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Identification of Brittle Deformation Zones and Weakness Zones

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SSM perspective

Background

In preparation for the review of Swedish Nuclear Fuel and Waste Management Company's (SKB) license application for disposal of spent nuclear fuel, Swedish Radiation Safety Authority (SSM) is conducting studies to evaluate the performance of the multi-barrier principle on which the KBS-3 concept is based. Copper canisters containing the spent nuclear fuel are placed into granitic bedrock at about 500 m depth and embedded in bentonite clay. Thus, the rock, the clay and the copper canister are acting as barriers in order to retard the possibility of spent fuel to escape the repository and reach the biosphere.

The proposed area for the repository is surrounded and affected by deformation zones. Knowledge of the zones at depth is obtained from drill cores. No common methodology of identification of the brittle deformation zones exists. The concepts of "respect distances" and "full perimeter intersection criteria" developed by SKB are based on the understanding of fracture extension and the definition of deformation zones. A common methodology in identification of deformation zones is therefore desirable.

Objectives

For SSM, the goal of this study is to improve the scientific knowledge of identification of deformation zones from drill cores. The purpose of this study is also to draw attention to the different viewpoints in the definitions of deformation zones and to the different classification systems.

Results

This study showed that an analyzing tool for characterization of brittle deformation zones is needed. It also showed that a methodology of defining different parts of the zones is needed. One method in identifying brittle deformation zones is suggested in this study. It is based on the concept of clustering fractures due to their separation seen from the drill core. The methodology is based on fixed steps and gives a good resolution. While comparing this methodology with others good consistency is shown.

Need for further research

Further research in the area of identification and definition of deformation zones is desirable.

Project information

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Contents

Abstract

In cratonic areas such as Scandinavia, brittle deformation zones formed in the crystalline Precambrian basement rocks have in most cases a long and sometime complex history. The history may contain healing events and events of reactivation. This implies that the present state of a brittle deformation zone differs from when it was formed. Consequently, parts of the brittle deformation zone may be stiff, while other parts can be soft and outline weakness zones. The objective of this study is to locate brittle deformation zones and weakness zones, mainly based on geological borehole data (core log data).

In order to do this there must be applicable definitions of the concepts of brittle deformation zones and weakness zones as well as systematic approaches to identify such zones. Existing definitions of the two types of zone have been applied. However, it was found that there is a need for a systematic methodology to locate and describe the zones. To develop such a methodology, which aims to identify and characterize brittle deformation zones and weakness zones in analogous ways, both types of zones are here treated to consist of core/-s and disturbed zones. Furthermore, complementary information needed regarding zones include criteria for the location of the boundary between the core zone and the disturbed zone as well as between the disturbed zone and the host rock.

A fundamental part in the identification of brittle deformation zones and weakness zones is how to describe the intensity of brittle deformation associated with the zones. In this study, the fracture frequency is not calculated by dividing the borehole (scan line) into fixed length intervals. Instead, the separation between fractures along boreholes is used together with the number of fractures needed to outline a zone, i.e. to form a cluster of fractures.

The approach developed in this study to locate and describe brittle deformation zones and weakness zones consist of six steps, all bringing basic data along, and many of the steps involve distinct questions giving a transparency to the process:

Step 1. Sorting of base data (regarding discrete fractures – while features mapped as zones are excluded at this stage, e.g. zones of crushed rock). All data are brought along as a general reference. Perform selection of groups of data to outline brittle deformation zones and weakness zones.

Step 2. Calculate separation of fractures for selected groups of fractures and all fractures. Select cluster parameters (minimum mutual separation of fractures and number of fractures to outline core zones and disturbed zones – two categories of clusters). Identify clusters of fractures.

Step 3. Sensitivity test. What are the effects of alternative selections of input data and cluster parameters?

Step 4. Locate brittle deformation zones and weakness zones and their internal parts (core/-s and disturbed zones). This is an interactive repetitive process consisting of merging of clusters. Present the applied basic concept for merging clusters (clusters appearing in swarms, for example widths of clusters in relation to separations) and the basis for stopping the process (minimum fracture frequency in the core zone/-s and disturbed zones) unless it stops by itself. Give also the premises to locate boundaries of different parts of zones. Start with merging clusters outlining zone core/-s. Introduce sections of intense deformation such as crushed rock in the core zones. Merge sections that represent disturbed zones. Is the result plausible?

Step 5. Present the results by, for example, visualization (composite logs showing the relation between brittle deformation zone, weakness zones and other geological features /such as ductile deformation, alteration/, indicated groundwater flow and geophysics) as well as in tables and text.

Step 6. Compile the characteristics of different sets of zones. This is part of a learning process that forms the basis for three-dimensional modelling of structures and tests the general knowledge of a site by comparing predictions versus outcome of further investigations/excavations.

The information used in this study is mainly geological borehole information acquired by the Swedish Nuclear Fuel and Management Co (SKB) during their detailed characterization of the Forsmark site located in north-northeastern Uppland, eastern central Sweden. The present investigation has used selected borehole section, especially in seven boreholes penetrating a gently inclined zone at different depths, from shallow to depths of more than 300 m.

Key words: fracture, fracture characteristics, core log, brittle deformation zone, weakness zone, definition, nomenclature and zone identification.

Kortfattad sammanfattning

Föreliggande studie har som syfte att ge en fristående beskrivning av strukturer undersökta med kärnborrhål. För att få en översikt i hur strukturer kan variera i karaktär utmed dess utbredning är det en fördel att de studerade strukturerna genomborras av ett flertal borrhål.

Denna studie omfattar bland annat en av de flacka spröda deformationszonerna som identifierats vid Svensk Kärnbränslehantering ABs (SKB) platsundersökning i Forsmarksområdet beläget i nordöstra Uppland. Zonen (SKBs benämning är ZFMA2) har genomborrats av sju kärnborrhål och har en lateral utbredning i sidled på cirka 4 km vid markytan samt stupar flackt (cirka 25°) söderut. Dess mäktighet bedöms variera mellan 9 till 45 m med en medeltjocklek på 23 m. Dominerande sprickor i zonen är subhorisontella.

Att utföra en jämförande studie, dvs. i detta fall en jämförelse av egenskaper hos olika delar av ett objekt, kräver en systematisk analysmetodik samt att objektet skall vara klart definierat. Med det sistnämnda menas i detta fall att termen spröd deformationszon skall vara klart definierad. Detta är speciellt viktigt i en geologisk miljö där objektet självt, den studerade spröda deformationszonen, ej är allena förekommande utan omges av ett geologiskt brus av strukturer.

Definitionen av spröd deformationszon skall kunna användas för att avgränsa zoners rumsliga utbredning och dess olika komponenters omfattning. Detta innebär att fastlägga zoners mer deformerade delar (kärna/-or) och övergångar från kärnan till det ostörda sidoberget, den så kallade övergångszonen eller störda zonen. Vid tillämpandet av en given definition (t.ex. den som använts i Forsmark av SKB) framgår det att det behövs ett analysverktyg för att på ett reproducerbart sätt karaktärisera en spröd deformationszon och dessutom måste principer tas fram för att fastlägga var avgränsningar av zoners olika delar skall sättas.

