures), altered fractures, sections with altered wall rock and sections with altered bedrock (Table 3-5). The subset comprising all fractures, open fractures, altered fractures wall rock show a separate structural pattern, interdependent of the character of the fractures, while the structural pattern outlined by altered rock have its own geometry. Fractures with altered wall rock, oxidized, are very uniform in all boreholes and similar to the different subsets of other fractures. This is remarkable as the three boreholes plunging southward are biased regarding sampling NW to NS- trending structures and generally enhance sampling of ENE-trending structures. The difference in the two structural patterns does tell us something about the evolution of the structural pattern in the bedrock. It reflects that younger structures may overprint older structures (cf. Table 3-6). To get a better understanding of the structural meaning of the rock alteration, the different types of alterations should be studied separately and compared with the alteration of fractures and the character of the fracture fills. However, it is obvious that ENE/vertical fractures and sub-horizontal have been open and allowed circulation of oxidizing fluids. The difference between these two sets of fractures is that the proportion of open fractures amongst the sub-horizontal fractures is much higher compared with the vertical ENE-trending fractures, at least at more shallow levels. Furthermore, sub-horizontal domains with altered rock are scarce and occur in boreholes with sub-horizontal lithological boundaries. It is indicated that the alteration of the bedrock occur in domains having similar orientation as the ductile deformation (Table 3-6).

Table 3-5: Dominating orientation of vertical to sub-vertical fractures with altered wall rock.

	Borehole				
Parameters	**KFM07A**	**KFM7B**	**KFM07C**	**KFM09A**	**KFM09B**
All fractures	NNW	ENE	ENE	NW	ENE
Open fractures	NNW	ENE	ENE	NW	ENE
Altered fractures	NNW	ENE	ENE	NW	ENE
Oxidized wall rock	ENE	ENE	ENE	ENE	ENE
Altered rock	NS	NW/SW	ENE+NNW	NW-NNW	NS-NNW

3.2.8 Fracture families

In addition to the steeply dipping to vertical fractures summarized in Table 3-6 there are also sub-horizontal fractures in all boreholes. The relative frequencies of fractures vary along boreholes and between boreholes (cf. Table 5-1). The sub-horizontal fractures may either be inclined northwards or be horizontal as in the boreholes KFM07A,B,C or inclined southward as in boreholes KFM09A,B.

A fracture set can be defined as a group of fractures of common origin and the orientation of the fractures are approximately parallel to each other (cf. definition of joint sets by Hobbs et al. 1976). In this case we do not know the relative age of sampled fractures and therefore we just use their orientations. In this report we use the concept fracture family to denote fractures with similar orientations. In boreholes KFM07A,B,C and KFM09A,B the fracture families are:

- ENE/vertical fractures (generally at a high angle to the foliation); dominant
- NNW/vertical fractures, (generally sub-parallel to the tectonic foliation)
- Sub-horizontal fractures (generally at a high angle to the foliation).

The three fracture families form what could be a pseudo-orthogonal fracture geometry in the bedrock. In borehole KFM09A there is a fourth family with orientation NW/vertical and it is assumed to be related to the deformation along a regional deformation NW-trending deformation zone, the Ekarfjärden deformation zone. The orientations of brittle structures are not fully conforming the framework of ductile and ductile-brittle structures in the rock, e.g. ENE orientated structures are outstanding in the population of brittle structures (Table 3-6).

Table 3-6: Summary of orientation of tectonic structures and alteration in boreholes KFM07A,B,C and KFM09A,B. (trends: NW=304-326°(azimuth), NNW=326-348, NS=348-360°, ENE=56-79°;dips: vert=90°, 80°<subvert<90°, steep<80°and sub-hor=sub-horizontal to horizontal, <15°: subdominant sets are given in parenthesis).

	Orientation of structures								
Borehole	**Foliation**	**Ductile shears**	**Ductile-brittle shears**	**Rock contacts**	**All fractures**	**Open Fractures**	**Altered fractures**	**Oxidized wall rock**	**Contacts of altered rock**
KFM07A	NNW to NS/vert	NNW to NS/vert	NS to NNW/steep E	NNW to NS/vert	NNW/vert ENE/vert	NNW/vert	NNW/vert Sub-hor	ENE/vert (NS/vert)	NS/vert
					Sub-hor	Sub-hor		Sub-hor	
KFM07B	NNW/steep W			NNW/steep W	ENE/vert	ENE/vert	ENE/vert (NW/steep W)	ENE/vert	NNW/steep W
						Sub-hor	Sub-hor	Sub-hor	
KFM07C	NNW/steep W	NNW/steep W		NNW/steep W	ENE/sub-vert N	ENE/vert	ENE/steep N	ENE/vert	ENE/steep N NNW/vert
				Sub-hor	Sub-hor	Sub-hor	Sub-hor	Sub-hor	(Sub-hor.)
KFM09A	NNW to NW/vert	NNW/vert	NNW/vert	NNW to NW/vert	NW/vert ENE/vert	NNW/vert	NNW/vert	ENE/vert	NNW/vert
					Sub-hor	Sub-hor	Sub-hor	Sub-hor.	
KFM09B	NNW to NS/vert	NNW to NS/vert		NNW/steep W	ENE/vert	ENE/vert	ENE/vert	ENE/vert	NS/vert ENE/vert
					Sub-hor	(Sub-hor)	Sub-hor	(Sub-hor)	

3.2.9 Sorting of fracture data

For each borehole the following sub-sets of data were sorted into:

1. The character of fractures; five sub-groups: a) all fractures, b) semi-open fractures, c) open fractures, d) sealed fractures, and d) altered fractures
2. The inclination of fractures (θ), five sub-groups: a) θ<20°, b)15°< θ<30°, c)30°<θ <60°, 50°<θ <80°,θ >70°).
3. The azimuth (trend) of steeply to vertical fractures, three subgroups: a) in sectors 40-80° and 225-260°, b) in sector 135-170° and 315-350°, and c) in sector 350-010° and 170-190°.

Histograms were constructed for all of the boreholes and each of the thirteen fracture sub-set listed in bullets 1 to 3 above. These were classified into three classes: 1) peaks (at least a three times higher value than the average frequency), 2) enhanced frequency (up to about twice the value of the level of the average frequency), and 3) below average fracture frequency. For each borehole all frequency data and the location of mapped crush zones (location and fracture orientation) were compiled in a composite log (a spreadsheet) as numerical values and colour-codes of the classes were presented in the background of each presented value. The cluster analysis of geophysical borehole logs (described in the following section) was also included as well as the hydraulic PFL-log. This composite data sheet was used as input data for the construction of the structural model described in Section 6, Brittle deformation model.

4. Cluster analysis using the K-means algorithm in analysing geophysical data from boreholes

4.1 Introduction

A methodology based on cluster analysis of geophysical logs in boreholes in order to identify locations where deformation zones intersect boreholes has been carried out in the SKI project *"Fingerprints of zones in boreholes – an approach to identify the characteristics of structures"* (Sträng, Wänstedt, and Tirén, unpublished report SKI 2006/690/200609025). Since then, some parts of the applied methodology have been refined based on the experiences gained during the previous work and during the processing of the data presented in the present study.

A test of the method has been carried out and evaluated using geophysical borehole data from one borehole in the southern part of the Forsmark candidate area (KFM03A). Comparison of the results from the cluster analysis with fracture mapping data and, further on, with the models from the SKB single hole interpretation (SKB MD 810.003, vers. 3.0, approved 060509: Geologisk enhålstolkning) showed that the analysis method was able to identify possible fractures and fracture zones using geophysical borehole data. The cluster analysis method is assumed to render useful data for the geological modelling activity and the result of the modelling is strongly influenced of this analysis. Therefore, poor background data derived from the cluster analysis process will most likely give an uncertain and, in worst cases, unlikely model.

Sections of the cored boreholes KFM07A,B,C and KFM09A;B included in the cluster analysis are given in Figure 4-1.

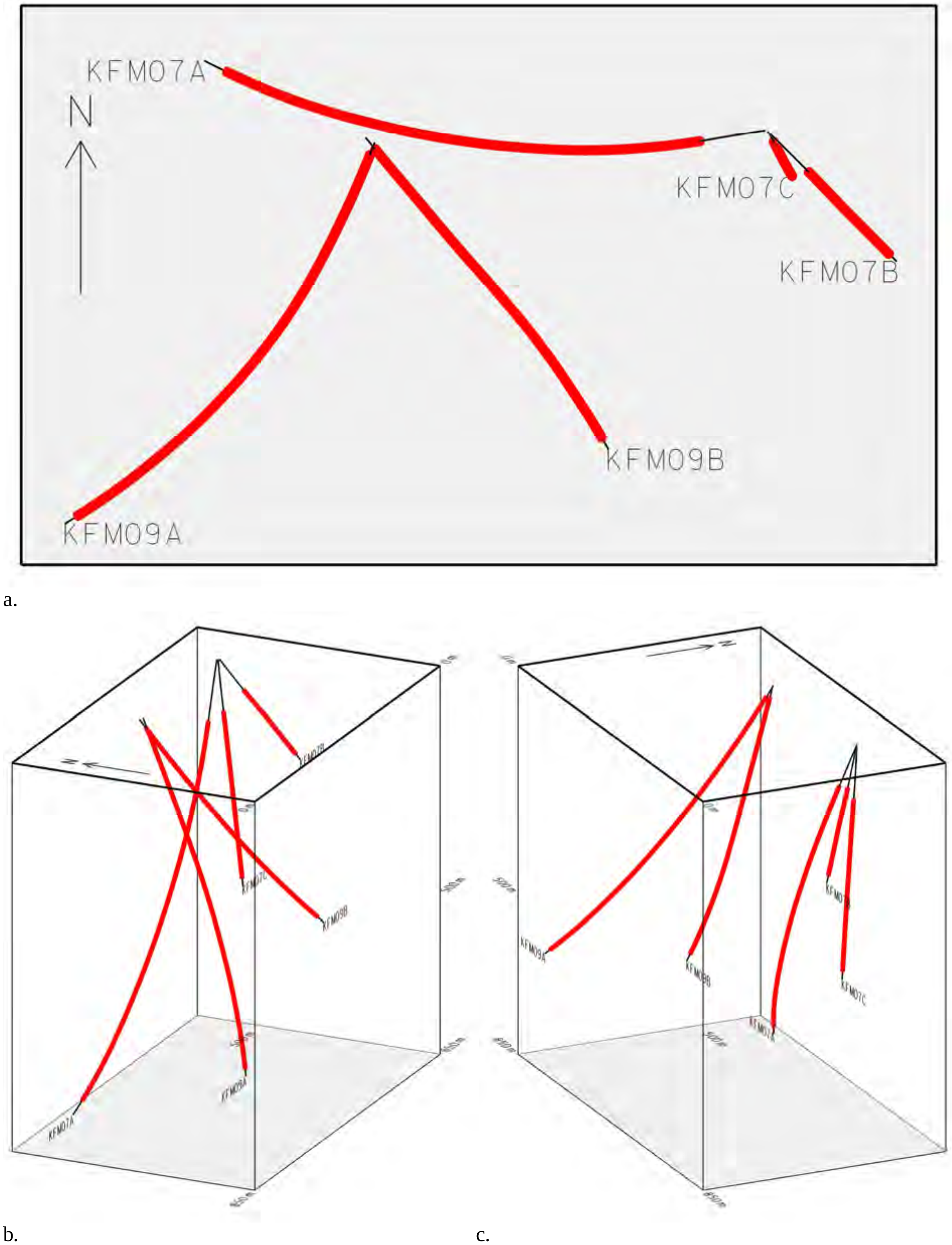
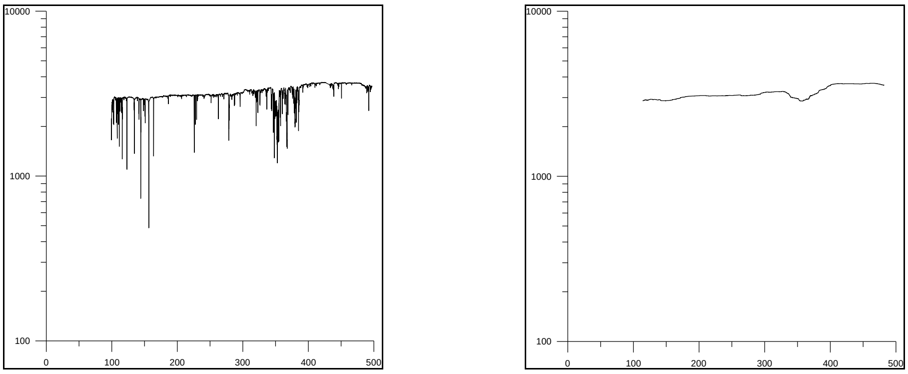


Figure 4-1: Sections of the boreholes included in the cluster analysis are marked with red: a. top view, b. inclined view from southwest, and c. inclined view from southeast. The size of the model is 550 by 900m by 850m deep.

4.2 Data preparation

Data was prepared in the same manner as described in Sträng et al. (unpublished report) and an example of processing steps is:

1. Use gamma, density (gamma-gamma). Magnetic susceptibility, resistivity data (focused 140 and 128cm) and sonic (P-wave) data. Perform basic filtering – removal of obvious outliers.
2. Apply a logarithmic scale conversion of the resistivity data (Figure 4-2).



a) raw data

b) running average filter (n=301)

Figure 4-2: Example of trend removal of resistivity data KFM07C focused resistivity140cm.

4.3 The cluster analysis methodology

The K-mean cluster analysis method is briefly explained in Sträng et al. (in press), Figure 4-3.

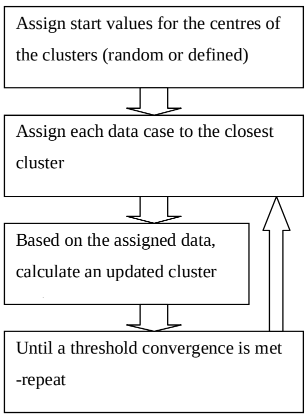


Figure 4-3: An algorithm describing the K-mean Cluster analysis technique.

Generally, data from the boreholes in the Forsmark region seem to work well with the K-means cluster analysis concept. The method, which was designed based on data from the KFM03 borehole, works well with the lithological conditions found in the Forsmark area. Bedrock units which exhibit similar geophysical responses will have similar background noise when trying to identify sections with fracture and fracture zones and facilitates the analysis. Inhomogeneous bedrock sequences containing rocks with contrasting geophysical signature may effect in the analysis and should therefore be considered.

Work flow for Cluster analysis (K-means) used is outlined as follows:

1. Import data into an appropriate statistical analysis programme (in this study: Statistica©), perform during the process of identifying data parameters.
2. Perform tree-clustering in order to inspect data clustering distances.
3. Perform K-means clustering for all data parameters using two clusters. Inspect to ensure that the parameters are contributing to the cluster analysis, i.e. fulfilling the criteria posted – all parameters should show relative negative values at the locations of fractures.
4. Extract cluster data and perform a second K-mean cluster analysis on that subset of data.
5. Apply a running average filter to the resulting data to enhance structures larger than 0.5m.

The used geophysical logs are listed in Table 4-1.

Table 4-1: Geophysical methods used in the cluster analysis process. A "+" sign denotes the use of a parameter while a "–" sign denotes that a parameter is discarded.

Method,	Gamma	Density	Magnetic susceptibility	Resistivity RES 300	Resistivity RES 140	Sonic
Run	1st / 2nd	1st / 2nd	1st / 2nd	1st / 2nd	1st / 2nd	1st / 2nd
Borehole						
KFM07A		+ /..-	+ / +	+ / -	+ / +	+ / +
KFM07B			+ / +	+ / +	missing	+ / +
KFM07C	+ / +	+ / +	+ / +	+ / -	+ / +	+ / +
KFM09A	+ / +		+ / +	+ / +	+ / +	+ / +
KFM09B	+	+		+	+	+

4.4. Results

Although it was attempted to use all of the parameters throughout the entire analysis it became obvious that the various parameters used contributed unequally to the analysing process. From a geophysical point of view, it might be obvious that certain of the parameters will "detect" open fractures better than others. Resistivity and P-wave velocity of the fractures almost always exhibit distinct anomalies for the fractures. This might not be the case for the gamma, density and magnetic susceptibility parameters. The background values of these parameters might not be high enough to cause to a large enough anomaly when measurements are carried out at a fracture.

The governing condition is that the cluster analysis must result in cluster means for each geophysical parameter that indicate a fracture (i.e. a negative anomaly). If this is not the case the parameter is dropped.

4.4.1 KFM07A

This borehole is 1002.1 metres long and geophysical logging is made below 100m. Due to the fact that a running average filter was used to create the trend-corrected data, a portion of the borehole at the top and at the bottom was omitted. This "loss" of data at the very bottom and top of the bore hole is applicable to all boreholes. A total of 8392 cases are used in the cluster analysis process representing the borehole sections between 128 and 967m.

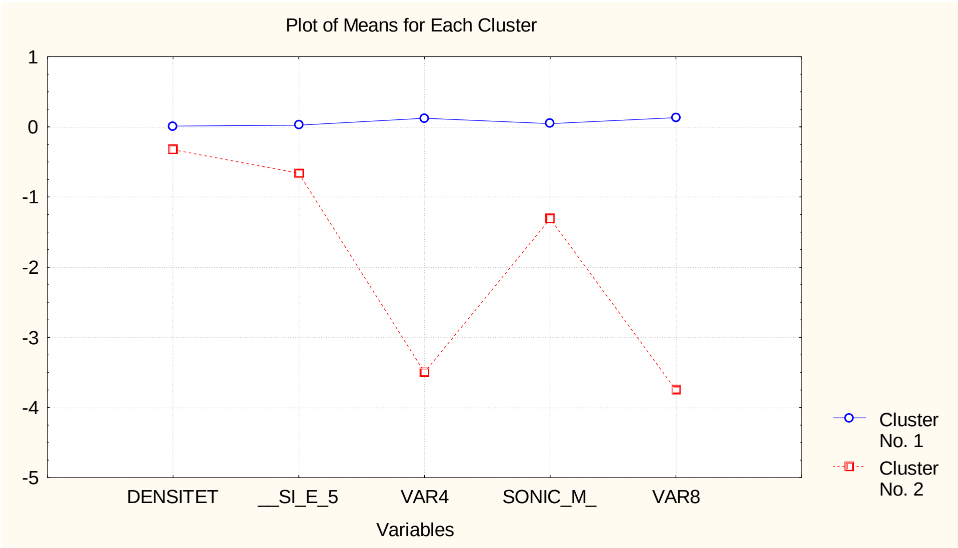


Figure 4-4: KFM07A. The results of the first run using the K-mean cluster analysis; a total number of 8392 cases were used. The cluster which denotes the occurrence of fractures is labelled as no. 2 and contains 285 cases. Cluster no. 1 consists of 8107 cases.