Spröda deformationszoner i berggrunden är föränderliga och har påverkats, på ett eller annat sätt, alltsedan de bildats och kan påverkas alltjämt. Under statiska förhållanden kan man förvänta sig att zoner läks genom utfällningar i sprickor och hålrum, medan justeringar (avlastning av lagrade spänningar) kan ske då belastningen av strukturer förändras. Sådana avlastningar kan hålla delar av befintliga strukturer öppna, dvs. den svaghet i berget som finns relaterat till en struktur kan ha en annan storlek och karaktär än vad den ursprungliga spröda deformationszonen hade. Plana till semiplana strukturer som har signifikant lägre hållfasthet än omgivande berg anges som svaghetszoner.

Det skulle vara fördelaktigt med en gemensam metodik för att identifiera spröda deformationszoner och svaghetszoner. Detta kan göras om spröda deformationszoner och svaghetszoner har analoga definitioner, dvs. baseras på hela eller delmängder av samma basdata samt att de två strukturerna har samma typ av intern uppbyggnad (kärna/-or samt övergångszon/störd zon). Det som skiljer de sprickgrupper som används för att identifiera spröda deformationszoner och svaghetszoner är att i den föregående ingår öppna, partiellt öppna och läkta sprickor medan vid utskiljning av svaghetszoner ingår ej sammanläkta sprickor (i Forsmarksfallet har valts att endast öppna omvandlade sprickor skall ingå). Framtagen metodik innehåller fasta steg och dessa innehåller i sin tur tydliga valsituationer och dessa val testas i ett separat steg som omfattar känslighetsanalys.

Basprincipen för här utvecklad metodik för identifiering av spröda deformationszoner och svaghetszoner vilar på identifiering av sprickkluster (anhopningar av sprickor) utgående från minimiseparation mellan sprickor samt lägsta antal sprickor som ett kluster skall innehålla. Vidare görs hela arbetet på så sätt att all originaldata för valda sprickgrupper följer med under analysens framskridande – resultat lämnas plats för och skrivs in basdatatabeller. Metodiken innehåller sex steg och dessa är i stort:

1. Val av ingångsdata; innehåller analys av data för val av adekvat datamängd.

2. Val av klusterparametrar och lokalisering av sprickkluster: Minsta antal sprickor och minimiseparation mellan sprickor som skall ingå i två typer av kluster. Dessa två har olika minimiseparation av sprickor för att sortera fram zonkärnor respektive störda zoner/övergångszoner. Utföra beräkning av separationer, klassning av separationer och lokalisering av kluster.

3. Känslighetsanalys: Vad händer om man ändrar ingångsdata eller klusterparametrar?

4. Läge på spröda deformationszoner och svaghetszoner samt deras interna delar: Detta steg är en interaktiv iterativ process och kräver beslut om premisser för att sätta yttre gräns för zoner (här har valts att den skall utgöras av ett kluster), samt villkor för att slå samman närliggande kluster (t.ex. relation mellan klusterbredd och separation mellan intilliggande kluster). Företrädesvis slås först de kluster samman som utgör zoners kärnor (partier med krossat berg och annat berg omformat i samband med förkastningsrörelser tas med i detta skede) och därefter sammanbinds kluster innehållande den störda zonen/övergångszonen. Denna iterativa process avslutas då inga fler kluster kan slås samman eller då kärnzoner och störda zonen/övergångszonen når sina gränsvärden avseende sprickfrekvenser. För att förenkla används här medelvärden på sprickfrekvenser i identifierade zonkärnor och störda zoner/övergångszoner över flertal avsnitt av borrkärnor (djupintervall), avsnitt som tillsammans innehåller ett flertal lokala strukturer.

5. Sammanställning och presentation av resultat. Detta ges som tabeller, figurer (loggar som visar zoner i relation till olika andra geodata, t.ex. kärnförluster, förkastningsbergarter inklusive plastiska strukturer, förekommande vittring, grundvattenflöden och geofysik) samt beskrivande text.

6. Sammanställning av egenskaper hos olika grupper (set) av zoner. Även denna del är en interaktiv del eftersom kunskapen om strukturer är en del av en lärandeprocess. Detta underlag användes därefter som underlag för modellering av strukturer och vid prediktering

av utfall av ytterligare undersökningar (t.ex. borrhål eller bergbyggnationer).

Den geologiska miljön i Forsmark avseende på spricktäthet varierar både i lateral och vertikal led. På grund av markant förhöjd allmän spricktäthet i vissa ytnära delar av berget kan det vara osäkert att bestämma läget för zonen ZFMA2 utgående från den generella sprickfrekvensen i berggrunden. Framtagen metodik ger i stort en god överenstämmelse mellan här framtagna och av SKB angivna bredder på zonen. Det skall noteras att den framtagna metodiken har god upplösning och är kapabel att identifiera strukturer med ringa bredd. Den största skillnaden mellan denna klassning av zoner och den som presenteras av SKB är att relativt stora delar av de spröda deformationszonerna här klassas som zonkärnor, dvs. deformationen är relativt fokuserad.

De andelar av den spröda deformationszonen ZFMA2 som kan klassas som svaghetszoner är i stort beroende på zonens djupläge i berggrunden. För ytliga lägen förekommer ett flertal svagare partier spridda inom zonen medan vid djupare lägen synes de svagare delarna av zonen utgöras av ett fåtal tunna strukturer (vanligen någon decimeter breda; meterbreda i extremfall).

Nyckelord: spricka, sprickkaraktär, sprickdata, spröd deformation, svaghetszon, definition, nomenklatur, analysmetodik.

1. Introduction

The strength, deformability and hydraulic properties of a tectonic discontinuity in the bedrock are unlikely to be homogenous across or along the discontinuity. For example, consider a structure mapped as a brittle deformation zone, for which the spatial variability in properties is related to the evolution of the structure. This is reflected in the internal structural pattern in the zone and the interference with pre-existing as well as overprinting structures. In addition, the character of a tectonic discontinuity changes with time (evolution) due to the interplay between sealing processes and re-activation (including all types and magnitude of differential movements). Thus, the present character of a tectonic discontinuity reflects the evolution of the structure.

From a geological point of view, to locate sections with increased fracturing (potential locations of brittle deformation zones), all discrete fractures need to be considered. From a rock mechanical and hydrogeological point of view fractures parting the core are of primary interest, as they indicate fractures with low *in situ* cohesion. However, such fractures may include fractures that are mechanically broken up during drilling or handling of the core, i.e. they are fractures that in a natural state are closed/sealed. Therefore, among all open fractures, those that are mapped as open and having indicated weathering of the fracture surface or/and the fracture fill are of importance to locate weak sections in the rock.