In the first run (Figure 4-4), five parameters were used (magnetic susceptibility, density, sonic P-wave and two resistivity readings: focused 140 and 300cm). In the second run, the density log was removed since it did not contribute to the analysis process.

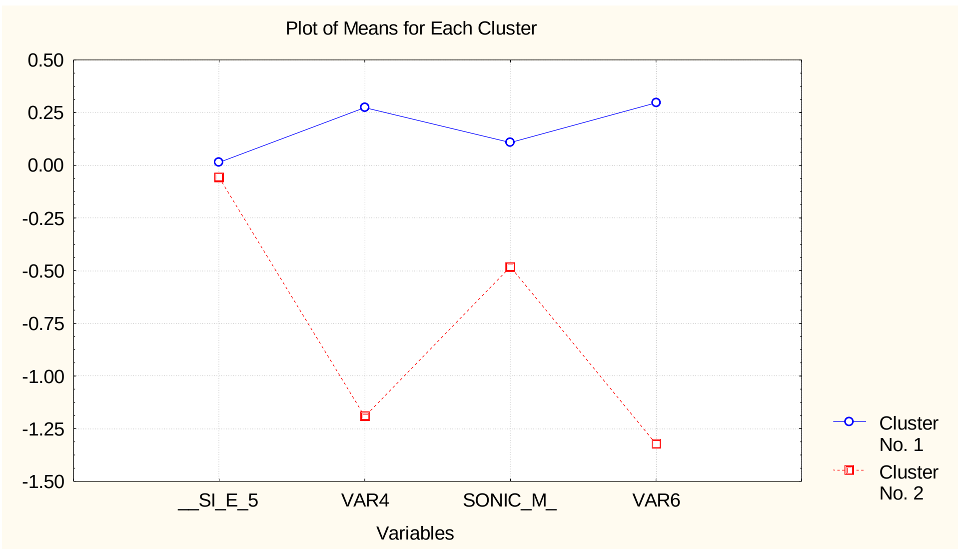


Figure 4-5: Cluster analysis second run KFM07A. Four parameters were used (_SI_E_5 = Magnetic susceptibility, VAR4= focused res300, SONIC_M_= Sonic P-wave, VAR6 = focused res140). Cluster 2 contains 55 cases.

The second run (Figure 4-5), using four parameters on a total of 285 cases indicated 55 cases belonging to the fracture cluster group, Figure 4-4.

4.4.2 KFM07B

The K-means cluster analysis was carried out with only 3 components (magnetic susceptibility, focused resistivity300 and P-wave sonic data), Figures 4-6 and 4-7. Only roughly 200m of borehole data was available (data were applied after removal of background resistivity). Analysed section of the borehole is from 91 to 282m borehole length.

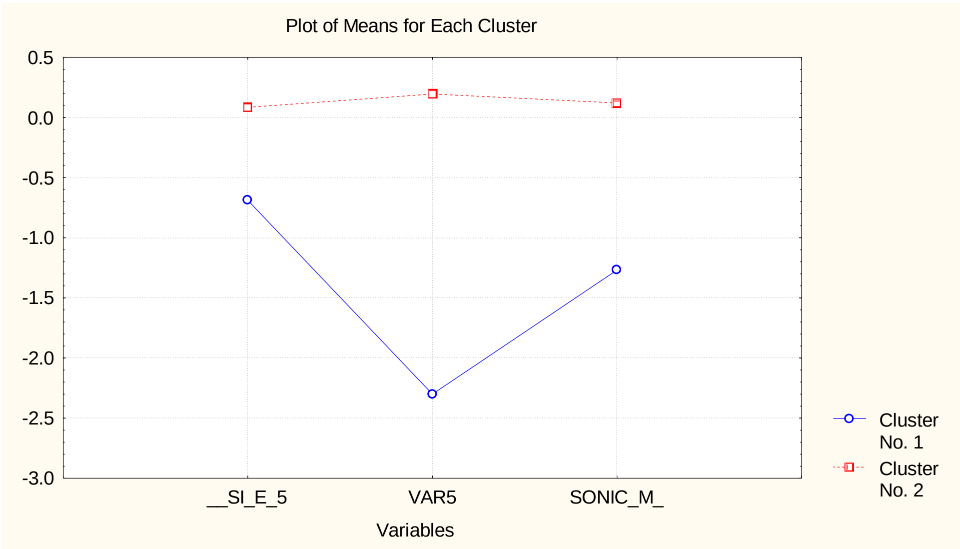


Figure 4-6: KFM07B. The result of the first run using the K-mean cluster analysis; a total number of 2009 cases were used. Three parameters are used (_SI_E_5 = Magnetic susceptibility, VAR5= focused res300, SONIC_M_= Sonic P-wave). The cluster which denotes the occurrence of fractures is labelled as no. 1 and contains 157 cases. Cluster no. 2 consists of 1852 cases.

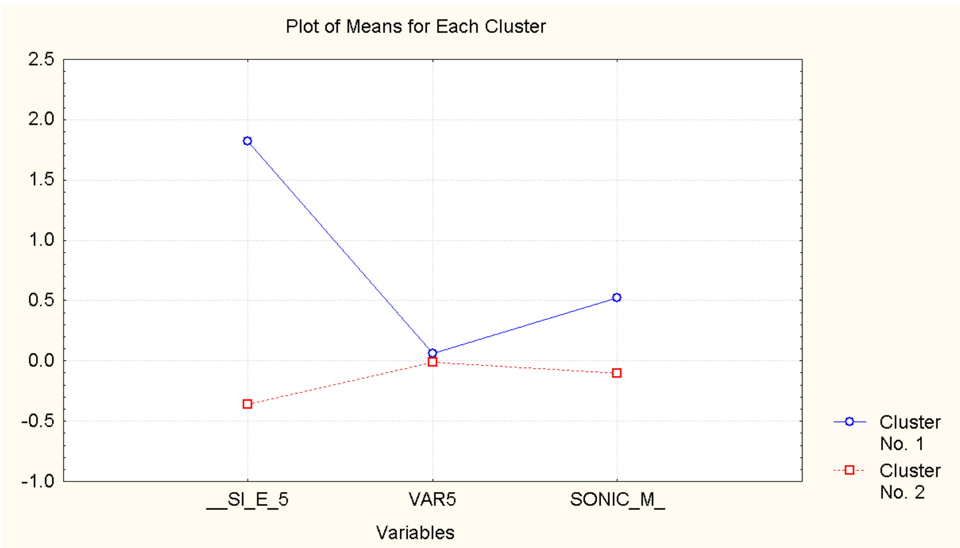


Figure 4-7: Result from the second run KFM07B, Cluster no. 2 contains 26 cases.

4.4.3 KFM07C

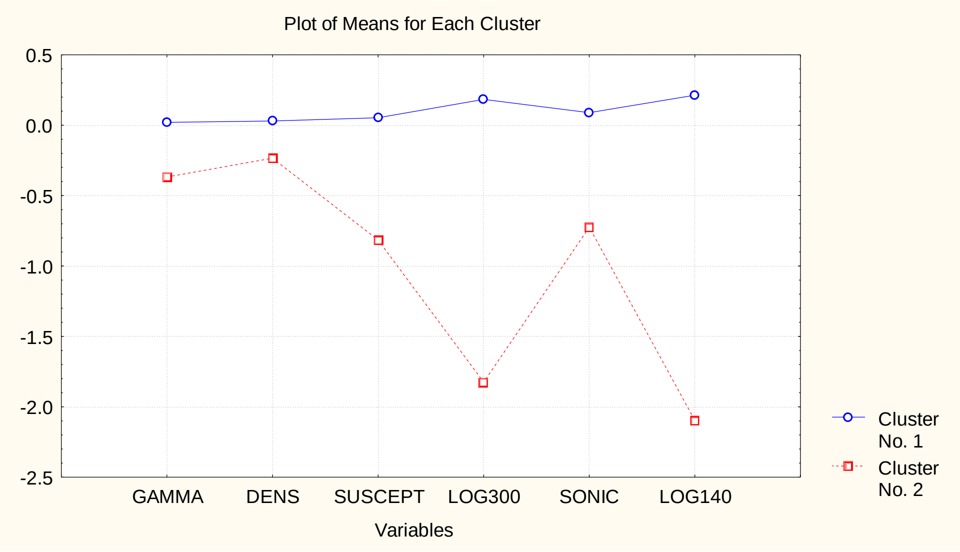


Figure 4-8: KFM07C. The results of the first run using the K-mean cluster analysis; a total number of 3627 cases were used using six parameters. A total number of 332 cases defines the fracture (no. 2) cluster.

In the second run (Figure 4-9, cf. Figure 4-8), comprising the borehole section 115 to 438m borehole length, it is evident that the res300 tool could not be used further in the cluster analysis process. In contrast to some of the parameters omitted for the previous boreholes, the resistivity parameter should contribute to the analysis process even in this case. The explanation for this is probably an incorrect trend removal of the resistivity data. The running average filter used to remove the trend in the data was not effective enough, thus leaving a trend in remaining data which is larger in amplitude than the remaining anomalies. This is clearly a setback for the method and the trend removal process needs to be refined and designed to be carried out in a more automatic way to retain the objectivity in the analysing process.

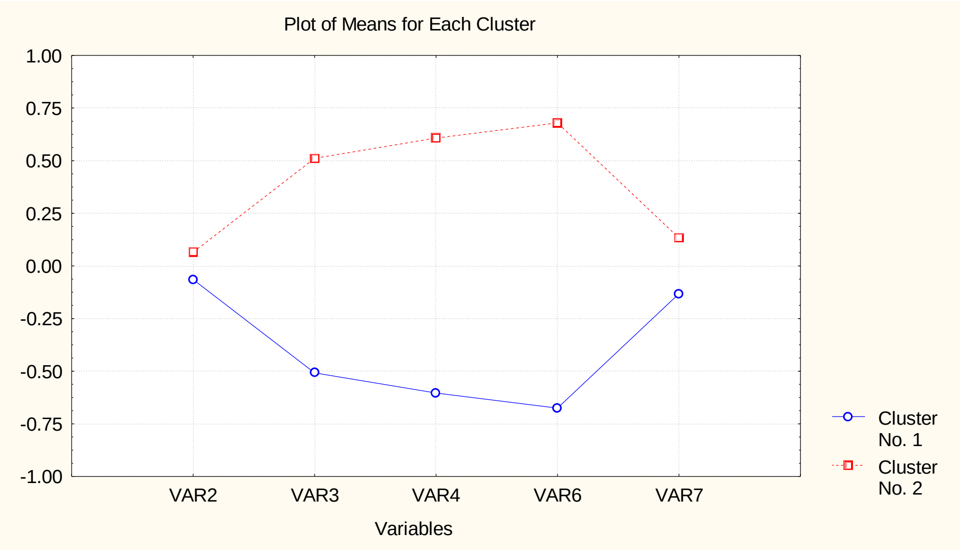


Figure 4-9: KFM07C. The result of the second run; a total number of 331 cases were used. Five parameters were used (VAR2= Gamma, VAR3=Dens, VAR4= Magnetic Susceptibility, VAR6= Sonic P-wave, VAR7= focused resistivity 140cm). The cluster which denotes the occurrence of fractures is labelled as no. 1 and contains 165 cases. Cluster no. 2 consists of 166 cases.

4.4.4 KFM09A

Figure 4-10: Result from cluster analysis KFM09A, a total of 7479 cases were used. Cluster no. 1 contains 1181 cases.

Analysed section is 24 to 782m borehole length. Two runs were performed (Figures 4-10 and 4-11).

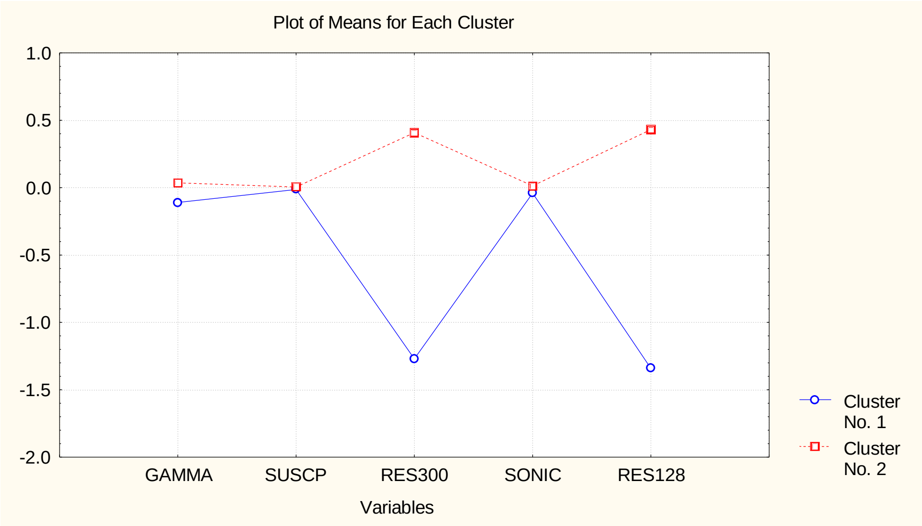


Figure 4-11: Result from second run borehole KFM09A. The cluster analysis is strongly influenced and controlled by the resistivity parameters. The analysis resulted in 287 cases for the fracture cluster (no. 1).

4.4.5 KFM09B

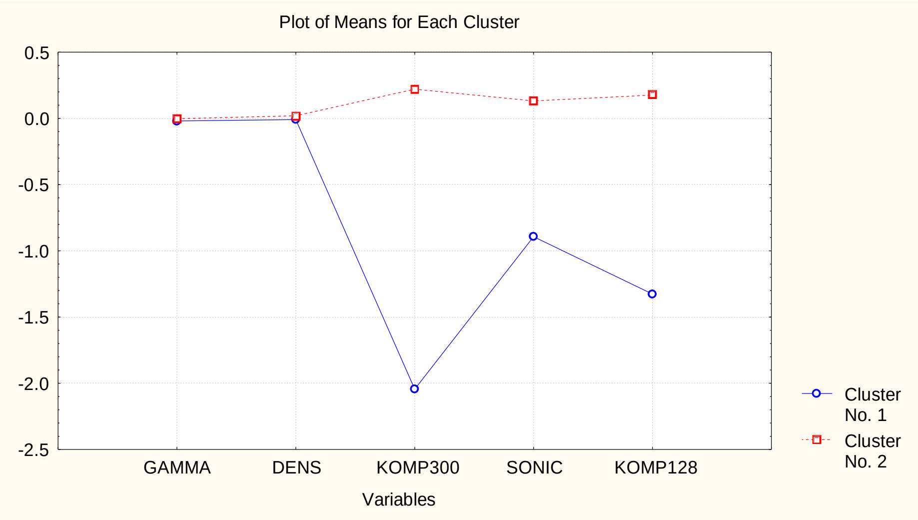


Figure 4-12: Result from cluster analysis KFM09B, a total number of 5687 cases were used. Cluster no. 2 contains 491 cases.

Only one run (Figure 4-12) was carried out since the second did not provide useful results.

4.4.6 Summary of results

The cluster analysis indicates 121 potential structure intersections in boreholes, Tables 4-2, 4-3 and 4-4 and Figure 4-13. When reading the tables one should consider that the data represent one-dimensional sampling (lines) of a three-dimensional structural framework.

Four of the five cored boreholes that are used in this study reach repository depth (400-500m b.s.l). The fifth borehole KFM07B is shallow and has an orientation close to that of the steeper borehole KFM07C, i.e. the two boreholes should sample the same set of vertical structures.

The two deeper boreholes KFM07A and KFM09A sample the rock below repository depth. However, the two boreholes have divergent directions and the distance between them below 500m b.s.l. is in the range of 508m to 516m. Borehole KFM07C, reaching a depth of c. 495m b.s.l., is the most centrally located borehole among boreholes KFM07A,B,C and KFM09A,B.

The highest numbers of clusters per length of boreholes are found in boreholes KFM07B and KFM07C (0.094 and 0.082 clusters/m, the mean separation of clusters is about 10m along the boreholes, Table 4-3) and also their ratios of total width of clusters to measured borehole sections are the highest (15% and 20%, respectively). Borehole KFM07B is shallow and moderately inclined while borehole KFM07C is relatively deep and sub-vertical. Corresponding values for the other three boreholes are 0.021 to 0.040 intersections per metre borehole length and the clusters make up about 6 to7 % of the borehole lengths. The separation of clusters along boreholes appears to be greater at repository level (400 to 600 m b.s.l.) than in shallower borehole sections.