Objective of the study

The objective of the study is to present geological parameters and to elucidate variation in rock mechanical properties along deformation zones and differences between the character of zones and the host rock. Of special interest is to locate weaker parts of the rock and structures along which groundwater flow occurs.

A special aim of the present study is to present a methodology/tool to locate and characterize sections with increase fracturing and sort out sections that at present time represent weak rock.

Organization of the report

The report consists of four chapters in addition to the introduction.

The following chapter (Chapter 2) presents the concept of brittle deformation zones, SKB's approach to identify brittle deformation zones, the data used in this study and the methodology used during the present investigation to characterise brittle structures based on borehole data (scan-line surveys). The concept of weakness zone in contrast to brittle deformation zone is also discussed.

Chapter 3 is extensive and comprises descriptions of seven borehole sections across a gently inclined brittle deformation zone at the SKB site at Forsmark in northeastern Uppland, eastern Sweden. Intersections of two steeply dipping brittle deformation zones are also described, although these zones are only observed in single boreholes. In the last section of this chapter a summary of the general fracturing in the seven investigated borehole sections are given together with a short description of the gently inclined brittle deformation zone.

Chapter 4 is the discussion section and it brings the methodology of characterizing sections of increased fracturing further compared to Chapter 3. Discussed are, for example, sensitivity tests, location of boundaries of deformation and weakness zones, and correlation between clusters of fractures and borehole geophysics.

Chapter 5 presents the results and conclusions. The presented approach to identify and characterize brittle deformation zones and weakness zones is based on the methodology presented in Chapter 2, applied in Chapter 3 and further developed in Chapter 4. The last section of this chapter contains a presentation of the character of the investigated gently inclined brittle deformation zone and its associated weakness zones.

2. Classification of brittle structures in boreholes – Methodology applied in this study

Character of deformation zones

The characterization of a deformation zone may have at least two purposes:

- To increase the structural geological understanding of site structures, including a description of geometrical relations and characters of structures formed on different scales (i.e. includes also the internal character of zones) and how the rock is affected by the formation of the deformation zones – a base for predictions.
- To develop a classification system that steers the layout, function and possible also the monitoring of a bedrock facility. Such a system may provide information about structures that are not allowed to intersect the bedrock facility and construction restrictions for other structures (layout criteria) to minimize adverse effects on the function of the bedrock facility.

The geological understanding of the formation of structures in an area is the basis for the identification of zones, the prediction of their extension and the relation to other structures. The process is interactive with increasingly refined understanding during the progress of the site investigation. Well exposed bedrock helps to characterize the variation in the character of geological structures along their extension. However, even though the thickness of the soil cover, the overburden, may locally be relatively thin (may topically exceed 15 m though the ground surface is flat), excavations are needed to map deformation zones as naturally exposed bedrock, outcrops, generally represent rock of better quality, i.e. less fractured rock.

Outcrops are in most cases small and analyses of self-similarity (scale invariance) of structures may compensate for the limited scale of exposed rock. Furthermore, the present character of a deformation zone is a product of its geological history (cf. Milnes 2006). Reactivations, especially partial reactivations, of geological structures are common. They may have occurred during different geological conditions than during the initial formation of the structure. The partial reactivation of deformation zones may result in contrasting properties of the structures along their extensions. A geological structure could, for example be a planar discrete structure and it could also be a non-planar feature formed by the linkage of partly reactivated segments of structures that intersect each other. A good geological understanding of the geological evolution may also be used as basis for an engineering, rock mechanical classification of structures (cf. Hagros 2006).

Syntheses of the characteristics of deformation zones, with their internal structural pattern and bifurcations (splays), overlaps, bridges, damage zones etc. as exemplified by Kim et al. (2004), are rarely described for the SKB sites and Posiva sites (Finland).

To classify deformation zones, minimum information include data on the deformation intensity across the deformation zones together with quantification of the minimum extension of the zones. To determine whether a structure should be avoided within a bedrock facility, such as a deep geological repository for radioactive waste, the geological characterization of the zone need to be complemented by engineering geological considerations.

Brittle deformation zones and weakness zones

The framework of structures existing in the bedrock today is the accumulated effect of the geological history on the bedrock. The structural pattern can be observed on different scales, from regional scale to microscopic scale. The character of the structural pattern may have similarities (self-similar patterns) but characterization of parameters describing the bedrock may be better achieved at some scales than others. The objective of the present study is to present a methodology that indicates location of fractured borehole sections that may represent brittle deformation zones and weakness zones.

Base data for identification of brittle deformation and weakness zones

A basic concept in identification of geological features is that the character of each studied features is known or can be quantified. In an optimal case, the bedrock is well exposed and the character of different types of structural features can be studied in detail along their extensions and the relation between the studied objects and other structural features can be investigated and described. Such information can then be summarized and a general description of, e.g., a set of brittle deformation zones can be made. This can then be used to indicate the existence of deformation zones where the scale of observation is restrained to, e.g. boreholes. However, this study has to rely solely on primary data from borehole investigations.

All data used in this study is from the SKB Forsmark site selected as a potential area for hosting a deep geological repository for radioactive waste and within which subsurface based investigations will be performed (SKB Doc ID 1207622; 2009.06.04). The available information consists of:

1. Primary geological borehole data from selected cored boreholes (boreholes KFM01B, 1C, 2A, 2B, 4A, 5A and 10A)) and constitute transcripts extracted from the SKB database SICADA:
    - KFM orient and length.xls – data on boreholes.
    - p_core_loss-KFM – sections in the boreholes where no core is retrieved.

- p_rock-KFM – rock types in section greater than 0.5 mbl.[1]
- p_rock_occur-KFM – rock types occurring in section less than 0.5 mbl.
- p_fract_core-KFM – discrete fractures.
- p_fract_crush-KFM – sections of crushed rock.
- p_rock_struct_feat-KFM – orientation of tectonic structures.
- p_fract_sealed_nw-KFM – sections with sealed fractures, network of hairline fractures.
- p_rock_alter-KFM – sections with altered rock, type of alteration is given.

2. Geophysical borehole data:
   - p_radar_direct –KFM – borehole radar data, reflectors with absolute orientation.
3. Interpreted geological and geophysical borehole data:
   - p_eshi p_shi – interpreted locations of deformation zones (DZ).
4. Data on flowing sections in boreholes (Posiva Flow Logs /PFL/) are extracted from SKB reports (no data from KFM01A and 01B; data from borehole KFM02A in SKB P-04-188 and P-05-37; KFM02B in SKB P-07-83; KFM04A in SKB P-04-190; KFM05A in SKB P-04-191; KFM10A in SKB P-06-190, also available in SICADA plu_pfl_inferr_anom.xls).
5. Three-dimensional geologic and structural models of the Forsmark site (SKB model database SIMON, rvs-files).
6. Main references used for the description of the geological model are SKB reports SKB R-07-45 and R-08-64 complemented by descriptions of kinematic indicators (SKB P-06-212, P-07-101 and P-07-111).

For each investigation method, SKB have published a method description (in Swedish), in this case:

- Method description - Boremap (SKB MD 143.006 Version 2.0, 2005).
- Nomenclature – Boremap (SKB MD 143.008, version 1.0, 2004).
- Geological Single Hole Interpretation (SKB MD 810.003 version 3.0, 2006).

All data were kindly provided by SKB. The borehole data are from the SKB database SICADA and the structural models are stored in the SKB model database SIMON. The published reports (SKB series TR, R and P) are available in digital format on SKB's website (www.skb.se).

[1] mbl. is the abbreviation for "metre borehole length".

The framework of brittle structures in the bedrock

The framework of fractures indicated in, e.g., boreholes is, as pointed out above, the result of the structural history and constitutes a wide range of events and processes that have deformed and also sealed the rock. In metamorphic gneissic terrains, such as Forsmark in northern Uppland, brittle deformation zones seldom predate the peak of metamorphism. However, the bedrock may have had juvenile structures that have acted as precursors for brittle deformations or structural pattern that in some other way steered the formation of the brittle deformations. This implies that there may have existed structures (ductile or brittle) that predates the main period of formation of brittle deformation zones and that those structures are reactivated as brittle deformation zones. The zones may later on be sealed and thereafter again reactivated or overprinted by other brittle structures. The character of a brittle deformation as seen in a borehole reflects the deformation of the rock where the borehole intersects the zone; some fractures are related to the zones while others might not be.

Nomenclature

The nomenclature concerning brittle deformation zones presented by Munier et al. (2003) and meant to be used by SKB in the site characterization work (Fig. 2-1) is adopted in the present report in order to have a uniform basis for the discussion of results. In the SKB concept of brittle deformation zones[2], fixed values of fracture density are used to distinguish between fractures occurring in the host rock (less than 4 fractures/m) and fractures inside the brittle deformation zone (4 or more fractures per m). The core of the brittle deformation zone has a fracture density greater than 9 fractures per metre.

In the special SKB task (Step 2 of the SHI) considering analysis of kinematic indicators the SKB concept of deformation zones is slightly modified (Nordgulen and Saintot 2006 and 2007, Saintot and Nordgulen 2007). "The term fracture zone is used to denote a brittle deformation zone without any specification whether there has or has not been a shear sense of movement along the zone. A fracture zone that shows a shear sense of movement is referred to as a fault zone" (Nordgulen and Saintot 2006[3]). However, in their following works, no distinction between brittle deformation zones and fault zones is noted (cf. Nordgulen and Saintot 2007, Saintot and Nordgulen 2007). The occurrence of fault rocks is also presented in the zone definition by Munier et al. 2003. Nordgulen and Saintot (2006) clarify that "The term fault zone is generally used for brittle structures in which loss of continuity

[2] The definition of brittle deformation zones has a dual character as it contains both structures that are qualitatively and quantitatively measurable (e.g. fractures) in terms of fracture density and structures that are not (e.g. crushed rock and fault gouge). Note that Munier et al. 2003 do not present any written definition of the term. Why the fixed values 4 fr/m and 9 fr/m are chosen as limits for the boundaries of brittle deformation zones and the core zones, respectively, are not discussed.

[3] The classification scheme for faults (containing structures that are non-cohesive, have secondary cohesion or are cohesive) suggested by Braathen et al. 2004 (cf. Sibson 1977) is use in kinematic studies. Structures in the bedrock all have their geological history. This implies that fault rocks belonging to the category of structures that are cohesive or have a secondary cohesion may indicate location of fault cores that deviates from fault cores defined by, for example fractures and crushed rock.

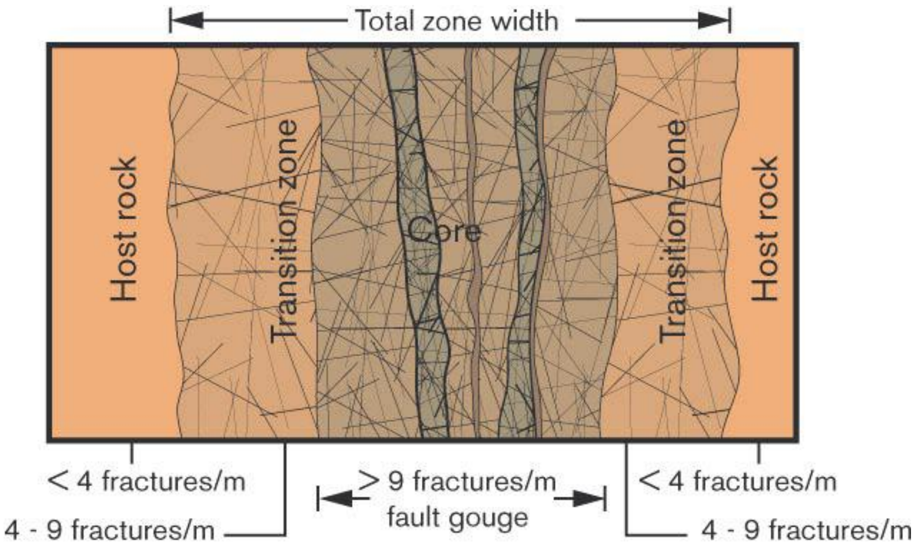


Figure 2-1: Brittle deformation zone; host rock – transition zone – core—transition zone—host rock. (From Munier et al. 2003 and modified by Nordgulen and Saintot 2006). The transit zone corresponds to the damage zone (cf. Kim et al. 2003 and 2004) and damage zone is generally used in the text.

and slip occurs on several discrete faults within a band of definable width". There are no limitations concerning the widths of structures denoted brittle deformation zones or fault zones. Furthermore, the fracture densities can be measured in scan-lines surveys (in boreholes). However, for optimal positioning of the location of the borders of a brittle deformation zones (external borders /zone to host rock/ and internal borders /damage zone to core zone/) a tool, how to measure, and guide lines, were to locate, are required.

The classification of brittle deformation zones applied by SKB does not give any information about how and where to locate the borders between the host rock and the transition (damage) zone and between the transition (damage) zone and the core zone (Fig. 2-1), respectively. Again, a methodology to do this is needed to obtain a uniform description of the architecture of deformation zones. However, this task is not simple as the deformation along a zone may be heterogeneous and the observed structural pattern may be affected by interference with pre-existing and over-printing structures.

For example, Caine et al. (1996) in their description of "fault zone architecture and permeable structures" use the terms fault core and damage zone to describe the hydraulic properties in different part of a fault zone. They pointed out that fault cores (according to their definition of the term) may consist of:

- Single fault surfaces.
- Unconsolidated clay-rich gouge zones.
- Brecciated and geochemically altered zones.
- Highly indurated cataclastic zones.
- Structures which hydraulic character may vary from a localized conduit to a localized barrier.