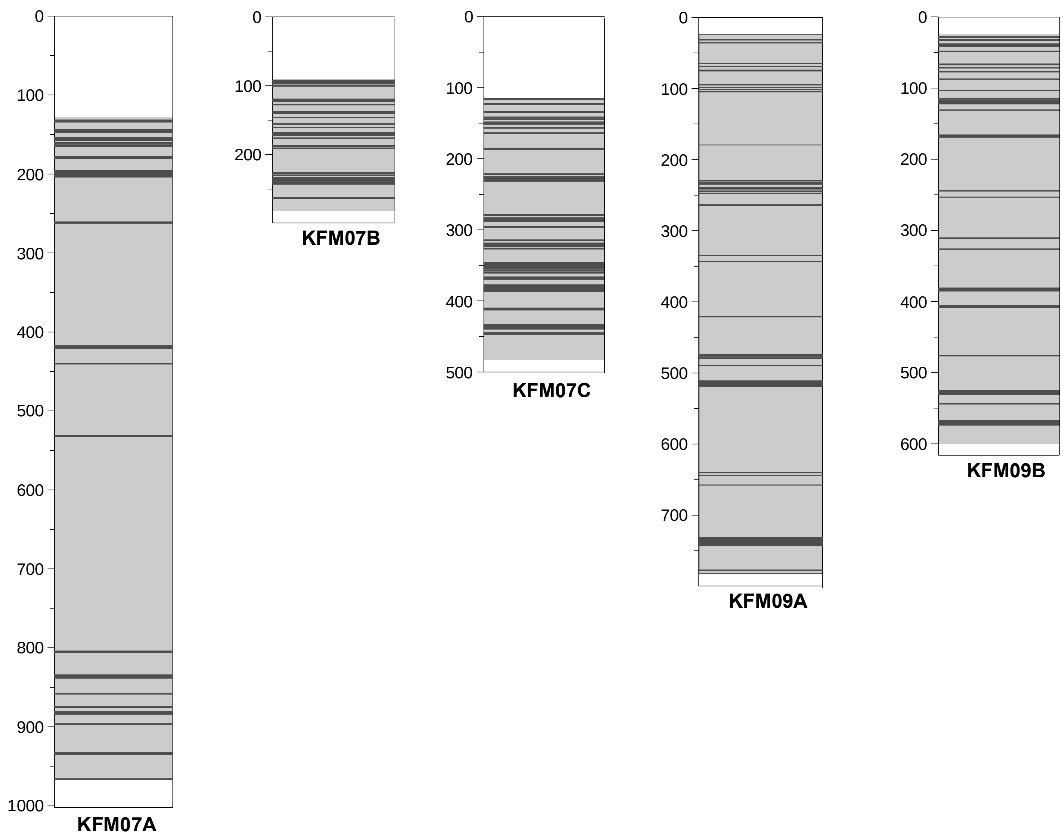


Figure 4-13: Location of clusters in boreholes KFM07A,B,C and KFM09A,B. Grey sections mark the cluster analysed sections.

Table 4-2: Clusters representing the potential intersection of deformation zones with boreholes KFM07A,B,C, and KFM09A,B. The more pronounced clusters are typed in bold letters (only distinguished in boreholes KFM07A,C and KFM09B). The depth-intervals are given by colour codes: red is above -300m b.s.l, light green is at the depth interval -300 to -400m b.s.l., dark green -400 to -600m b.s.l., and yellow deeper than -600m b.s.l. The given borehole section (bh-section) is the part of the borehole included in the cluster analysis. (Bh/bh = borehole; m bh.l. =metre borehole length).

Borehole	***KFM07A***		***KFM07B***		***KFM07C***		***KFM09A***		***KFM09B***	
Bh-section (m)	*128-967*		*91-282*		*115-483*		*24-782*		*25-600*	
Bh-orientation	*261/59*		*134/55*		*143/85*		*200/85*		*140/55*	
Cluster ID KFM0YZ:X	*Secup (m bh l.)*	*Seclow (m bh.l.)*	*Secup (m bh.l.)*	*Seclow (m bh.l.)*	*Secup (m bh.l.)*	*Seclow (m bh.l.)*	*Secup (m bh.l.)*	*Seclow (m bh.l.)*	*Secup (m bh.l.)*	*Seclow (m bh.l.)*
1	**131.5**	**134.5**	91.6	97.6	114.5	116.7	**30.5**	**32.2**	27.2	29.3
2	**143.2**	**147.5**	99.1	100.9	122	123.8	35.2	36.2	31.3	33.1
3	153.6	157.6	119.2	123	133.6	135.0	64.6	65.1	37.6	41.7
4	160.2	161.7	126.7	127.9	141.0	142.2	69.3	69.7	48.0	49.0
5	162.8	165.1	137.5	140.3	143.6	144.9	**73.8**	**75.7**	66.0	67.4
6	**177.8**	**180.3**	145.5	146.5	147.9	148.9	**94.2**	**95.3**	71.1	72.2
7	**195.5**	**204.0**	155.0	156	149.8	151.6	98.5	99.0	76.3	77.4
8	**260.5**	**262.0**	160.1	161.1	**155.6**	**157.1**	101.4	101.8	87.1	88.0
9	**417.3**	**421.12**	167.6	169.5	163.3	164.5	**103.6**	**104.9**	103.1	103.9
10	439.4	440.6	170.2	171.9	**184.8**	**187.0**	179.1	179.6	114.7	116.0
11	**531.1**	**532.4**	175.5	176.5	**221.0**	**222.2**	**228.9**	**230.3**	117.3	122.4
12	803.9	806.0	186.0	188.6	225.2	226.4	**231.8**	**234.9**	130.6	131.4
13	**834.0**	**838.5**	190.0	191.0	227.0	228.1	**238.7**	**241.7**	165.6	169.3
14	**857.6**	**858.8**	225.9	228.0	229.0	230.0	**243.9**	**245.5**	244.3	245.0
15	873.9	875.5	229.2	230.5	230.6	231.6	247.5	248.0	253.0	253.7
16	880.4	884.4	232.8	238.8	278.0	280.2	**263.4**	**264.6**	310.6	311.5
17	**896.1**	**897.2**	239.6	243.1	282.8	283.9	334.7	335.3	326.0	326.7
18	**932.5**	**935.5**	262.2	263.5	**284.7**	**288.1**	343.2	343.9	380.9	385.6
19	965.7	967.2			295.2	296.8	420.9	421.3	405.6	409.1
20					**313.8**	**315.6**	**474.0**	**476.0**	475.7	476.7
21					**318.3**	**323.6**	**477.1**	**477.7**	525.2	531.0
22					**325.4**	**327.1**	**478.4**	**479.6**	543.6	544.4
23					**345.9**	**355.6**	489.0	489.5	566.8	573.9
24					**356.7**	**358.2**	**511.1**	**519.1**		
25					**359.8**	**361.0**	640.2	640.9		
26					**366.0**	**369.6**	644.1	644.7		
27					**377.0**	**382.9**	657.4	658.0		
28					**383.9**	**386.8**	**731.0**	**741.3**		
29					409.7	412.9	**742.2**	**743.3**		
30					**433.2**	**439.7**	**776.9**	**778.1**		
31					444.4	447.1				

Table 4-3: Width and separation of clusters in boreholes KFM07A,B,C, and KFM09A,B. The width is measured along the drill core (m bh.l.) and the separation is given as a measure of the distance of the centre points of clusters (C_x) along the drill core (C_x-C_{x-1}). Colour codes are explained in Table 4-2. The given borehole section (bh-section) is the part of the borehole included in the cluster analysis. (cl. = cluster; Std = standard deviation)

Borehole	KFM07A		KFM07B		KFM07C		KFM09A		KFM09B	
Bh-section (m)	128-967		91-282		115-483		24-782		25-600	
Bh-orientation	261/59		134/55		143/85		200/85		140/55	
Cluster ID KFM0YZ:X	Width (m bh.l.)	C_x-C_{x-1} separation (m bh.l.)	Width (m bh.l.)	C_x-C_{x-1} separation (m bh.l)	Width (m bh.l.)	C_x-C_{x-1} separation (m bh.l)	Width (m bh.l.)	C_x-C_{x-1} separation (m bh.l.)	Width (m bh.l.)	C_x-C_{x-1} separation (m bh.l.)
1	3.0		6.0		2.2		1.7		2.1	
2	4.3	12.4	1.8	5.4	1.8	7.3	1.0	4.4	1.8	4.0
3	4.0	10.3	3.8	21.1	1.4	11.4	0.5	29.2	4.1	7.5
4	1.5	5.3	1.2	6.2	1.2	7.3	0.4	4.7	1.0	8.8
5	2.3	3.0	2.8	11.6	1.3	2.7	1.9	5.3	1.4	18.2
6	2.5	15.1	1.0	7.1	1.0	4.2	1.1	20.0	1.1	5.0
7	8.5	20.7	1.0	9.5	1.8	2.3	0.5	4.0	1.1	2.6
8	1.5	61.5	1.0	5.1	1.5	5.7	0.4	2.8	0.9	10.7
9	3.8	158.0	1.9	8.0	1.2	7.6	1.3	2.7	0.8	16.0
10	1.2	20.8	1.7	2.5	2.2	22.0	0.5	75.1	1.3	11.9
11	1.3	91.8	1.0	4.9	1.2	35.7	1.4	50.3	5.1	4.5
12	2.1	273.2	2.6	11.3	1.2	4.2	3.1	3.8	0.8	11.2
13	4.5	31.3	1.0	3.2	1.1	1.8	3.0	6.8	3.7	36.5
14	1.2	22.0	2.1	36.5	1.0	1.9	1.6	4.5	0.7	77.2
15	1.6	16.5	1.3	2.9	1.0	1.6	0.5	3.1	0.7	8.7
16	4.0	7.7	6.0	6.0	2.2	48.0	1.2	16.3	0.9	57.7
17	1.1	14.3	3.5	5.5	1.1	4.3	0.6	71.0	0.7	15.3
18	3.0	37.3	1.3	21.5	3.4	3.0	0.7	8.5	4.7	56.9
19	1.5	32.5			1.6	9.6	0.4	77.6	3.5	24.1
20					1.8	18.7	2.0	53.9	1.0	68.9
21					5.3	6.3	0.6	2.4	5.8	51.9
22					1.7	5.3	1.2	1.6	0.8	15.9
23					9.7	24.5	0.5	10.3	7.1	26.3
24					1.5	6.7	8.0	25.9		
25					1.2	2.9	0.7	125.5		
26					3.6	7.4	0.6	3.9		
27					5.9	12.2	0.6	13.3		
28					2.9	5.4	10.3	78.4		
29					3.2	25.9	1.1	6.6		
30					6.5	25.2	1.2	34.8		
31					2.7	9.3				
Total width of clusters (m bh.l.)	52.9		41.0		75,4		48.6		52.1	
Total width of cluster, % of bh-section	6.3		14.5		20.5		6.4		9.1	
Mean width of clusters (m bh.l.)	2.8		2.3		2.4		1.6		2.2	
Std, cluster width (m bh.l.)	1.8		1.6		2.0		2.2		1.9	
Mean cl. separation (m bh.l.)	46.3		9.9		11.0		25.7		24.5	
Std, cluster separation (m bh.l.)	68.2		8.8		11.2		32.1		22.9	

5. Structural characterization of clusters

Each of the identified geophysical clusters was described by its fracture characteristics. In this case, fracture patterns above, within and below each cluster were plotted in stereograms and the fracture families within working documents, one for each borehole, and the orientations of fracture families characterizing each cluster were filed. Oriented data to be used in the structural modelling were sorted into sub-sets; each sub-set containing structures having strikes within a 10°-interval and dips within a 10°-interval (that makes a maximum of 36*9 sub-sets of structures for each borehole and type of oriented data). Each of these sub-sets was plotted as a plane in the CAD-system (one sub-set per level) and could be visualised in any combinations.

A test was also performed to identify the disturbed zones adjacent to the clusters. This work was not carried through as it was too time-consuming and in many cases the results were uncertain as the fracture population on detailed scale may be relatively inhomogeneous. To get a general overview of the fracturing in the bedrock in the relation to the location of clusters the latter were incorporated in the spread sheet with statistical fracture data (cf. section sorting of fracture data above).

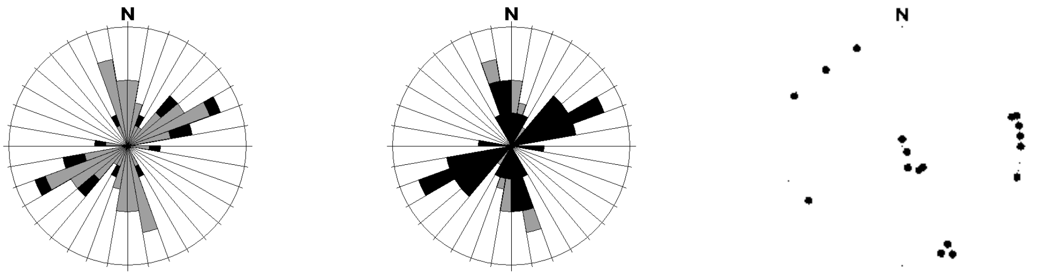
A total of 121 clusters were identified and most of these clusters display shifts in fracture orientations and density compared with the surrounding rocks. The clusters are generally associated with sections with an increase of open to partly open fractures and mapped crushed rock. Sections containing only sealed fractures do generally not appear in the cluster analysis. One cluster has no mapped fractures though. The relation between fracture occurrence and clusters should be further investigated. However, it is apparent that the physical character of the fracture wall rock is of importance in the cluster analysis.

Clusters with a dominating or a very pronounced proportion of sub-horizontal fractures are most common in the shallow part of the bedrock. However, sub-horizontal fractures are inhomogeneously distributed at all levels of the bedrock (Table 5-1). On the average, about forty-five percent of all clusters contain a high proportion of sub-horizontal to gently dipping fractures, with a range from thirty-two to sixty-eight percent among all of the boreholes.

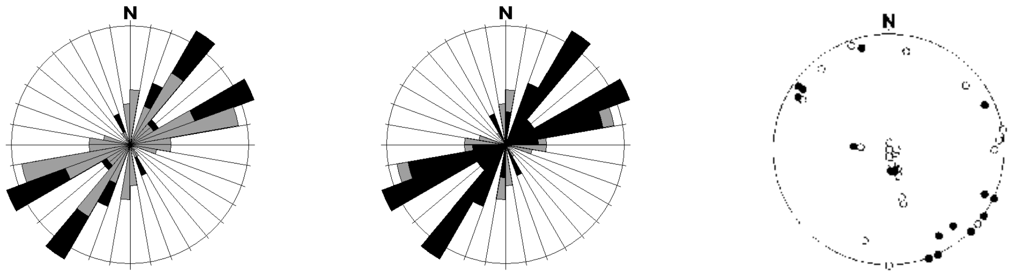
In boreholes inclining southeast, i.e. boreholes KFM07B,C and KFM09B, clusters with an enhanced fracture orientation in NE to ENE/vertical dominate, while clusters with dominant fracture orientation NNW to NW/vertical are few. In borehole KFM07A, inclining westward, the clusters are dominated either by NS or NNW- trending vertical fractures. In borehole KFM09A, inclining southwest, the most common orientation of fractures in clusters is NW to NNW/vertical (Figure 5-1).

Table 5-1: Number of fractures and fracture frequency (fr/m bh.l) for clusters in cored boreholes KFM07A, B, C and KFM09A, C. Marked with grey background are clusters with a dominant or very high proportion of sub-horizontal fractures (cf. Table 5-2). Colour codes are explained in Table 4-2.

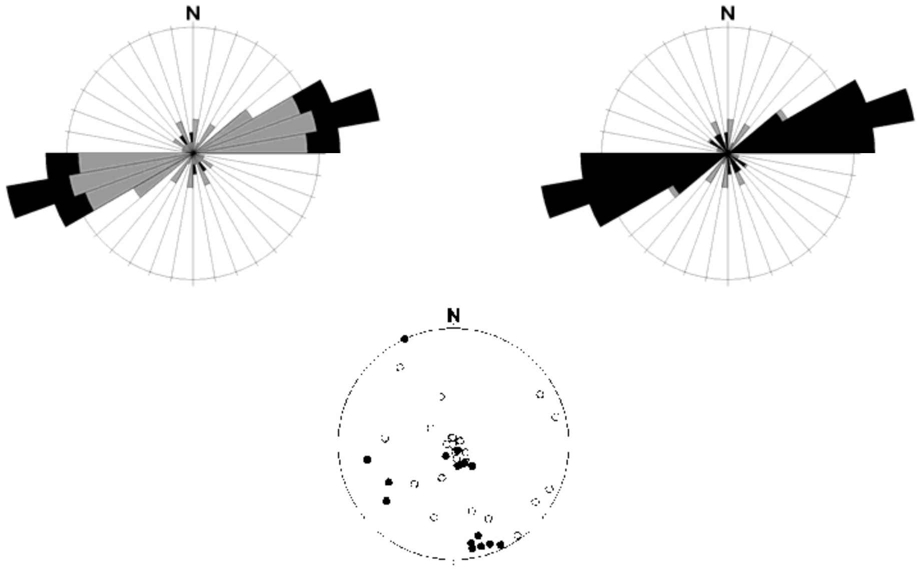
Borehole	*KFM07A*		*KFM07B*		*KFM07C*		*KFM09A*		*KFM09B*	
Bh-section (m)	*128-967*		*91-282*		*115-483*		*24-782*		*25-600*	
Bh-orientation	*261/59*		*134/55*		*143/85*		*200/85*		*140/55*	
Cluster ID KFM0YZ:X	*Number of fractures in cluster*	*Fracture frequency* (fr/m bh.l)	*Number of fractures in cluster*	*Fracture frequency* (fr/m bh.l)	*Number of fractures in cluster*	*Fracture frequency* (fr/m bh.l)	*Number of fractures in cluster*	*Fracture frequency* (fr/m bh.l)	*Number of fractures in cluster*	*Fracture frequency* (fr/m bh.l)
1	14	4.7	91	15.2	9	4.1	11	6.5	16	7.6
2	30	7.0	21	11.7	13	7.2	6	6.0	19	10.6
3	27	6.8	44	11.6	5	3.6	6	12.0	77	18.8
4	15	10.0	11	9.2	6	5.0	1	2.5	16	16.0
5	17	7.4	20	7.1	2	1.5	25	13.2	19	13.6
6	23	9.2	2	2.0	4	4.0	3	2.7	18	16.4
7	63	7.4	5	5.0	4	2.2	5	10.0	18	16.4
8	17	11.3	9	9.0	7	4.7	1	2.5	85	94.4
9	37	9.7	24	12.6	3	2.5	11	8.5	28	35.0
10	7	5.8	13	7.6	11	5.0	4	8.0	10	7.7
11	14	10.8	7	7.0	n.a.	n.a.	8	5.7	53	10.4
12	21	10.0	11	4.2	3	2.5	8	2.6	9	11.2
13	43	9.6	6	6.0	3	2.7	10	3.3	45	12.2
14	5	4.2	12	5.7	3	3.0	9	5.6	9	12.9
15	17	10.6	12	9.2	9	9.0	5	10.0	12	17.1
16	47	11.8	8	1.3	12	5.5	5	4.2	14	15.6
17	7	6.4	39	11.1	6	5.5	21	35.0	7	10.0
18	28	9.3	5	3.8	6	1.8	3	4.3	36	7.7
19	11	7.3			17	10.6	5	12.5	33	9.4
20					13	7.2	14	7.0	5	5.0
21					31	5.8	3	5.0	87	15.0
22					23	13.5	8	6.7	5	6.3
23					57	5.9	1	2.0	13	1.8
24					11	7.3	30	3.8		
25					8	6.7	9	12.9		
26					36	10.0	6	10.0		
27					55	9.3	5	8.3		
28					46	15.9	146	14.2		
29					39	12.2	15	13.6		
30					42	6.5	20	16.7		
31					21	7.8				
Mean fracture freq. (fr/m bh.l)		8.4		7.7		6.1		8.5		16.1
Std. (fr/m bh.l.)		2.2		3.8		3.7		6.5		18.3