The damage zone (Caine et al. 1996) is a "network of subsidiary structures that bound the fault core and may enhance fault zone permeability relative to fault core and the undeformed protolith" (the host rock).

Four types of fault zone architecture were distinguished (Caine et al. 1996) based on the hydraulic character of the core zone and the width of the damage zone (unsealed fractures). The end members are (cf. Fig 2-2):

- Localized Conduit (core zone and no damage zone; I).
- Distributed Conduit (conductive core zone and damage zones; II).
- Combined Conduit-Barrier (conductive damage zone and tight core zone; IV).
- Localized barrier (tight core zone and no damage zone; III).

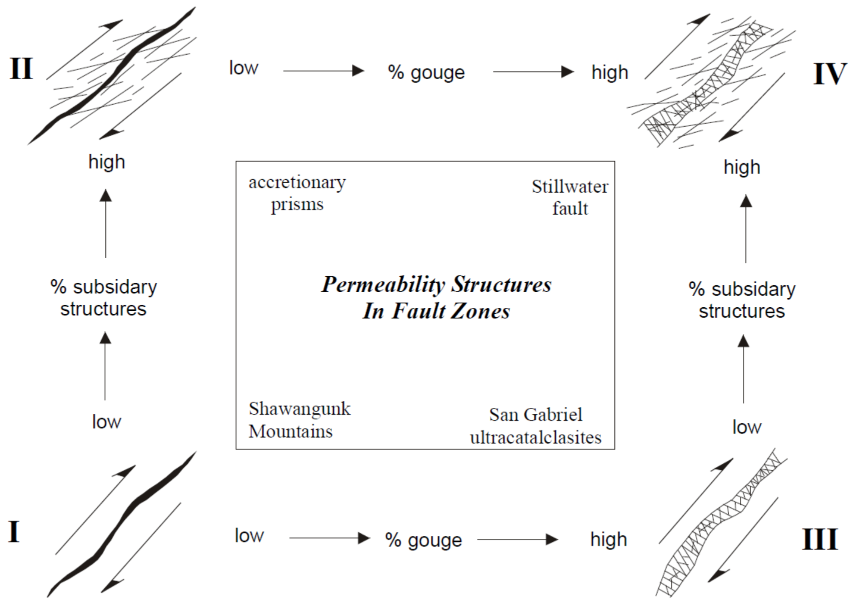


Figure 2-2: Conceptual scheme for fault-related fluid flow. Four main groups of fault zones related to density and distribution of fracture and fault gouge (Caine and Foster 1993).

Although Cain et al. (1996) introduce a fault zone indices based on the widths of the fault core and damage zones. However, they do not discuss how the widths should be measured. Furthermore, the conceptual fault zone model presented by Caine et al. (1996) always contains a core zone. Kim et al. (2003 and 2004) discuss in more detail the concept of fault damage zone.

The brittle deformation zone nomenclature presented by Munier et al. (2003) is not genetic. However, where core zones appear in a SKB brittle deformation zone model they are denoted fault cores (Stephens et al. 2008, Appendix Table A-4). Furthermore, Munier et al. (2003) include in their schematic illustration of brittle deformation zones also fault rocks in the core zone, e.g. fault gouge, without a discussion whether the fault rock is cohesive (sealed) or not. The character of fault rocks has been described and discussed by, for example Sibson (1977), Braathen et al. (2004) and Milnes (2006). Once again, many early ductile deformation zones have also acted as precursor for brittle deformation, i.e. all deformed rock found within a brittle deformation zone may not be brittle in character.

All structures formed in the bedrock are more or less affected by the geologic evolution since the structures were formed. Precipitation of fracture mineral and weathering of fracture walls and fills are example of processes that decreases the water permeability in fractures, while changes in the stress field may cause disturbances that keep structures open or reopen structures. Furthermore, when characterizing a brittle deformation zone it is an advantage to have the structure well exposed so the structural relation between different parts of the structure can be studied and also how structures inside the zone is related to structures in the host rock outside the zone. Such knowledge is useful when performing structural interpretation of borehole data.

The strength of the rock within, for example, a brittle deformation zone is generally not uniform (cf. Fig. 2-2). This is, as pointed out above, partly due to the interplay between fragile deformations and sealing processes. In rock engineering and construction the main concerns are related to the actual properties and behaviour of the rock (Palmstrøm 1995), especially zones of weakness. The general term “weakness zone” denotes "a part or zone in the ground in which the mechanical properties are significantly lower than in the surrounding rock mass. Weakness zones can be faults, shears/shear zones, thrust zones, weak mineral layers, etc." (Norwegian Rock Mechanics Group, 2000, Palmstrøm and Broch 2006). This implies that weakness zones may fully coincide with or only form a minor part of brittle deformation zones. If a brittle deformation zone is sealed then it may not form a zone of weakness (although it will form a scar). However, brittle zones may reactivate and the probability for reactivation of sealed zones is very little studied (not known to the author). What is described is that reactivations occur.

An alternative methodology (cf. SKB geological Single Hole Interpretation, SHI, described in the following section) to identify sections of fractured and weak rock in boreholes is given in subsequent sections. First a review of the SKB approach is given.

Review of SKB Geological Single Hole Interpretations and location of zones

The main aim of the SKB geological Single Hole Interpretation (SHI: SKB MD 810.003, version 3.0) is to support the construction of deterministic three-dimensional geological models and stochastic DFN modelling of fractures in the rock outside brittle deformation zones. The input data are geological and geophysical borehole data (and borehole TV; BIPS) and the classification of data embrace rock units (RU; rock type) and possible deformation zones (DZ). Interactive control of interpretation by visual inspection of the core is performed to refine the classification. The process of interpretation of deformed rock within the SHI investigation is made in two steps:

Step 1: A general description of the character of deformation zones (DZ’s; e.g. brittle, ductile or transitional) and a detailed description of parameters supporting the identification of each zone. The confidence of the zone interpretation is also given (3 classes: high, medium and low).

Step 2: Focused on characterization of zones with high confidence (step 1) regarding the following parameters: type of deformation across zones, characterization of fault rock, location of core zones and kinematic analysis. The parameter information should be complemented with a short interpretation of the structural evolution of the zone. The second step is reported separately.

It is stated that the Single Hole Interpretation (SHI) is the first action regarding zone interpretation and it is separated from a second action (the Extended Single Hole Interpretation; ESHI) when more precise locations of deformation zones are determined. The ESHI is performed during the actual modelling of structures in three dimensions. For identification of SHI/ESHI there is no limitation regarding the size of their extension along the boreholes. In the Geological Single Hole Investigation the fracture frequency statistics is presented as floating averages (e.g. 5 m window and 1 m steps) for all fractures, open fractures, partly open fractures, sealed fractures and sealed fracture networks. The floating average statistics has a smoothing effect on the fracture frequency curves.