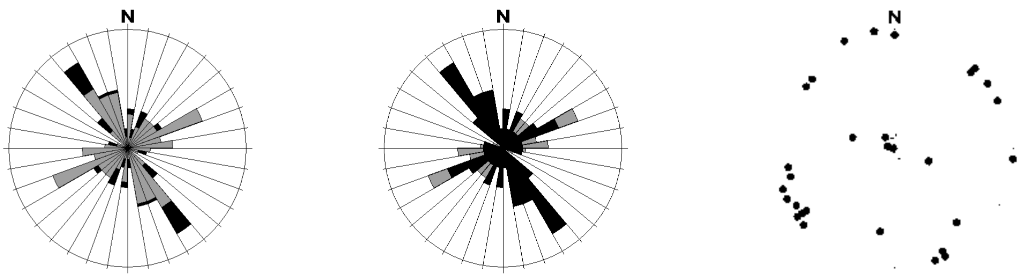
a. KFM07A



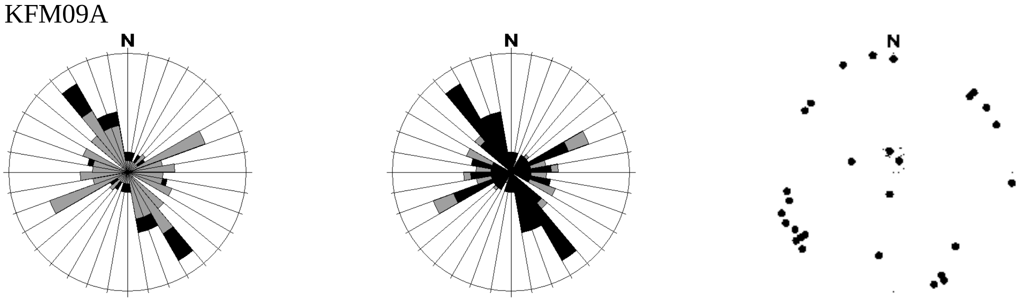
b. KFM07B



c. KFM07C



d. KFM09A



e. KFM09B
(The figure caption is given on the following page)

Figure 5-1: Rose diagrams (radius equal to 10%) displaying all recognized fracture sets (grey in rose diagrams) and the dominating fracture set (black) in each cluster in the modelled cored boreholes. Stereograms give the orientation of all fracture sets in clusters (white+ black) and the orientation of the dominant sets in each cluster (black) in boreholes.
a) Borehole KFM07A; 19 clusters with a total of 27 readings of fracture sets; 18 clusters have a dominant fracture set.
b) Borehole KFM07B; 18 clusters with a total of 42 readings of fracture sets; 18 clusters have a dominant fracture set.
c) Borehole KFM07C; 31 clusters with a total of 55 readings of fracture set; 30 clusters have a dominant fracture set (one cluster with no mapped fractures).
d) Borehole KFM09A; 30 clusters with a total of 52 readings of fracture sets; 30 clusters have a dominant fracture set.
e) Borehole KFM09B; 23 clusters with a total of 50 readings of fracture set;, 23 clusters have a dominant fracture set.
The orientation of the dominant fracture direction in each cluster is given in Table 5-3.

Common for all clusters are fractures with an ENE orientation (Figure 5-1). Clusters dominated by sub-horizontal to gently inclined fractures are preferentially located in the shallow parts of the bedrock (Table 5-2). However, there are clusters dominated by sub-horizontal fractures at repository depth. The orientation of the dominant fracture direction in clusters is given in Table 5-3. It is obvious that boreholes with similar orientations exhibit similar fracture orientation (Table 5-2) and that fracture data in borehole KFM09A differ from other boreholes.

Table 5-2: Number of clusters dominated by sub-horizontal fractures in boreholes KFM7A,B,C, and KFM09A,B as a function of depth (m b.s.l). Note that in Table 5-1 clusters with frequent occurrence of sub-horizontal to gently inclined fractures are presented while in Table 5-3 the dominant orientation of fractures in each cluster is given.

	Borehole				
Parameters	**KFM07A**	**KFM07B**	**KFM07C**	**KFM09A**	**KFM09C**
Number of clusters; at shallow depths (m)	5; <222	2; <132	11; <223	3; <148	1; 103
Single clusters; at depth (m)			1; 281		1; 258
Single cluster; at repository depth (m)			1; 405	1; 524/1	

Table 5-3: Dominant orientation of fractures in clusters boreholes KFM7A,B,C, and KFM09A,B.: Coloured background indicates fractures inclined more than 20° while gently inclined to horizontal fractures have no background colour; yellow to greenish colours indicate fracture orientations with trends in NNE to ENE; bluish colours indicate fracture trends in NNW to WNW and red-pink are NS trending fractures while EW trending fractures have a lilac background.

Borehole	***KFM07A***		***KFM07B***		***KFM07C***		***KFM09A***		***KFM09B***	
Bh-section (m)	*128-967*		*91-282*		*115-483*		*24-782*		*25-600*	
Bh-orientation	*261/59*		*134/55*		143/85		*200/85*		*140/55*	
Cluster ID KFM0YZ:X	*Strike*	*Dip*	*Strike*	*Dip*	*Strike*	*Dip*	*Strike*	*Dip*	*Strike*	*Dip*
1	90	5	265	15	240	15	245	85	255	80
2	225	20	35	80	255	15	70	90	55	90
3	165	45	65	90	255	15	50	10	255	80
4	65	80	5	25	245	15	1	1	265	85
5	230	5	30	80	255	15	5	90	65	90
6	255	15	205	80	255	15	350	80	65	90
7	65	90	65	90	260	15	345	80	70	90
8	235	20	75	80	255	15	15	30	65	90
9	345	90	255	15	250	15	330	85	245	85
10	355	90	70	90	260	75	20	5	235	85
11	45	80	35	85	n.a.	n.a.	230	70	210	85
12	245	80	45	90	230	20	90	85	80	15
13	250	85	230	75	235	5	35	80	70	90
14	205	90	240	75	350	65	65	90	30	90
15	165	85	155	80	260	75	155	85	75	15
16	0	90	35	90	330	55	160	90	70	90
17	350	90	25	90	320	65	155	90	280	15
18	330	80	65	90	305	10	160	90	240	85
19	15	90			255	80	325	80	60	90
20					245	85	325	85	320	80
21					260	80	260	90	175	85
22					255	70	245	90	10	90
23					260	80	135	80	25	75
24					260	80	140	90		
25					260	80	135	85		
26					60	60	150	75		
27					245	85	200	25		
28					250	80	145	90		
29					235	5	280	60		
30					245	85	145	85		
31					245	85				

6. Brittle deformation model

The objective of the present study is to present a structural model displaying brittle deformation zone based on interpretation of borehole data. To emphasize this restriction of the study the extension of displayed structure were displayed accordingly, i.e. the interpreted structure were not extended outside the volume covered by the five cored boreholes KFM07A, B, C and KFM09A, B (Figures 6-1 and 6-2). This implies that:

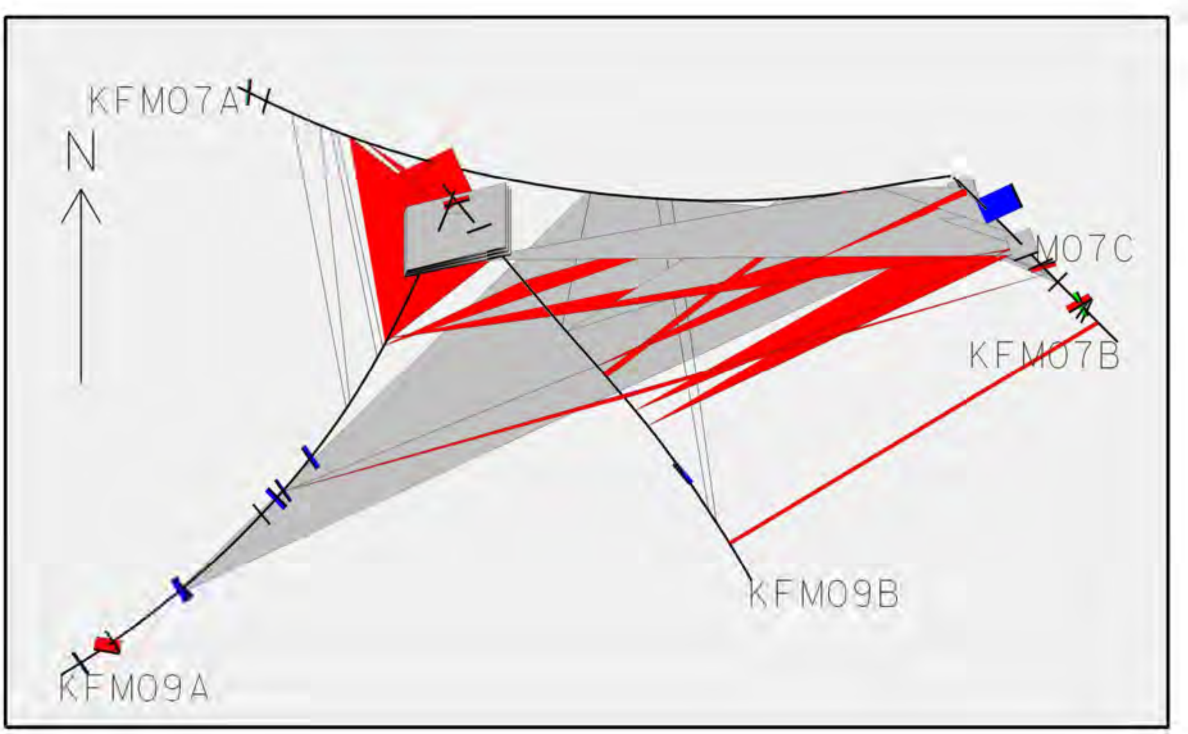
1. Structures found only in one borehole (found 44; 42 defined by clusters and two by sections with crushed rock) were modelled as 20 by 20 m quadrates (the size is just chosen to make the structures visible in the model). However, in reality these structures may have a far greater extent.
2. Structures found to be intersected by two boreholes (16 structures) were modelled as 20m wide stripes and their extensions are according to the distance between observation points.
3. Structures found to be intersected by 3 to 5 boreholes (16 structures) were drawn as triangles or polygons using lines connecting the observation points.

Polygons were drawn as planar structures or composed by triangular elements (only deviations in orientation of the order of a few degrees were accepted).

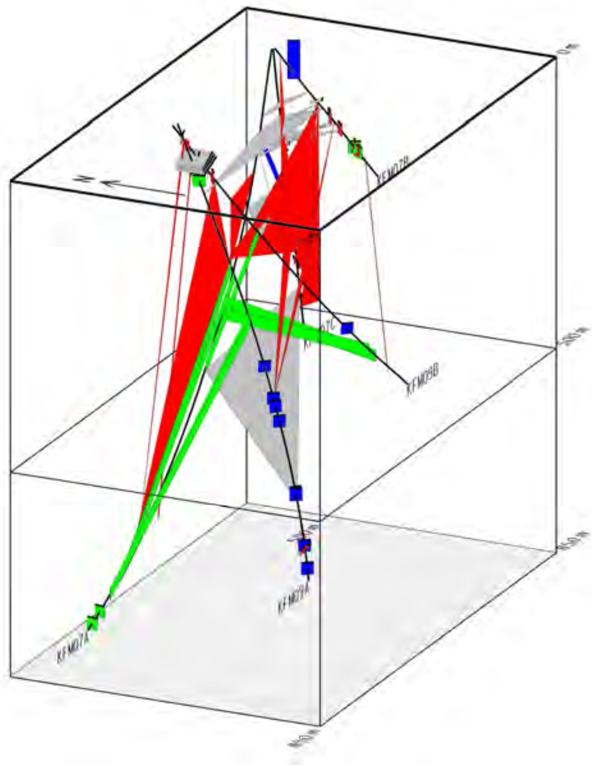
A minor deviation of these principles was made when testing the correlation of a shallow section of crush rock in borehole KFM07B with a lineament. The geometrical pattern of fractures in the zone gave its orientation and it was found out that the lineament was enveloped by the zone, .i.e. a good correlation.

6.1 Description of the model

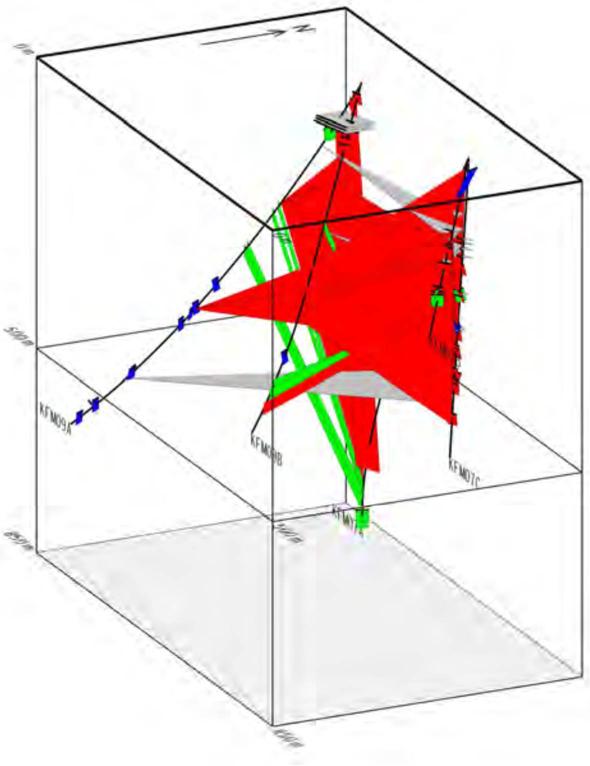
Modelled structures were grouped into three major sets of structures and these are oriented ENE to NE/vertical (dominating), sub-horizontal and NNW to NS/vertical (Figures 6-1 and 6-2). There is also a forth set oriented NW/vertical. The NW-trending fractures zones are most common in the western part of the model and are thus mainly covered by borehole KFM09A. The NW-trending fractures have the same trend as the western boundary zone of the Forsmark area, the regional western border zone (Figure 1-2).



a.

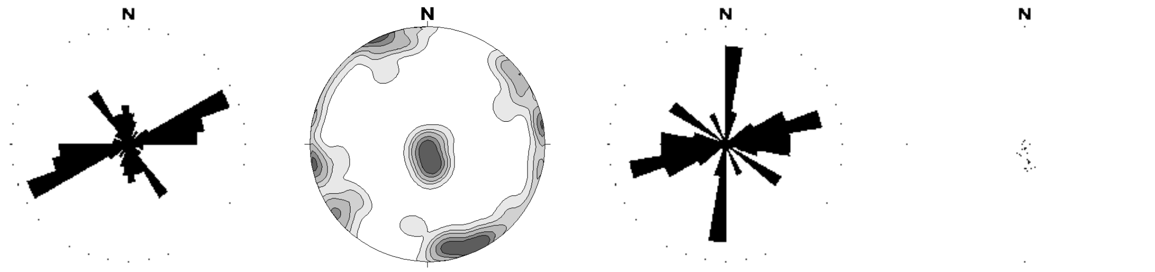


b.



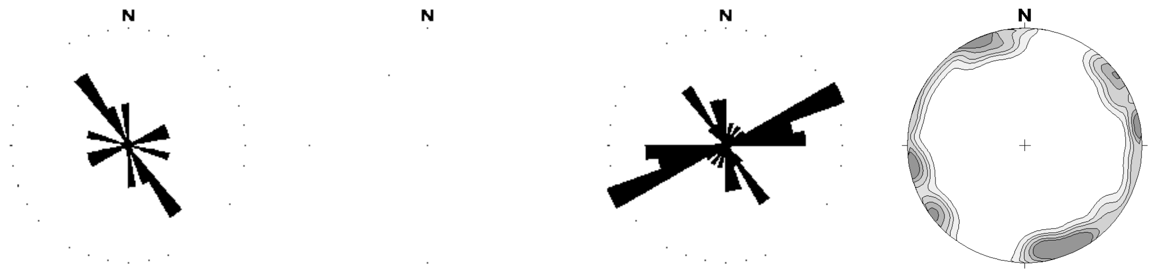
c.

*Figure 6-1: An alternative model of brittle deformation zones of the northwestern part in the Forsmark candidate area (76 zones) at drill-sites DS 7 and DS 9 based on borehole information from cored boreholes KFM07A, B, C and KFM09A, B (76 structures): a) Top view, b) View from the southwest and c) View from the southeast. See text for further explanations. Colour-codes give the orientation of structures: Grey = gently to sub-horizontal structures, Red = NE to EW-trending structures, Green = NS-trending structures, and Blue = NW to WNW-trending structures. Structures in the direction of the view are shown as lines. The size of the model is 550*900m*850m deep.*



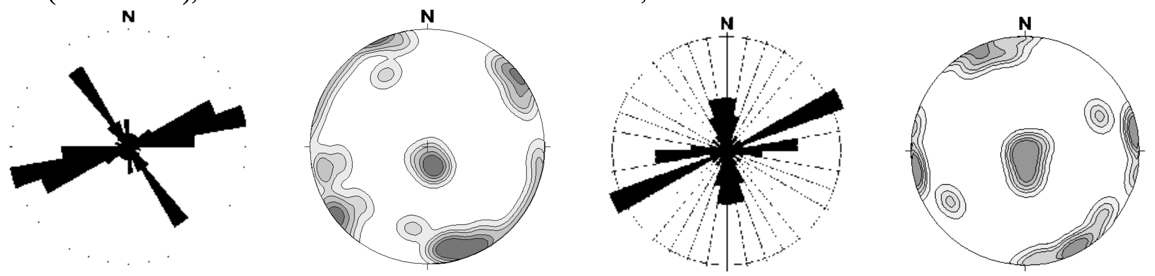
All modelled brittle deformation zones, N=76

Modelled gently inclined brittle deformation zones, N=18



Modelled moderately inclined brittle deformation zones (incl. 60-70°), N=7

Modelled sub-vertical to vertical brittle deformation zones, N=51



Modelled brittle deformation zones defined by only a single borehole intersection, N=44

Modelled brittle deformation zone defined by 2 to 5 boreholes intersections, N=32

Figure 6-2: Orientation of brittle deformation zones (a total of 76) within the modelled sub-volume in the northwestern part of the SKB-candidate area at Forsmark.

The description of the model starts with a presentation of structures identified in three to five boreholes (16), Figure 6-3. The only structure identified in five boreholes is a shallow, gently inclined surface in the shallow parts of the model. In the boreholes at drill-site DS7, there are also a number of such structures. However, most of these structures were not observed in boreholes KFM9A, B. A gently inclined structure appears to be located at depth. The extension of an extensive sub-horizontal to gently inclined structure at depth can be questioned. The fact is, however, that there are several indications of sub-horizontal fractures within the whole modelled volume and also at depths, although less frequent.

Common are also NE to NNE-trending structures, steeply dipping, predominantly towards northwest. These structures appear to be extensive and may truncate the modelled volume. Their relative frequency in boreholes KFM7B, C and the middle part of borehole KFM09B indicate the existence of a wide zone/domain crossing the modelled area. The NE-trending structures found in the upper part of borehole KFM09B and lower part of KFM07A may outcrop between drill-sites DS7 and DS9.

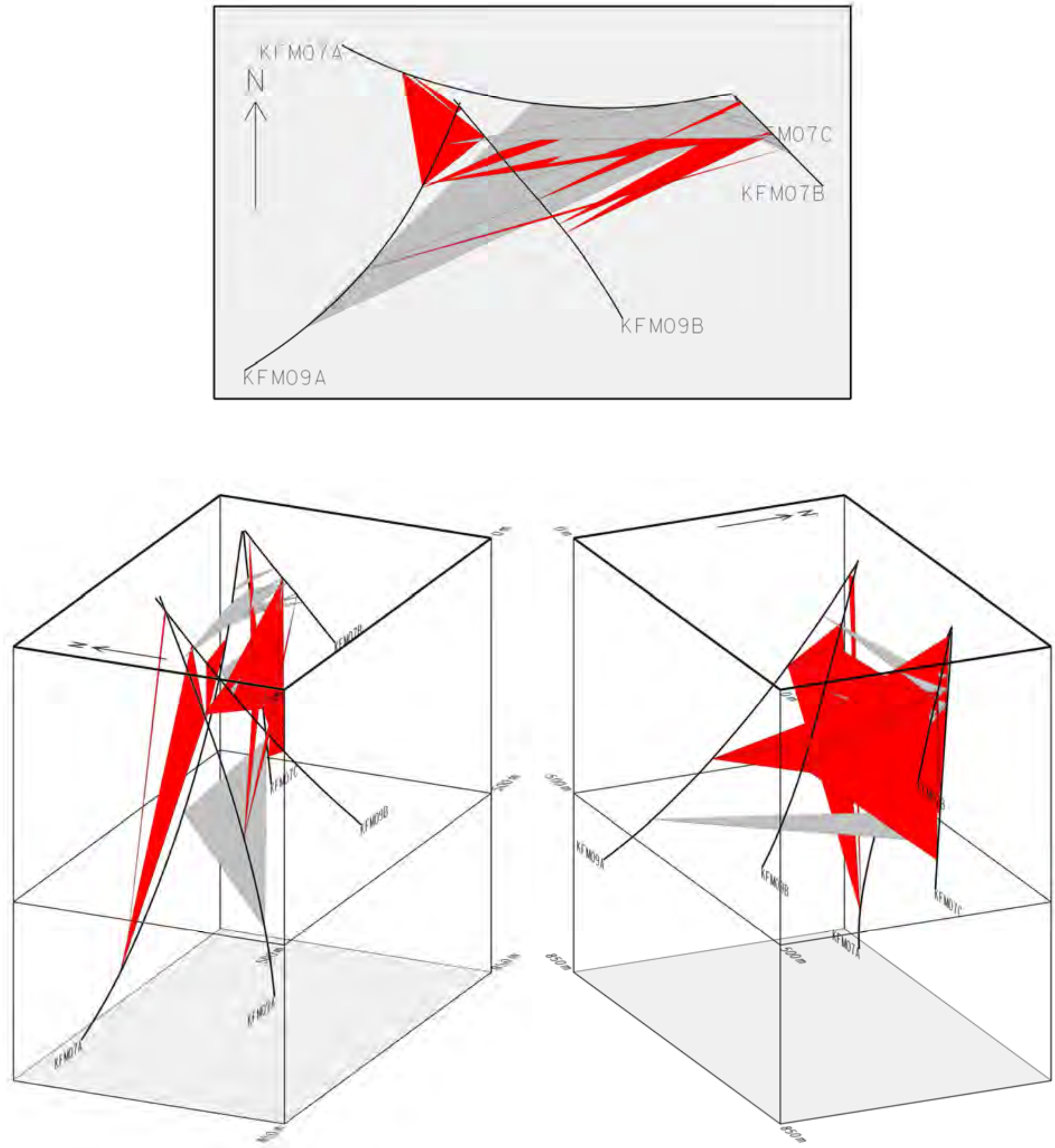


*Figure 6-3: Modelled brittle deformation zones identified in 3 to 5 boreholes, alternative structural model based of structures in boreholes KFM07A,B,C and KFM09A,B, SKB Forsmark candidate area (16 zones). Colour-codes are given in Fig. 6-2. The size of the model is 550*900m by 850m deep.*

For the modelled structures intersecting two boreholes (Figure 6-4, 16 zones), the structures interpreted with greatest confidence are the gently-inclined structures in the uppermost part of boreholes KFM09A,B.

Most frequent are NS-trending structures and they occurring in the central part of the modelled area covered by boreholes KFM07A and KFM09A,B. This may be due to that these boreholes best sample NS-trending zones (Figure 6-4). The inclination of the NS-trending zones is vertical. NE-trending sub-vertical zones are also found in same part of the model as structures with the same orientation indicated by three to four borehole intersections.

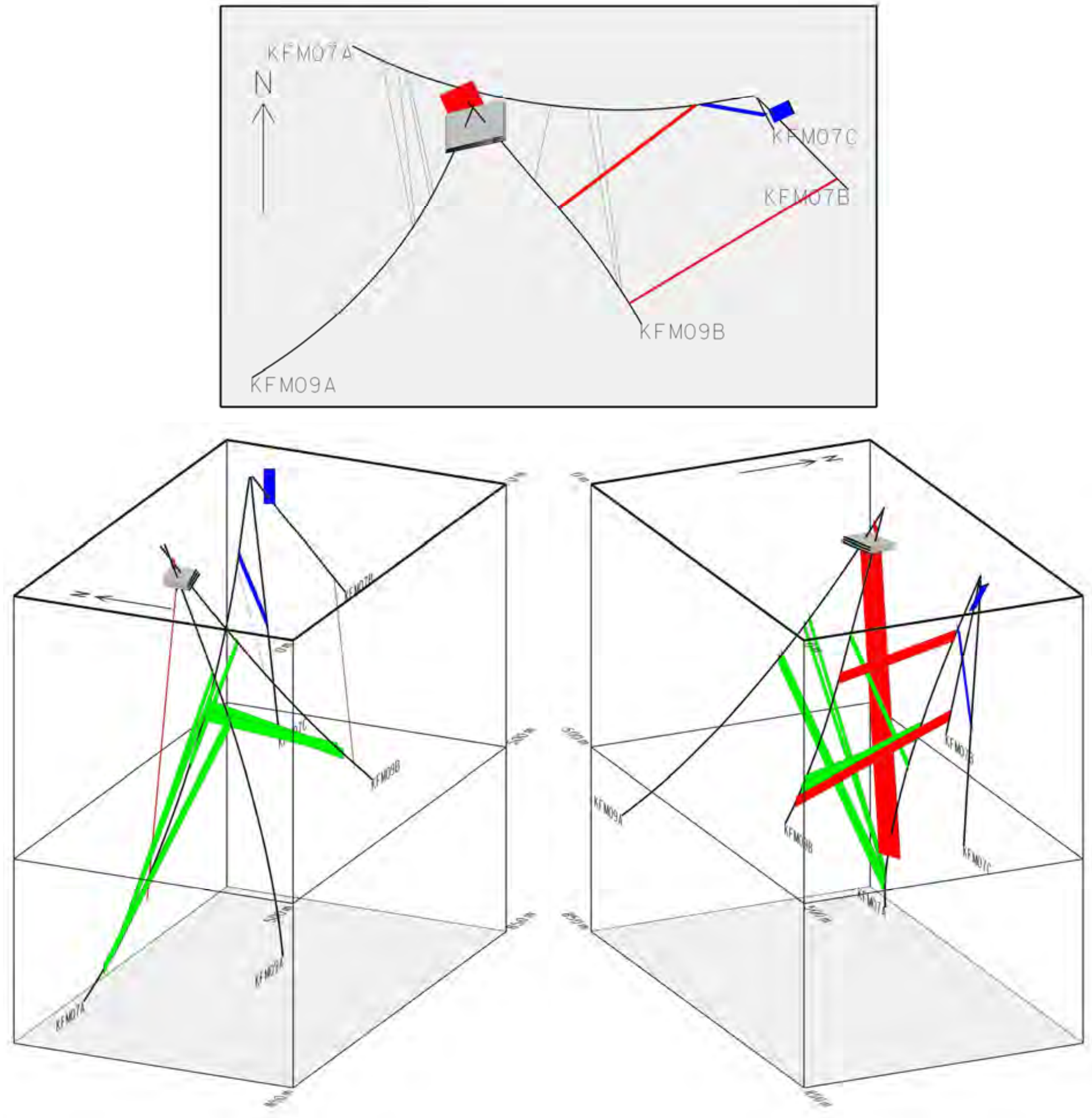


*Figure 6-4: Modelled brittle deformation zones identified in 2 boreholes, alternative structural model based of structures in boreholes KFM07A,B,C and KFM09A,B, SKB Forsmark candidate area (16 zones). Colour-codes are given in Fig. 6-2. The size of the model is 550*900m*850m deep.*

Notable is the occurrence of a steeply-dipping NNW-trending zone in the eastern part of the modelled volume.

For structures intersecting single boreholes (44 brittle deformation zones, 42 indicated by clusters and 2 by crushed rock; Figure 6-5), sub-horizontal structures are indicated in the shallow parts of boreholes KFM07B,C. However, they are not connected due to divergences in orientations in relation to their positions. In the same two boreholes NE-trending structures are frequent and they are not connected, for the same reason. Even though there is an increase of NE to ENE-trending structures in the uppermost part of borehole KFM09B, this types of fracturing is not dominant in clusters in the uppermost part of borehole KFM09A.

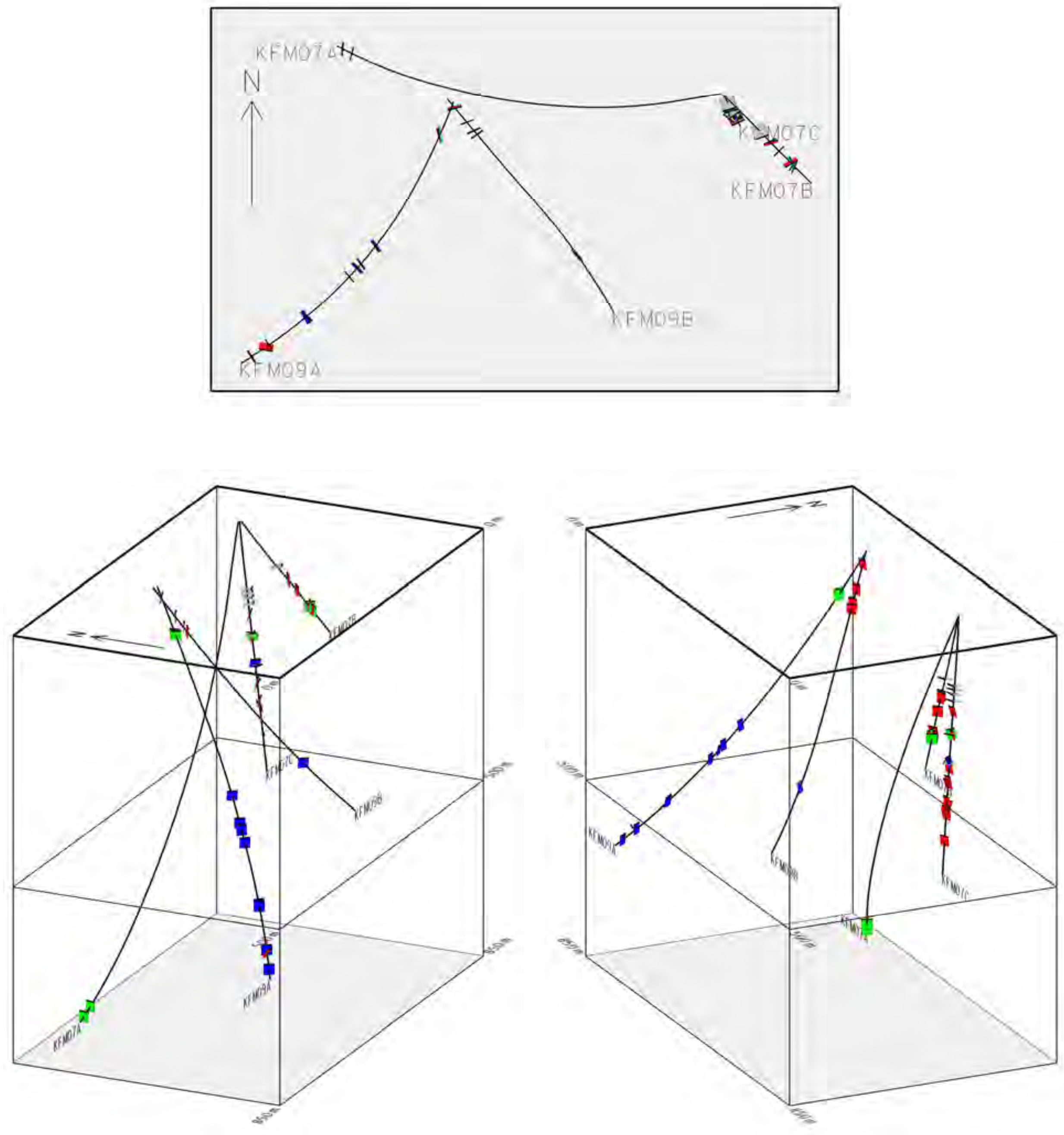


Figure 6-5: Modelled brittle deformation zones recognized in only one borehole (44), alternative structural model based of structures in boreholes KFM07A,B,C and KFM09A,B, SKB Forsmark candidate area (44 zones). Colour-codes are given in Fig. 6-2. The size of the model is 550 by 900m by 850m deep.

NS-trending vertical structures exist in most boreholes (except KFM09B). The lack of NS-trending structures in the central part of borehole KFM07A, which has the optimal direction to detect such structures, indicate NS-trending structures to be extensive as they only are represented as two-point intersection structures in this part of the model (cf. Figure 6-4).

NW to WNW-trending single point intersections (Figure 6-5) occur in many of the boreholes across the model volume and the absence of such structures in two of the boreholes may be due to the dip direction of the structures (southwestwards). The possibility that a section of crush rock in the upper part of borehole KFM07B is correlated with a NW-trending lineament indicates that NW-trending structures dip steeply southwestwards. Such structures are sparsely sampled, considering the possibility of multi-intersections of structures and boreholes. Furthermore, the borehole configuration has a planar domain of “open space” (without any boreholes) between the boreholes KFM07A,B,C and KFM09A,B allowing for NW-trending structures to go un-noticed in the central part of the model.

The increase of NW-trending fractures in the lower part of KFM09A (Figure 6-4) indicates that the borehole approaches a larger-scale deformation zone, the regional western border zone, having a NW-trend and steep southwestward inclination. The location of this regional zone has not been established in this study, but if it is located according to the SKB model the zone of influence (damage zone) related to the regional zone may well be several hundreds metre wide. Even minor structures related to this zone may occur at greater distances. The existence of an approximately EW-trending structure in the sequence with NW-trending structures in the lowermost parts of KFM09A either indicates that the EW-trending structure is deformed by the NW-trending zone or penetrates the NW zone. In any case, it does indicate that EW-trending structures are not truncated by the NW-trending border zone.