In summary, the SHI and ESHI classification should be better described by SKB regarding systematics and applied methodology in the classification process to obtain a uniform classification process that is fully transparent and reproducible. This holds especially for the ESHI classification as it appears not to have a comprehensive method description. The results of the SHI/ESHI (the location of interpreted structures) are stored in the SKB database SICADA.

In the Forsmark area the number of indicated intersections of brittle deformation zones in boreholes (KFM01A-10A; 23 cored boreholes with a total length of about 15 km) was 114 in the first SHI step and they constitute 24.5 percent of the total mapped core length. The second classification step (ESHI) introduced 12 more potential zone intersections and adjustments of the position of 10 SHIs. Thereby the length of potential intersections of brittle deformation zones in the boreholes increased by slightly less than ten percent (9.8) so that the ESHI intersections occupies about 26.9 percent of the total length of mapped cores (ESHI; range in width from 0.5 to 215 mbl. and the mean value is 32 mbl.). The shallower part of the bedrock in the Forsmark area is notably more fractured than its deeper parts and in spite of this about 46 percent of all ESHI are located at depth below 300 m a.s.l.[4], note that most boreholes are target-drilled. However, it is beyond the scope of this study to elaborate on this further.

In the study of kinematic indicators to identify shear displacement along faults a selected number of SHI DZ sections (84) were studied (cf. Appendix Table A-4 in Stephens et al. 2008) and the more intensely deformed sections forming the fault core (cf. Fig. 2-1) were identified. Amongst the studied SHI DZ sections 52 percent contain fault cores (no tables compiling width and location of fault cores was found by the author) and 79 percent of the

[4] m a.s.l. is the abbreviation for metres above sea level.

investigated SHI DZ sections were included in the 2.3 version of the geological SDM for Forsmark.

A final remark is that the all SHI DZ are used as input data in the SKB structural modelling process, i.e. the construction of the geological Site Descriptive Model (SDM). The boundaries of the zones may be adjusted during the modelling (transformed to ESHI) and all SHI DZ sections in boreholes may not be included in the presented model. Due to criteria for including structures about 35% of the number of all SHI DZ sections, i.e. about 19 percent of the total length of all SHI DZ sections in boreholes, are not included in the 2.3 version of the geological SDM for Forsmark. However, in the geological SDM several structures are not intersected by boreholes but indicated by ground geophysics only.

Classification system for identification of brittle deformation zones and weakness zones in boreholes

During an initial stage of the present study, an attempt to increase the resolution in the interpretation of fracture data from boreholes was made by studying fracture frequency in intervals of 0.5 mbl. The idea is simple and assumes that an increase in the resolution in the interpretation will increase the understanding of the distribution of fractures along the boreholes. However, by applying fracture statistics, averaging data, the direct coupling between base data and fracture characteristics was lost. Furthermore, averaging over fixed distances may suppress structures that are thinner than the interval width used in the statistics.

Instead of using intervals along which fracture characteristics can be averaged, the mutual separation between fractures is used to identify clusters of fractures. This is to apply a fracture-scale resolution. Separation between fractures can be transformed into fracture densities/frequencies, when such measures are needed. Calculation of mutual separation between observations can be made in the base data tables (in this case in an added column for data in the worksheet) maintaining the coupling between the separation of fractures and the character of fractures in the base table. This ensures optimum resolution in the classification of data.

A classification system should require the following:

1. The classification system should be objective.
2. Input data should be available in a treatable format; data to classify and information that might affect the classification system (data on the geological environment within which the object for classification is located).
3. The classification should be systematic and uniform, i.e. being transparent and reproducible.
4. Clear steps in the classification process and presentation of refinements of the classification for each step.
5. Simple to make sensitivity tests, i.e. test outcome against chosen parameters steering the classification.

6. Presentation of results is a communication process and should be customised and observation regarding relations between data sets (geometric or genetic) be described and visualized.

The objective of the classification system

The objective of the classification system presented in this study is to sort out sections along boreholes that may represent structures in the bedrock that affect its mechanical strength and the flow of groundwater, i.e. weakness zones. At the same time, sections with a general increase in fracture density (considering all fractures) that may represent brittle deformation zones are located. However, the effort is not to identify extensive discrete fracture planes (cf. large fractures, SKB 2010).

Input data

Basic input data comprise the fracture logs (including discrete fractures, crushed rock, and core loss). Data describing the geological environment are lithological logs (including rock types, orientation of lithological contacts, and alteration of the bedrock), data on ductile deformation (foliation and ductile shear zones), data on zones formed by brittle deformation (brittle-ductile shear zones, cataclastic rock, breccia, “sealed network of fractures”, crushed rock and core loss), borehole radar data (absolute orientation of reflectors) and data on fluid transport into or out from the borehole (flow logs /e.g. PFL/). Borehole TV-logs (BIPS) have been used during the SKB mapping of the cores to orient structural features. The BIPS method can be used to obtain detailed in situ pictures of structural relationships. However, BIPS data have unfortunately not been used in the present study to support the presented classification of drill cores. In this study, classified fracture data are presented in composite logs together with locations of water-conductive structures.

Systematic and uniform classification

Important in all classification systems is that the nomenclature and classification procedure are well defined and the system is applicable within a wide range of fracture densities. The simpler a classification system is the higher is its reproducibility and transparency. However, the identification of sections of increased fracturing can be based on relative increases in fractures frequencies (relative to the general fractures density in investigated borehole) or by using fixed absolute values regarding fracture separation (used here, however, by choosing small numbers the difference will be minor) when setting class boundaries. Progressive refinement in the classification procedure may be conducted (cf. item 4 in first part of this section).

Clear steps in the classification process

A stepwise performed classification procedure will enhance the understanding of data and it also demands arguments for each performed step. Interactivity in the process provides feedback and forms the base for refinements of the classification.

Sensitivity tests

Tests of sensitivity can be made part of the classification system. This is simple when the classification is based on one parameter but becomes more intricate when the classification is based on two or more parameters. For fracture distribution and identification of clusters, three parameters should be considered:

1. Minimum number of fractures in a cluster.
2. Minimum mutual distance of fractures.
3. Selection of fracture population (for example; all, open or sealed fractures and fresh versus altered fracture and sets of fractures or a combination of these fracture characteristics).

The sensitivity test performed in this study (Chapter 4 Discussion) considers all fractures in one borehole section (KFM10A). The test consists of changing the minimum number of fractures to form clusters (4±1) and also varies the minimum mutual separation between fractures to outline clusters (from 0.1 and 0.2 to 0.5 mbl.; the latter corresponding to a minimum fracture frequency of 2 fractures per metre borehole length[5]).

Presentation of results

The presentation of results should be performed is such manner that the results can be easily used by other geodisciplines and also in such a way that it communicates the essence of the result of the classification. The former can be done by presenting tables while the latter can be made by visualization of results (composite logs or three dimensional figures showing, e.g. structural relationships). Both presentations should be accompanied by descriptive text.