To further clarify the distribution of different orientation sets of modelled brittle deformation zones, all modelled structures are shown in Figure 6-6.

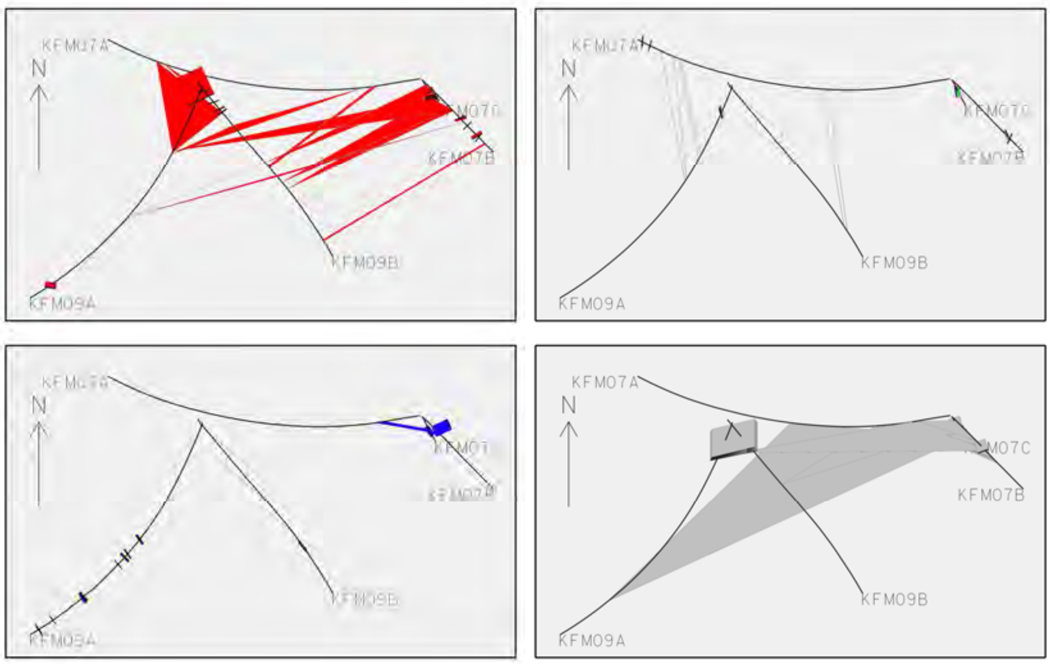
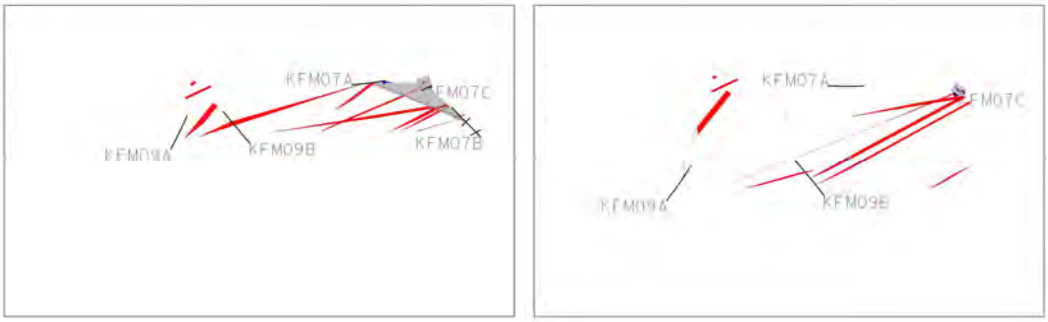
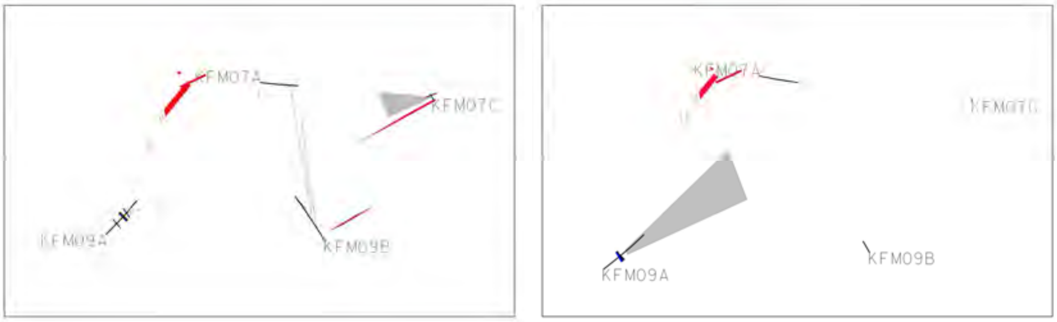


Figure 6-6: Modelled brittle deformation zones displayed in colours according to their orientation (cf. figure text in Figure 6-1). The size of the model is 550 by 900m.

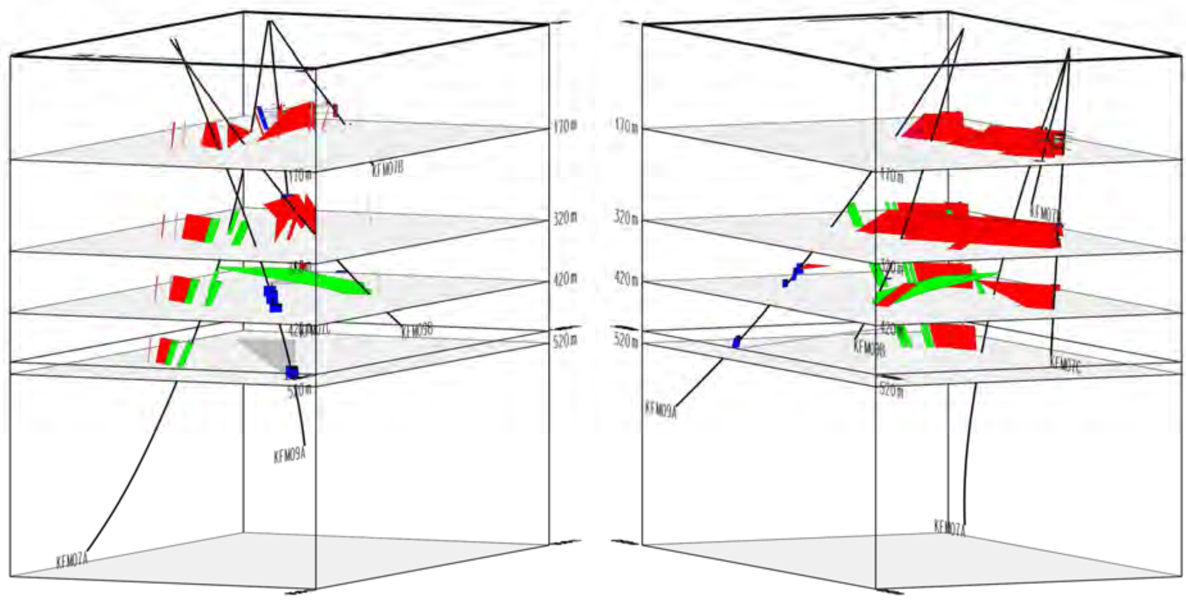
The structural model is visualized as 40m wide horizontal slices showing a sectionalized model within depth-sections 139 to 170m (centred at 150m), 280 to 320m (300m), 380 to 420m (400m) and 480 to 520m (500m), Figure 6-7.



a. 130 to 170 m depth interval b. 280 to 320m depth interval



c. 380 to 420m depth interval d. 480 to 520m depth interval



e. f.

Figure 6-7: Alternative structural model in sections, all sections are 40m high: a. top view section sections 130 to 170 m, b. top view 280-320m, c. top view 380 to 420m, and d. 480 to 520m, e. view from SW and d. view from SE. The size of the model is 550 by 900m by 850m deep.

The occurrence of structures in the central part of the model decreases with depth (Figure 6-7). This is an effect of the spatial separation of data (cf. Fig. 6-1), which increases with depth as the boreholes diverge. However, making the unrealistic assumption that all fractures (at least the two-point intersections) have infinite lengths, the picture will be the opposite. Such modifications of the model are needed for, for example, planning a layout of a potential repository.

Some characteristics of the clusters are given in Table 6-1. An analysis of these data should consider the sampling biases in the different boreholes. There is a relatively high proportion of structures having lengths greater than 250m, constituting 25 to 75 % of all structures indicated by clusters. The relative proportion of structures exceeding a certain size has an almost linear decrease in the presented model, Figure 6-8. The graph is also related to the capability of the interpreter and her/his understanding of the structures, e.g. the external shape of the zones and their internal geometry/fracture characteristics. Maximum extension of a modelled zone is 700m. The deformation zone dips very gently westwards (160/10) and is located in the deeper part of the model, Figures 6-3 and 6-7.

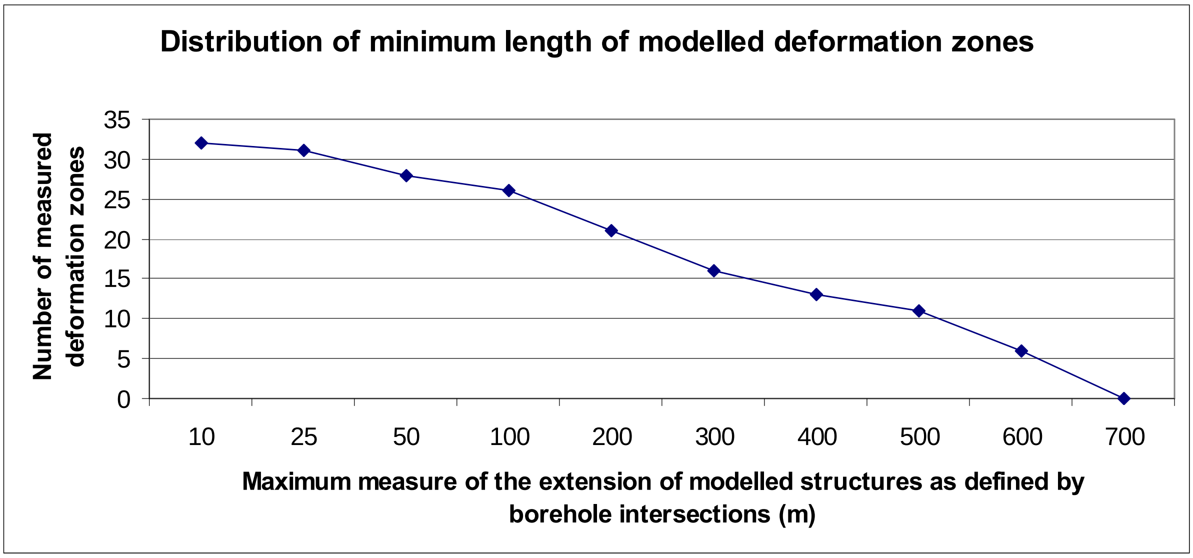


Figure 6-8: Distribution of minimum size of modelled structures in the vicinity of cored boreholes KFM07A,B,C and KFM09A,B.

Table 6-1: Summary of structural interpretations based on cluster analysis and length of modelled structures. Clusters not used in the model do either not display a distinct fracture orientation or are located close to other clusters with similar fracture orientations.

	Cored boreholes				
Parameters	**KFM07A**	**KFM07B**	**KFM07C**	**KFM09A**	**KFM09B**
Numbers of clusters per borehole:	19	18	31	30	23
Number of clusters not used in the structural interpretation:	1	1	1	5	0
Correlation of clusters in one borehole to clusters/structures in other boreholes:					
Found only in the borehole, no correlation to clusters/structures in other boreholes.	1	8	19	11	5
Found also in another borehole.	8	1	1	8	10
Found also in two other boreholes.	8	7	7	5	6
Found also in three other boreholes.	0	0	3	1	1
Found also in four other boreholes.	1	1	1		1
Number of clusters per metre borehole	0.023	0.094	0.162	0.0396	0.0400
Total length of clusters in percent of the investigated section (%)	6.3	14.5	20.5	6.4	9.1
Mean separation between centres of clusters measured along boreholes (cf. Table 4-3) **(m).**	47	10	11	26	25
Minimum extension of deformation zones intersecting the borehole:					
Number of interpreted structures >10m.	17	9	11	14	17
Number of interpreted structures >50m.	17	9	11	10	13
Number of interpreted structures >100m.	17	9	11	10	13
Number of interpreted structures >250m.	13	4	6	10	12
Number of interpreted structures >500m.	7	1	3	9	3

6.2 Uncertainties

The description of uncertainties in a geological model is a multi-faceted task and can be accomplished in a variety of ways; five are treated here:

1. Sampling with respect to anisotropy/isotropy in the bedrock – the geometrical configuration of boreholes.
2. Relation between investigated volume and the extension of structures – confidence in the investigation.
3. Restraints in the investigation approach (including the geometry of modelled objects).
4. Comparison with other models and the use of data.
5. Refinement of investigation approach.

6.2.1 The geometrical configuration of boreholes

The dominant trends of structures in the northwestern part of the Forsmark candidate area is given in the SKB geological Site Descriptive Models of the area (cf. Section 1; previous investigations). From the helicopter survey detailed ground magnetic measurements (cf. Stephens et al., 2007; Figure 3-37, the detailed ground magnetic measurements do not cover the area of the present study) indicate a dominance of WNW to NW and ENE-trending structures and the occurrence of NS-trending structures. According to the SKB models the regional structure that outlines the western boundary of the area is steeply inclined with a dip of 70° westwards. The ENE structures are either sub-vertical or gently inclined southeastwards and the NS-trending structures are sub-vertical.

Modelling in a fully three-dimensional model gives the opportunity to plan the orientation of boreholes in order to get an optimal sampling of the rock volume. However, boreholes may target certain objects and by that the three dimensional coverage may be affected (reduced). The location of the drill-sites may also have been restricted in order to minimize the impact of the investigation on nature. For example, viewing the modelled site from the east towards the west (Figure 6-9) it appears that the boreholes are located approximately within two planes (trends: both EW; dips: 60° and sub-vertical N). This implies that structures dipping gently to moderately southwards and outcropping in the central to southern part of the modelled area will not appear since they are not sampled. However, structures inclined northwards will generally be well sampled.

There is a non-sampled domain in the borehole configuration for structures with northwesterly trend and dipping steeply towards the southwest. This is the orientation of the regional border structures just west of the candidate area.

Down to a depth of approximately 240m, extensive horizontal deformation zones will be sampled by all five boreholes, and down to approximately 470m the structures may be found in four boreholes. Further on, 500m is the lower limit for three borehole intersections for a horizontal zone, 620m is the lower limit for 2 borehole intersection and below 820m no borehole will intersect a horizontal deformation zone.

For vertical ENE-trending brittle deformation zones (70/90) there is only a 50m wide planar domain within which extensive deformation zones is sampled in four boreholes and the width of similar domain increases to 200m when considering three-borehole intersections (actually two sectors; 75 and 125m wide).

For NW-trending vertical structures (145/90) there is a 50m wide planar domain within which such structures can be found in three boreholes. For steeply SSW-dipping zones there is a-wedge shaped domain (approximately 170 m wide at the surface and widening up downwards) between the boreholes where such structures can pass trough without being detected, Figure 6-9. NW-trending structures may also go un-noticed. This implies that there are constraints in the representation of structures in the modelled volume. This is one reason why the presented model is restricted to only show the extension of structures as they are indicated by the borehole information.

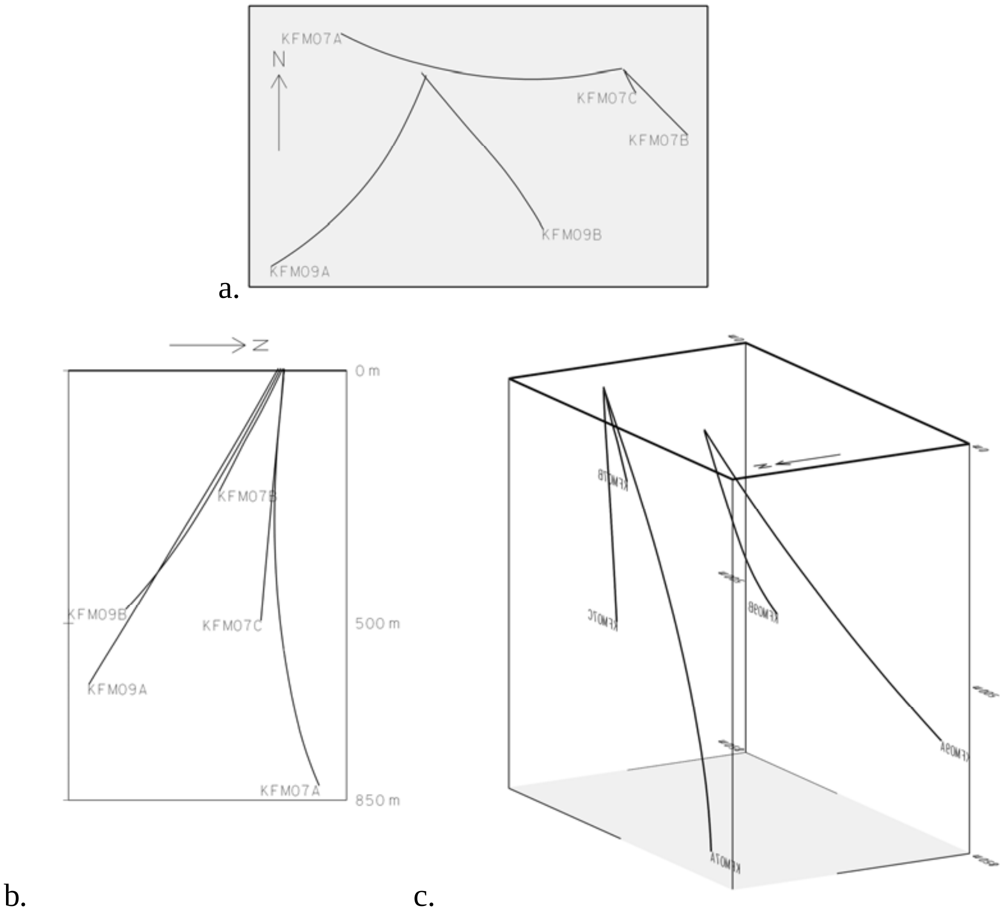


Figure 6-9: Borehole configuration – Cored boreholes KFM07A,B,C and KFM09A,B:
a) Top view; b) Vertical cross-section, looking west; c) modelled volume viewed from the northwest towards the southeast.