Step by step performance – identification of sections with increased fracturing in boreholes

Classification of brittle deformation may in well exposed areas be based on continuous mapping of structures along their extent. However, such areas are relatively rare. Deformation zones are often more easily eroded than the host rock why they form depressions in the bedrock surface and often are, evenly in relatively well exposed areas, covered by soil.

The classification procedures used (Chapters 3, 4 and 5) are based on borehole data and consist of sequences of steps. The first step (cf. section Data handling below) involves selection of data to base the classification on. The

[5] fr/mbl. is the abbreviation for "fractures per metre borehole length".

subsequent steps consider how to locate sections in the borehole representing possible locations of brittle deformation zones and weakness zones.

The use of relative density of fractures to identify potential location of brittle deformation zones requires good overview regarding the general homogeneity of fracturing along the boreholes. The SKB definition of a brittle deformation zone (Fig. 4-2) applies fixed values on fracture frequencies. A brittle deformation zone may have core zone/-s for which the density of fractures is set by SKB to be greater than 9 fractures per metre[6]. However, this fracture frequency cannot directly be compared with, for example, the RQD (Rock Quality Designation, see Formula 1 below) as the RQD considers fractures parting the core. For core sections with core pieces equal to or shorter than 0.10 m the RQD is zero. Furthermore, some of the fractures breaking the core may be broken up during drilling and handling of the core.

RQD (Deere 1964) is defined as the quotient in percent:

$$RQD = \left(\frac{l_{\text{sum of 100}}}{l_{\text{tot core run}}}\right) \times 100 \qquad \text{(Formula 1)}$$

l_{sum} *of 100*= Sum of length of all core sticks longer than 100 mm measure along the centre line of the core (in the measured section)
l_{tot} *core run*= total length of core run (the measured section).

However, it is not apparent what fractures are to be considered in the SKB definition of brittle fractures (all fractures?). In the classification presented here, all fractures are used initially to locate possible positions of brittle deformation zones. On the other hand, to locate weakness zones open altered fractures are used[7], i.e. a sub-group of all fractures parting the core (cf. RDQ). However, using all fractures to identify fracture zones may be cumbersome in bedrock with high average fracture densities, especially when the fracture population is composed of a mix of several sets of fractures (cf. Chapter 3). That is, the clusters may represent, for example, cross-cutting zones or a more or less random interference of fracture sets. In such cases, each set of fractures are to be treated separately. Furthermore, identification and characterization of zones is a learning exercise. During the interpretation supporting data on potential zones should be kept together with data (e.g. in the same worksheet) on fractures outside the zone. By comparing fracture sets inside and outside a zone, fractures that may predate or overprint the zone may be indicated.

In this work, one approach is to let fracture clusters with a fracture frequency of 10 or more[4] open altered fracture per metre borehole length to be used to

[6] The definition of brittle deformation zones presented by Munier et al. (2003) considers both the fracture density and the occurrence of fault rock (cf. Sibson 1977, Milnes 2006). The fault rocks, except for sections mapped as crushed rocks are in the Forsmark site cohesive, i.e. form different types of rock, cf. tectonite. Crushed rock is by the definition applied by SKB composed of open fractures while "sealed network of fractures" appears as a system of hair-line fractures and breccia is a fragmented rock held together by mineral cement or fine-grained matrix.
[7] However, the selection of fractures can be discussed. Fractures mapped as open can be: a. open fresh without fracture minerals, b. open fresh with fracture minerals, c. open altered without fracture minerals and d. open altered with fracture minerals. Fresh fractures may either been broken up during drilling or handling of drill cores or representing non-connected fractures or fractures that have been open up very late. Open altered fractures have been chosen as such fractures have been affected by the groundwater. This issue is treated further in the Chapter 4 Discussion, section Sensitivity test.

indicate the core zone of weakness zones. Similarly, the core zone of a brittle deformation zone should be defined as fracture clusters contain 10 or more fractures per metre considering open, partly open and sealed fractures together. Sections of crushed rock are initially not considered. However, they are at a later stage in the process considered as parts of core zones.

As a guide to locating the contact between the core zones and the outer rim of a brittle deformation zone (the damage/transition zone), clusters with a fracture density that is half the density of fractures in clusters outlining the core zone/-s can be applied for the damage zone (i.e. in this case fracture separation of 0.20 m or less; cf. 4 fr/m is suggested by Munier et al. 2003 for the transition zone).

However, the separation of fractures along a borehole is related to the angular relation between the borehole and the fractures (the alpha angle). This relation can be considered by separate analysis of sets of fractures and recalculate the separation of fractures along the borehole to true separations (separation along borehole = (true separation)/sinα; α[8] is the intersection between the borehole and the fracture; cf. sampling bias, Terzaghi 1965).

In the classification system presented in this study the separation between fractures is used as a relative measure. The advantage of this is that it gives precise locations for sections classified as brittle deformation zones or weakness zones. When a section of increased fracturing is identified its fracture frequency can be calculated. Furthermore, the original data are retained during the classification and the character of fractures within each outlined interval can be directly described. This holds also for fractures outside and adjacent to zones.

The next parameter in the classification system is the number of fractures needed to “identify” a zone. Definition of brittle deformation zones does generally not give a unique number regarding the number of fracture needed (in a cross section). A fault zone must contain at least one fracture along which displacement has taken place (Caine et al. 1993, cf. Fig. 2.2). Three fractures are needed to outline two sections in the core. Choosing three fractures gives a high resolution but it may, however, comprise large parts of the fractures in the core. However, it gives the possibility to check the sensitivity of the classification system as sections with four and more fractures will be listed simultaneously (part of the sensitivity test, cf. Chapter 4). However, in the base case clusters formed by at least four fractures was performed in this study (Chapter 3).

The last step is to join adjacent cluster to outline zones (Chapter 4) according to the applied definition of zones. This step need also, except from the minimum magnitude of fracture frequencies in core and damage zones, guidance regarding how to locate the boundaries of zones. This step also draws attention to inhomogeneity in zones.

[8] Data on intersection angles (α) between the borehole axis and fractures are presented in SKBs databas SICADA.

Input data

The SKB fracture log (SKB SICADA base; data file p_fract_core-KFMXXY[9]) contains several fracture parameters, for example Borehole ID[10]*, position in borehole (adjusted secup*), if the core is broken/unbroken* and if fractures are open/partly open/sealed*, width and aperture(*) of fractures, confidence in the presented aperture (3 classes), types of fracture fills*, morphology of fractures (planar to irregular), roughness of fracture surfaces, indication of displacement along fractures, fracture alteration*, orientation (strike/dip*), type of host rock and absolute coordinates of observations.