6.2.2 Relationships between the investigated volume and the extension of structures

The extension of deformation zones is an important issue in the safety analysis of a site and this is difficult to resolve by borehole data only. The extension of the structures outcropping within the investigated area is best obtained by remote studies (structural interpretation of topographical and geophysical data). In the present study area, the upper part of the bedrock has a high density of sub-horizontal fractures and some of these are open and filled with Quaternary sediments. There is a possibility that the shallow fracturing is different (the sub-horizontal fracturing excluded) than the fracture pattern at deeper levels.

The distances between boreholes are, in most cases, more than a hundred metres and, at most, up to one kilometre (Table 1-1). The confidence in the interpretation increases with the number of borehole-intersection points each structure has and the smaller the distances between the intersections are. Another parameter is the conformity in the model, i.e. if the model shows some degree of symmetry and/or structurally understandable pattern (not a random pattern).

6.2.3 Limitations in the investigation approach.

The present study is mainly based on selected borehole geophysical logs, borehole fracture data and a good accurate spatial documentation of the measurement/observation locations. The geophysical logs have been processed separately by using cluster analyses to identify sections with deformed rock (clusters) and based on the clusters the fracture data have been used to characterize the brittle deformation in and adjacent to the clusters. The fracture data have also been classified in order to identify fracture anomalies (regarding: “all”, “partly open” and “sealed fractures”, “crushed rock”, “altered fracture surfaces” and “altered rock”). The clusters cover most of the sections with increased fractures but occasionally miss sections with an increased density of open fractures (more than 5 fractures per metre borehole length), located within sections with a relatively small increase in the general fracture density (less than 10 fractures per metre).

Oriented, such as borehole radar and refection seismics, were looked at but not used. Borehole radar investigations of sections of crushed rock, show, in several cases, a marked divergence in orientation between the upper and lower boundaries of the section. The area is covered by a network of refection seismic profiles. However, no reflectors are found within the investigated area.

One test has been performed to relate the internal fracture pattern in a shallow borehole section to the orientation of a corresponding surface structure by extending a zone of crushed rock in the borehole and find out if it is correlated with a distinct NW-trending lineament. The result was that such correlation was clearly indicated. Thereafter, the interpretation continued by modelling of structures at the beginning of the boreholes and down the boreholes; in order to build up continuously refined experience. This approach may be easier to apply in homogenous rock volumes. The studied area appears not to be uniform and there are also indications that the sampling is biased.

One significant source of uncertainty is how to correlate structures over large distances, when there are several equally possible alternatives, without knowing the natural extension of the structures. In the model, single planes (20*20m) are inferred when the fracture patterns in clusters are distinct and there is no other structure to correlate with (assuming that the structure has a planar geometry), i.e. there is no indication in other boreholes or there is no borehole to be intersected.

Structures based on two borehole intersections are uncertain as a small shift in the assumed orientation of the modelled structure, or a non-planar geometry, can give alternative interpretations, i.e. it is possible to correlate the structure with other structure intercepting in the other borehole.

6.2.4 The use of data and comparison with another model

This section may be divided into two main parts:

- A comparison between the two interpretations of deformation zones in the boreholes (SKB 2.2 version of the geological model and the model based on the cluster analysis presented in this study); the relation between structural interpretations and groundwater flow in the rock (Posiva Flow Log, PFL; if data are available); a comparison of primary fracture data and interpreted location of brittle deformation, Figure 6-10 and Table 6-2.
- A comparison of the SKB 2.1 brittle deformation model (as this was available in digital format) with the present study, Figure 6-11.

The SKB geological Single-Hole Interpretation (SHI) is based on a method to identify geological features, e.g. brittle deformation zones, based on the geological and geophysical borehole logs and it is described in the SKB Method Description MD 810.003 (Geologisk enhålstolkning; version 3.0 approved 060509). There is no method description for the Extended Single Hole Interpretation (ESHI) used in the 2.2 version of the Geological Model of Forsmark, Figure 6-10a-e. However, the ESHI is briefly described in the Geological Site Model (Olofsson et al. 2007, page 21-26) and the differences between SHI and ESHI appears to be a matter of resolution in the interpretation.

Fracture densities referred to in the text below are in units of fractures per metre borehole.

In the following section (6.2.5) interpretation of borehole data performed in the two studies are compared.

6.2.5 The interpretation of borehole data – a comparison

In this section the SKB ESHI interpretation is compared with the single hole interpretation performed in this study. Most of the information given in the text is summarized in Table 6-2 and Figure 6-10.

KFM07A

In all of the SKB-ESHI deformation zones there are structures indicated also by the cluster analysis. There are six SKB ESHI deformation zones (DZ1, 2, 3, 4; DZ4 is subdivided into three structures). In the long ESHI deformation zones in the upper (DZ1) and lower (the three DZ4) parts of the cored borehole KFM07A, there are six and eight clusters, respectively. This reflects the structural inhomogeneity in the extensive ESHI deformation zones. These ESHI deformation zones contain sections with the highest density of fractures per metre in the borehole, i.e. the highest total number of all fractures and open fractures per metre borehole length (maximum total number of fractures/m is 32 in deformation zone DZ1 and 22 in the lowermost DZ4, and corresponding values for open fractures per metre are 12 and 9). Furthermore, there are three clusters that are located outside ESHI sections and they are characterized by moderately increased density of open fractures (less than 10 fractures per m borehole length and a crushed section in the drill core). Sixteen out of nineteen clusters are located in ESHI deformation zones, i.e. the cluster analysis gives a more detailed subdivision of the bedrock than the ESHI interpretations. On the other hand, neighbouring clusters may reflect internal deformation branches inside a single zone or splays related to a zone.

Table 6-2: Comparison in the use of data and structural elements in the present model and SKB 2.1 brittle deformation model.

	Cored Boreholes				
Characters	**KFM07A**	**KFM07B**	**KFM07C**	**KFM09A**	**KFM09B**
Number of:					
SKB Extended Single Hole Interpreted (ESHI) deformation zones.	6	4	3	6	8
Clusters.	19	18	31	30	23
Section of increased fracturing, whole borehole.	51	34	30	98	56
Sections of increased fracturing, in the cluster analysed section of the borehole.	43	21	26	91	55
Posiva Flow Log anomalies (PFL), section which are hydraulically connected.	13	n.a.	12	n.a	n.a
PFL anomalies in the cluster analysed section of the borehole.	8	n.a	9	n.a	n.a
Sections mapped as crush zone.	10	1	3	7	3
Sections of crush zones in the cluster analysed section of the borehole.	5	0	1	6	1
Number of:					
Sections of increased fracturing in ESHIs.	39	11	17	30	39
ESHIs without sections of increased fracturing.	0	0	0	0	0
Clusters in ESHIs.	16	8	10	15	16
ESHIs without clusters.	0	0	0	1	1
Sections of increased fracturing in clusters.	20	13	14	18	25
Clusters without sections with increased fracturing.	3	8	19	12	3
Crushed zones in ESHI.	9	1	3	3	3
Crush zones in clusters.	4	0	0	3	1
Number of:					
PFL anomalies in ESHIs.	12	n.a.	2	n.a.	n.a.
PFL anomalies in clusters.	6	n.a.	9	n.a.	n.a.
Clusters with PFL anomalies.	4	n.a.	9	n.a.	n.a.

The clusters generally coincide with PLF anomalies in the upper 200m of the borehole, while the PFL anomaly at c. 917m borehole length is not contained in any of the clusters.

Sixteen out of nineteen clusters are located in sections with increased fracturing (in all 20 sections with increased fracturing). Thirty-one other sections of increased fracturing are not related to any of the clusters. Eight of the fifty-one sections with increased fracturing are located outside the cluster-analysed interval. The sections of increased fracturing located outside clusters are all less than five metres wide, and the density of mapped open fractures is generally less than four fractures per metre (16 of these sections have 0 to 2 open fractures per metre borehole length). Almost forty percent of all sections with increased fracturing exhibit less than two open fractures per metre. However, a section with nine open fractures per metre is missed by the cluster analysis and it is located at 942m borehole length in the central part of the lowermost ESHI deformation zone. The ESHI deformation zones catch slightly more than seventy-five percent of the sections with increased fracturing (39 out of 51), while the corresponding number for clusters is just above forty-five percent (20 out of 43). The ESHI deformations zones are wider than the clusters, and cover several sections of the boreholes that have very few open fractures. The ESHI deformation zones constitute twenty-five percent of the length of the borehole while the clusters only six percent.

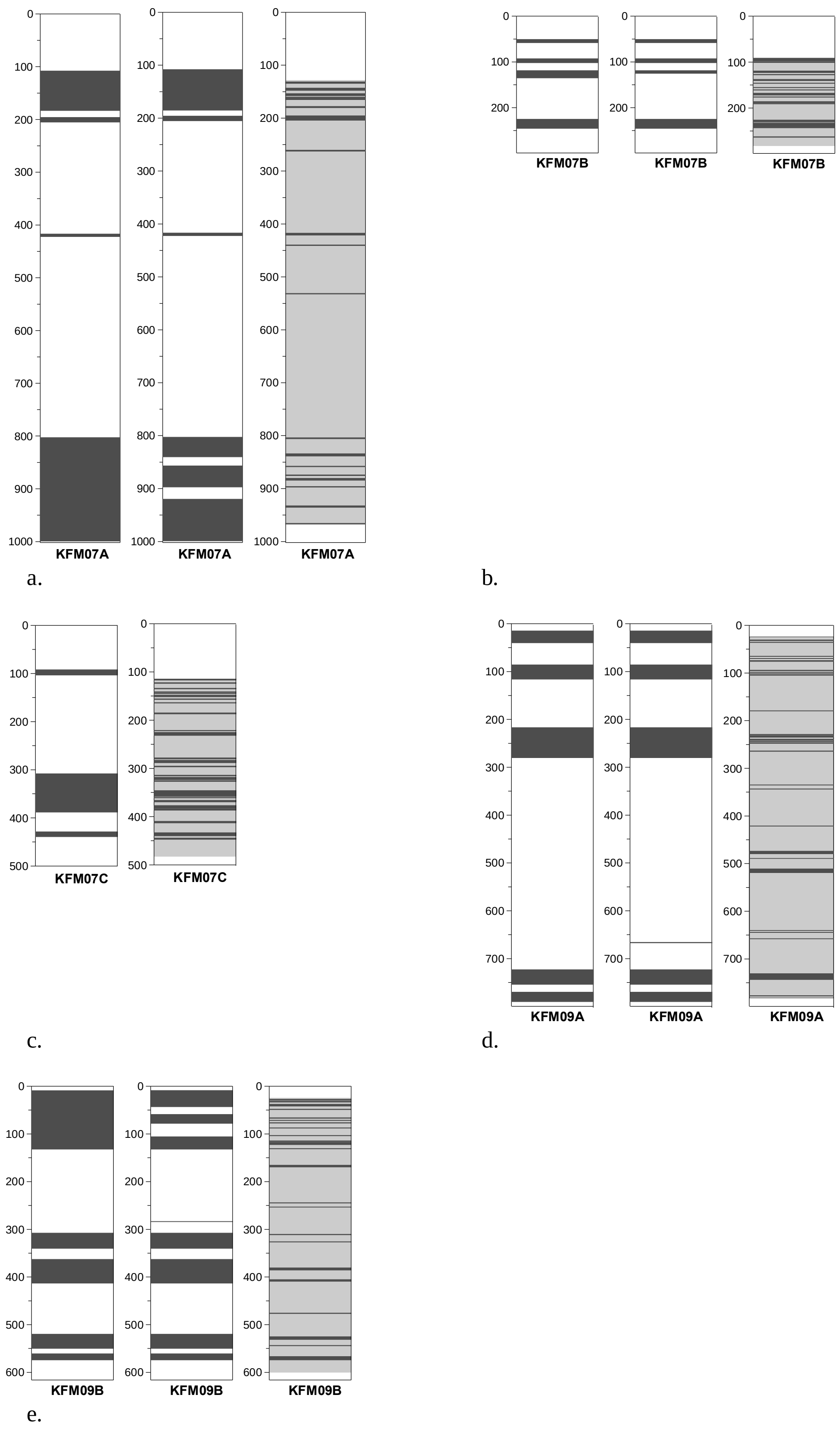


Figure 6-10: Comparison between three interpretations of deformation zones in boreholes KFM07A, B, C (a-c) and KFM09A, B (d-e): Left column is according to SKB Geological Single-Hole Interpretation (SHI), central column is according to SKB Extended SHI (ESHI; ESHI and SHI are the same in KFM07C) and right column is the cluster analysis based on borehole geophysical logs; the cluster-analysed section of the borehole is in grey (cf. Figure 4-12 cluster analysis).

KFM07B

The most shallow SKB-ESHI deformation zone (DZ1) is located above the cluster-analysed section of the cored borehole KFM07B and is highly fractured (the range in the fracture density per metre is 5 to 22 fractures for “all fractures” 1 to16 fractures per metre for “open fractures”). The other three ESHI deformation zones cover sections with clusters. The second ESHI deformation zone exhibits the most fractured section in the borehole (6 to 29 fractures per metre for “all fractures” and 1 to 14 fractures per metre for “open fractures”) and it contains two clusters. The most deeply located ESHI deformation zone (containing 0 to 16 fractures per metre for “all fractures” and 0 to 5 fractures per metre for “open fractures”) covers four clusters. Ten of the clusters do not correspond to any ESHI deformation zone. They generally contain less than 10 fractures per metre for “all fractures” and less than eight fractures per metre for “open fractures”; most commonly the density of open fracture range from two to five fractures and in the lowest cluster no open fractures are observed. In this borehole the clusters cover most parts of ESHI deformation zones. There are no flow-log data (PFL) from this borehole.

The fracturing in the shallow section (above the cluster-analysed section) is inhomogeneous with several metre-wide sections with increased fracture density (9; the range in fracture density for “all fractures” is from 8 to 25 for and for “open fractures” the maximum is 16 fracture per metre). Within the cluster-analysed section of the borehole, more then sixty percent of the sections with increased fracturing are located at clusters (13 out of 21). Thirteen of the sections with increased fracturing are located outside cluster-analysed sections. At a borehole length of about one hundred metres, the more fractured sections contain up to fourteen open fractures per metre borehole length. This section is caught both by an ESHI zone and a cluster. The density of open fractures in fracture sections decreases to two fractures per metre borehole length in the deeper parts of the borehole. A few decimetres wide crush zone, the only one found in this borehole, is located in the shallow part of the borehole.

The ESHI deformation zones catch about thirty percent of the sections with increased fracturing (11 out of 34). The ESHI deformation zones constitute fourteen percent of the length of the borehole, which is the same as for the clusters. Three of the sections of increased fracturing have less than two open fractures per metre; two of these sections coincide with PFL anomalies and the third with a cluster. The locations of the ESHI deformation zones and the clusters are not fully identical, Figure 6-10.

KFM07C

In the cored borehole KFM07C an ESHI deformation zone, with five to twenty-eight fractures per metre for “all fractures” and one to twelve “open fractures” per metre, is located above the section analysed by cluster analysis. The second ESHI deformation zone in the borehole, with zero to twenty-four fractures per metre for “all fractures” and zero to seven fractures per metre for “open fractures” per metre is relatively wide and covers the location of several clusters (9 in the borehole section at 308-388m borehole length). The third ESHI deformation zone located at approximately 230 to 240m borehole length corresponds to one of the clusters. However, there are twenty-one clusters that do not correspond to any of the ESHI deformation zones. Most of these are located between the two first ESHI deformation zones. The fracture frequency is generally very low in these clusters, less than five fractures per metre, but may occasionally be more than ten fractures per metre. Noteworthy is, that one cluster does not contain any detectable fractures, which may be explained by its nearness to a deformation zone.

All PFL-indicated hydraulic anomalies in the cluster-analysed section are located in or at clusters. There are three PFL-indicated anomalies in the shallow part of the borehole above the cluster-analysed section. Two of them appear to be related to discrete fractures and the third, the shallowest one, is related to a fractured section in the rock.

A centimetre wide section of crushed rock is found in the upper part of the bedrock and an approximately 0.4m wide section is mapped at c. 430m borehole length, the latter section representing the upper part of the lower SKB ESHI deformation zone, but not identified in the cluster analysis.

Slightly more than fifty-five percent of all sections with increased fracturing are located within ESHI deformation zones (17 out of 30) and slightly less are caught by the clusters (14 out of 26).

Almost fifty percent of all sections of increased fracturing are interpreted as having less than two open fractures per metre and of these sections five are covered up by clusters. The total width of the ESHI deformation zones constitutes twenty percent of the length of the borehole and the corresponding number for the clusters is also about twenty percent. The overlap in location of the ESHI zones and clusters is described above.

KFM09A

The cored borehole KFM09A is the most fractured borehole of the five investigated in this study and it has six ESHI deformation zones according to SKB's classification. Five of these contain clusters, while the sixth zone is the thinnest of all of the ESHI deformation zones (0.5m wide) in the investigated sub-area and has no "open fractures". This zone was added at a late stage of the SKB modelling work. Fifteen clusters are located outside the ESHI deformation zones and, generally, these have a lower total fracture density and density of open fractures as compared with the other ESHI deformation zones (all zones, except the last one, have a range for "all fractures" from below ten to up to about twenty fractures per metre and corresponding values for "open fractures" is zero to fourteen fractures per metre; the highest value for "open fractures" is at a borehole length of 732m).

There are no PFL data from this borehole.

Seven sections with crushed rock have been mapped and they vary in width from a few centimetres to 0.9m borehole length. The widest section of crushed rock is caught by a cluster, as is the case also for narrower sections. The sections of crushed rock missed by the cluster analysis are 0.01 to 0.12m wide. There are several (98) sections with increased fracture density and the density of "all fractures" is in general in the range of ten to fifteen fractures per meter while extreme values are more than twenty fractures per metre. The average density of "open fractures" in these sections is about five fractures per metre borehole length. Noteworthy is, that about thirty percent of all sections with increased fracturing have less than two open fractures per metre; two such sections are caught by clusters. Thirty percent of all sections with increased fracturing are covered by ESHI deformation zones (30 out of 98) while the clusters catch twenty percent of the sections with increased fracturing (18 out of 91). The ESHI deformation zones make up little more than twenty percent of the length of the borehole and the clusters about five percent.

KFM09B

In the cored borehole KFM09B, the upper three ESHI deformation zones were initially identified as one zone by SKB (an SHI zone). The density of “all fractures” in the ESHI deformation zones vary significantly, all with peak values above seventeen fractures per metre and three ESHI zones with maximum values in the interval of twenty-three to twenty-six fractures per metre. Except for the uppermost ESHI deformation zone, all other zones have densities for “open fractures” less than eight fractures per metre and all but one contain at least a one metre section without any mapped open fractures.

There are no PFL data from this borehole.

Three sections with crushed rock are mapped in the borehole; two are very shallow and a few decimetres wide and the third is a few centimetres wide and located in the middle of the borehole. All sections of crushed rock are located in ESHI deformation zones and the deepest one is caught by a cluster; the uppermost sections of crushed rock are located above the section studied by cluster analysis.

Fifty-six sections with increased fracture frequency for “all mapped fractures” are found. The ESHI deformation zones cover above seventy percent of all sections (39 out of 55). The clusters catch about forty-five percent of all sections (25 out of 55). About thirty percent of all sections with increased fracturing have an average fracture density of “open fractures” less than two fractures per metre borehole. In borehole KFM09B, the total length of the ESHI deformation zones constitutes the highest proportion, slightly more than thirty percent, compared with all of the other boreholes in this study. The corresponding number for the clusters is just below ten percent.

6.2.6 Brittle structural models

In this brief comparison of structures the SKB Geological Model version 2.1 is used as a reference model as this model has been provided in digital format by SKB. The cluster-based model chosen for the comparison is the complete model (all structural elements included) even if this model gives a somewhat more “disordered” impression. The main reason for using the full model is that the model based on three to five borehole intersections of structures misses NS structures indicated by two-borehole intersections. A second reason is that it is more objective to use a full model than a thematic sub-model (e.g. sorting modelled zone according to their orientations). The comparison is not simple due to the differences in presentation of the models, Figure 6-11.

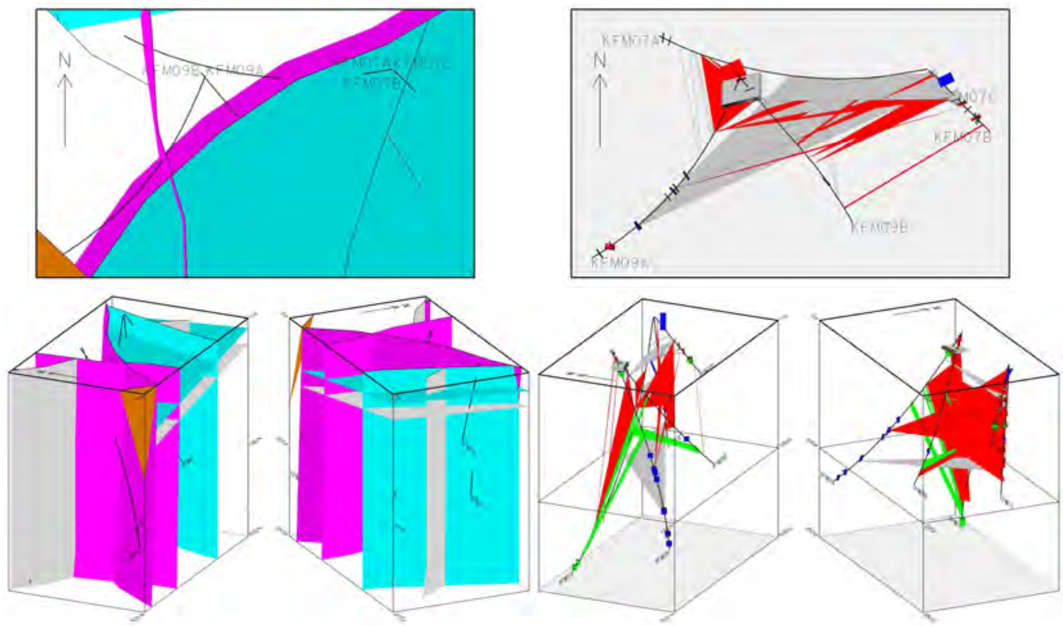


Figure 6-11: Brittle deformation models of the northwestern part of the Forsmark candidate area; To the left is the SKB geological model 2.1 (SKB delivered 2007.01.15), and to the right is the model presented in this work.

Differences in the presentation of the two models somewhat obscure the overall picture. Such differences consist of:

1. The modelled deformation zones in the SKB model may curve along the trend of the structures and down-dip they are straight (unfolded), while the cluster model include just a few deformed planes (drawn as jointed triangular elements; the deviation in orientations of the triangles are just a few degrees) and other planes are all fully planar.
2. The SKB brittle deformation zones have extensions (horizontally and vertically, if not truncated against other structures) equal to the trace length of the corresponding lineament. In the cluster model, the borehole intersections outline the position of the rim of the modelled structures if the interpreted structure is not based on one or two borehole intersections.
3. The thickness of brittle deformation zones is not presented in neither of the two models. This is a problem with the SKB model as the interpreted ESHI brittle deformation zones related to modelled structures are all relatively wide (mean width along boreholes is 28m and the standard deviation is 24m; maximum is 80m) and constitute 14 to 33 percent of the borehole length. In the cluster model this is a minor problem as the zones are generally just a few metres wide (mean width for all clusters is 2m and the standard deviation is 2m).

Structural similarities between the models:

1. The sub-horizontal structures in the shallow part of the model.
2. The existence of NE to ENE-trending steeply dipping structures in the central part of the model.
3. The NW to WNW-trending, steeply dipping structures in the western part of the model (indicated as one-point intersections in the cluster model).
4. The existence of a NS-trending vertical structure in the western and eastern parts of the model.
5. The extension of the NE to ENE-trending deformation zones appears to be affected by the NW to WNW-trending zone in the western part of the model.

Structural differences between the two models:

1. The existence of sub-horizontal brittle deformation zones at depth (at c. 400-500m b.s.l.) in the alternative model.
2. The NE to ENE-trending brittle deformation zones appear to occur in a relatively wider domain than shown in the SKB model.
3. The NW to WNW-trending structure occur in a wider section than shown in the SKB model, which may indicate the existence of a several hundred metres wide disturbed zone (transitional zone).
4. There are indications of the existence of several NS-trending zones in the cluster model. The SKB model shows two NS-trending zones.

In summary, the two models show the same set of brittle deformation zones although the spatial distribution of structures may be compared in more detail than performed in this study. The inhomogeneous existence of sub-horizontal fractures at depth should also be investigated further.

6.2.7 Refinement of investigation approach

Fracture characteristics (e.g. distribution of all and open fractures, crush zones and alteration of fracture surfaces and wall rock together with the type of fracture fills) should be included as a parameter in the cluster analysis. In a further refined cluster model, hydrogeological logs (e.g. PFL-logs) should also be included. The reason for this is that there are structures with a relative high proportion of open fractures and indicated water pathways that are not indicated either by the ESHI or the cluster analysis. The development of the cluster analysis is an iterative process. The aim should be to get a tool to identify potential structures that may affect the location of deposition holes.

7. Summary and conclusions

The conclusions can be divided into method-specific and area specific conclusions.

The method-specific conclusions regarding modelling brittle deformation zones are:

- It is beneficial to work with a high resolution in the modelling performances. Generalization can always be made at a late stage of the work.
- Apply a systematic modelling approach, from sorting of primary data to construction of a model.
- If a classification tool is used (e.g. cluster analysis), it should be iteratively checked against all relevant primary data.
- Cluster analysis of geophysical borehole logs can be used to identify sections in the bedrock with similar physical character along a borehole, e.g. brittle deformation zones and rock alteration associated with zones. Cluster analyses performed in this study are based on single-hole data and is a single hole interpretation.
- The cluster analyses, e.g. based on geophysical borehole logs as in the present study, should be checked against other primary data, especially the fracture log. This can be done by listing the fracture characteristics of the clusters (e.g. fracture orientation, fracture density, wall rock alteration, fracture fill and fracture alteration) and also in the rock adjacent to the clusters.
- The study emphasizes the need of a QA-routine in the sorting, classification and modelling of data.

Proposed refinements of the modelling approach:

- Fracture logs can be included in the classification tool (e.g. cluster analysis) in the single borehole interpretations. Fractures should be sorted into three or four groups: 1. All fractures, 2. Open fractures (can go together with partly open fractures), 3. Partly open fractures and 4. Sealed fractures. Sections of crushed rock should also be included, but effects of mechanical damage on the drill core should be considered.
- A multi-borehole interpretation of non-oriented data can be developed, e.g. a cluster analysis, in order to enable a uniform interpretation of borehole data. However, if oriented are used the correction for sampling bias must be considered.
- Oriented data are needed and exist. However, the existing data have some limitations. For example, the borehole radar may have large uncertainties in the interpreted orientation of reflectors and reflection seismics have restricted limited resolution. Posiva uses an electric method, Mise-a-la-Masse, to detect local zones in ONKALO, the Finnish underground rock laboratory.
- Mapping the zone of influence at a deformation zone requires visualization of the borehole wall (e.g. BIPS or inspection of cores). Using only core-logs and geophysical logs may not be sufficient for a satisfactory interpretation.
- General knowledge about the geometry of structures will enhance the modelling work. A catalogue of reference structures, all structures are not unique, might be useful. Most of the genetically related structures have some common features. The interpreter should on a regular basis interactively update the description of the reference structures.
- Fractures conducting water should be described, including when these occur along discrete fractures.
- The character of the fracture fill and the deformation and alteration of the wall rock support the interpretation of its geological history, i.e. its relation to other structures in the rock.

The area-specific conclusions are:

- The foliation, ductile shear zones, brittle-ductile transitional shear zone and lithological contacts all have more or less similar orientation (approximately NNW/vertical to steep SW). However, in borehole KFM07C the existence of a group of sub-horizontal lithological contacts is notable.
- The fracture configuration in the rock is pseudo-orthogonal and contains two set of vertical fractures trending ENE and NNW and sub-horizontal fractures dipping mainly northwest. In the western part of the model area, vertical NW-trending fractures form the third set of vertical fractures. The relative proportions of different fracture sets may vary with depth, e.g. sub-horizontal to gently dipping fractures are more common at shallow levels.
- The proportion of all open fractures (mapped as open and partly open fractures) in relation to all fractures (mapped as open, partly open and sealed) generally decreases with depth along boreholes. However, in borehole KFM09A, a borehole directed towards a regional NW-trending border zone, the proportion of open fractures increases downwards along the borehole, e.g. when approaching the zone. This holds also for the lowest part of borehole KFM07A when approaching the same zone. In the former borehole NW-trending fractures are dominant in the whole borehole, while in the latter borehole the dominating direction of sub-vertical fractures shifts from ENE at shallow levels to NNW at depth.
- Altered fractures display the same pattern as for open fractures with respect to orientation and relative occurrence. There is no simple relationship between the densities of open and altered vertical fractures in the boreholes, e.g.,
  a) in the borehole dominated by NNW- trending fractures the open fractures are more frequent than the altered fractures (KFM07A),
  b) in borehole dominated by ENE-trending fractures the density of altered fractures is slightly greater (KFM009B) or the same (KFM07C); (the relation in KFM07B is uncertain due to inconsistent use of nomenclature) , ,
  c) in the borehole KFM09A approaching a regional NW-trending border zone, the density of altered fractures is lower than the density of open fractures.
- Sub-horizontal to gently dipping fractures (total, open, altered and fractures with oxidized wall rock) form a distinct fracture set in all boreholes. Sub-horizontal rock domains with altered rock occur in boreholes KFM07A,B,C.
- The main orientation of steeply dipping to vertical sections/domains with altered rock mapped in boreholes differs in orientation compared to fractures (total fractures and fractures with oxidized wall rock) and the differences are:
  a) NS compared to ENE fractures in the shallow part of borehole KFM07A.
  b) NNW compared to ENE fractures in borehole KFM07B.
  c) NNW-NS and ENE compared to only ENE fractures in borehole KFM07C.
  d) NS and NW compared to a mix with ENE and NNW fractures in borehole KFM09A.
  e) NS and ENE compared to ENE fractures in borehole KFM09B.
  This may indicate that the pattern of connected structures during the period of rock alteration was different than the present system of open fractures and that the system of connected structures at that time had the same trend as, for instance, the regional structures forming the border zones of the candidate area. Furthermore, the relative percentage of fractures with altered wall rock constitutes about five to eight percent of all mapped fractures. Altogether, this indicates that the present fracture population has been formed successively. The relation between the density of open and altered fractures may reflect the interplay between how the fractures are connected, the hydraulic paleo-flow along the fractures and possibly also reactivation of structures.
- The dominating orientations of open fractures are related to orientation and location of boreholes. In borehole drilled westward and approaching the regional western border

zone the dominant orientation of vertical fractures is NNW. In boreholes drilled southwards and located inside the site area the dominant orientation of open fractures is ENE (sub-horizontal fractures are described above).

- The cluster analysis captures nearly forty percent of all borehole sections with increased fracturing, i.e. intervals consisting of one-metre-sections of the borehole having more than ten fractures (all mapped fractures). More than sixty percent of the clusters contain sections with such an increase in fracturing. Most of sections with increased fracturing that are missed by the cluster analysis contain few open fractures. However, there are fractured sections not detected by the cluster analysis that might be of interest. In these sections, the total fracture density is less than ten fractures per one-metre-borehole length and the density of open fractures is greater then five open fractures per one-metre-length of the borehole.
- On a two to three metre scale (i.e. the size of mean width of clusters) the fracturing can be inhomogeneous along the boreholes. An example is the sub-horizontal to gently inclined fractures and such fractures are frequent in the shallow part of the borehole and occur also at deeper levels.
- In boreholes that were investigated using the Posiva Flow Log (PFL), the clusters catch nearly eighty percent of all flowing sections. However, the sample size is relatively small (15 out of 19).
- The results of the cluster analysis were checked against primary data, especially the fracture log. This was done by listing statistics on fracture characteristics in the clusters (e.g. fracture orientation, fracture density, fracture and wall rock alteration) and also in the rock adjacent to the clusters. The clusters have in general a contrasting fracture pattern compared with that in the host rock. However, a sequence of clusters may have similar fracture characteristic indicating that the clusters represent sections in a wider zone, e.g. with an internal network geometry.
- Borehole orientation/borehole configuration was studied to evaluate sampling biases. For inclined structures the borehole configuration is most sensitive to EW-trending structures moderately to steeply inclined southward. Structures parallel to the regional NW-trending and steeply southwestward dipping zones in the west are relatively poorly sampled.
- Modelling was performed in a fully three-dimensional space (MicroStation©), performed systematically and with simultaneous documentation. It was found that the orientation of brittle deformation zones appears to approximately conform the dominant orientation of fractures in the clusters.
- The dominant orientations of modelled zones are steeply dipping to vertical and the trends are ENE, NW and NS. Gently dipping brittle deformation zones are frequent, mostly occurring at shallow levels but also at depth. ENE-trending zones form a wide domain crossing the model area. NW-trending brittle deformation zones occur mostly in the westernmost part of the modelled area, at regional deformation zone. NS-trending zones are found throughout the whole model volume.
- The constructed brittle deformation zone model contains 76 zones. Sixteen structures are interpreted to be intersected by three to five boreholes, the same number of structures is interpreted to be intersected by two boreholes and forty-four structures are found just as single borehole intersections.
- The only structure intersecting all five boreholes is a gently inclined shallow zone, while another large sub-horizontal zone with an extension of 700m is found at depth in three boreholes. The latter zone is the most extensive structure in the model. Twenty of the modelled structures have an extension greater than 250m; three of these are gently dipping.
- Structures in the model are fairly thin (less than a few metres) and some are indicated to be extensive.

- The disturbed zone/transition zone east of the regional NW-trending zone in the western part of the model is indicated to be some hundreds of metres wide.
- Some relations between structures are indicated. The NW-trending structures in the western part of the model appear to truncate or refract NS-trending structures. ENE-trending structures are sparse in the western part of the model. However, an approximately EW-trending zone is found.
- The SKB 2.1 model of the Forsmark area agrees with the presented alternative model. However, the relatively large width of borehole zone intersections in the SKB model may camouflage the existence of minor structures.

Issues related to the safety case for a repository for spent nuclear fuel touched upon in the present study are:

- The modelled structures are relatively extensive (the given numbers are minimum extensions of modelled deformation zones and the range is from 20 to 700m).
- Indicated existence of gently inclined brittle deformation zones may affect the layout of a repository. A similar topic is the understanding and character of sub-horizontal to gently inclined fractures at repository depth.
- The width of the disturbed/transition zone at regional deformation zones – i.e. the width of the transition zone at the eastern side of the regional NW-trending regional border zone, which is parallel to the major Ekarfjärden deformation zone, located less than 500m further to the west. The borehole KFM09A, directed towards the zone, has mean densities of open and sealed fractures that are higher than in the other four boreholes in the area. Generally, the density of sealed fractures dominates over the density of open fractures in borehole KFM09A. However, the width of the transitional zone is uncertain due to inhomogeneous deformation along the early formed ductile shear zone and the interfering structures trending NNW and ENE to NE.

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