Data handling

The identification of clusters of fractures along the borehole is best made using a worksheet (e.g. Excel). During the analysis all base data for each analysed group of fracture are kept and the space for noting the outcome of analysis is obtained by adding columns in the base data table.

The steps in the data handling are as follows:

1. Select a group of fractures (e.g. all, open, partly open or sealed or set of fractures – in this case all and thereafter open altered fractures are chosen and in some cases also sets of fractures).
2. Calculate the mutual separation between fractures along the core for the selected group of fractures.
3. Give the parameters for the cluster identification (minimum number of fractures and maximum separation between the fractures; in this case minimum 4 fractures and ≥0.10 and ≥0.20 m => the two cluster parameters to identify core zone and damage zone, respectively) and apply these parameters to the data. Give upper position, lower position and number of fractures for identified clusters in separate columns.
4. If distinct fracture sets exist repeat the analysis for each set and consider the orientation bias when applying fracture separation for different classes of clusters (i.e. repeat steps 1 to 3).
5. Compile cluster data obtained and present a summary table (for example Tables[11] 3-6, 3-12 or 3-16) and visualize the location of the clusters in a composite diagram (for example Figs.[3] 3-61, 3-101 and 3-132).

Performance

The step-wise analysis presented below (step A to E) and performed in Chapters 3 and 4 forms the base for the developed approach of localizing zones. The outcome of the performed analysis is presented in Chapter 5,

[9] KFMXX: K=kärnborrhål (cored borehole), FM=Forsmark, and XXY is the number of the borehole, for instance 01A.

[10] Parameters noted with * are used in this study. Fracture apertures(*) are only used in borehole KFM10A (Chapter 4; cf. Table 4-3).

[11] Chosen examples give zone to borehole intersections at various depths and several groups of fractures /clusters are treated.

Results and conclusions, and a somewhat refined performance to locate and describe brittle deformation zones and weakness zones is presented.

Step A

This initial step considers all data and provides an overview of the spatial distribution of fractures along the borehole (cf. data handling above).

The aim is to identify borehole sections that in geological time have been affected by brittle deformation. However, using all fractures may not indicate which section(s) of the borehole that today have potential to contain fractures with low tensile strength or water-conducting fractures. On the other hand, it may give information about fracture sets that together form the cluster and how the fracture pattern inside the clusters are related to the fracture pattern outside the clusters.

Step B

The data examined in the next step are all open fracture, i.e. including fractures breaking the core and where the core pieces do not exactly match. The base for this choice is an assumption that these discrete fractures contain the weak fractures (cf. Chapter 4; interpretation of broken sealed and altered open fractures) and the water-conductive fractures (number of weak fracture are greater or equal to the number of water conductive fractures?).

This step indicates the relative distribution of open fractures in relation to all fractures, i.e. it could give information about the present effective width of zones.

However, amongst the open fractures there are those with fresh surfaces and those with altered fracture surfaces. In most cases open fractures with fresh surfaces are subordinate and they have similar orientations as open altered fractures why this step is not performed in all boreholes (due to time and budget constraints).

Step C

In this step open altered fractures are analysed. These fractures represent weak fractures and the alteration of the fractures indicates that they have been in contact with fluids.

This step may indicate whether or not flowing groundwater has been focused along narrow sections in the rock.

Steps A and C are demonstrated in Chapter 3 for selected borehole sections; sections that are located in seven cored boreholes where they cross a gently inclined zone.

Step D

A sensitivity test checking the outcome (location and size of clusters) by using alternative criteria for the identification of clusters, i.e. use variable minimum number of fractures to be included and minimum mutual separation of fractures to outline clusters. (In the present study only executed is the sensitivity test for fracture data in a selected section of borehole KFM10A, Chapter 4).

Step E

Steps A to D are performed to locate clusters, i.e. potential locations for brittle deformation zones and weakness zones. In the discussion chapter (Chapter 4) a next step (step E) is proposed regarding joining closely spaced clusters together in order to define the borders of potential zones. As pointed out already, this step needs rules for the location of zone borders. The identification of zones is a learning process and it is important to use reference structures (mapped on exposed rock surfaces and/or experience gained during the construction of geological models) to support the interpretation of borehole structures.

Fractures with measurable apertures

In the Forsmark bedrock there are relative few fractures with apertures greater than the resolution of the BIPS instrument. However, many of these fractures appear as solitary fractures and are located outside clusters of fractures (cf. Chapter 4) and some of these fractures are noted as fresh. Some comments on fractures having noted apertures greater than 0.5 mm are given in Chapter 4 (cf. Table 4-6).

3. Description of borehole data and zone intersections

The selected area for the present study is the SKB Forsmark site in northern Uppland, about 120 km north of Stockholm. The area is one of the most studied areas in Sweden regarding location and character of deformation zones as it is the selected area for underground characterization of the bedrock (SKB 2008 and references therein). It is the proposed site for building a final repository for high-level nuclear waste in Sweden.

The investigation of the Forsmark area (Figs. 3.1 to 3-3) has indicated the existence of brittle deformation zones having relative large extensions. One of the zones (gently inclined) is penetrated by several cored boreholes at various depths (Table 3-1 and Figs. 3-1 and 3-5). This is advantageous in a method study, i.e. that the studied object is a single structure. However, the studied structure may not originally be uniform along its extent and it is clear that the structure locally interferes with other structures or has superimposed alteration. Still, it is the same structural unit that may have some common characteristic features conserved.

Examples to illustrate the character of the bedrock inside and in the vicinity of deformation zones are given in this chapter. The methodology using fracture separations to identify fracture clusters, presented in the previous chapter, is applied (steps A to C). The main studied object is a gently inclined and extensive brittle deformation zone in the SKB Forsmark site; SKB brittle deformation zone ZFMA2 (Fig. 3-5; cf. Stephens et al. 2007, Stephens et al. 2008, and SKB 2008). Sub-vertical brittle deformations zones trending ENE and NW are also described when occurring adjacent to zone ZFMA2 in boreholes (Figs. 3-4, 3-6 and 3-7). Fractures described in this report are discrete fractures (SKB database SICADA files p_fract_core-KFMXXY.xls) if not nothing else is presented.

The locations of zone ZFMA2 and other SKB zones intersecting the investigated sections in the seven core-drilled holes are briefly described in the first section of this chapter and the second section (the main part of this report) presents the character of the seven investigated borehole sections.

Borehole KFM01B, section 12.5-120 mbl., is described in more detail than the intersections in the other six boreholes. The reason for this is to select categories of fractures essential for identification and characterization of sections with brittle deformation affecting the present strength of the bedrock and transport paths for groundwater. The borehole also emphasises the difference in fracture characteristics at shallow levels (depths less than 50 m) and at deeper levels of the bedrock.

The section describing fracture characteristics in borehole KFM04A is also extended as the borehole is located within the rim of a regional scale NW-SE trending ductile shear zone at the western border of the Forsmark site, and the ductile zone has partly been re-activated as a set of brittle deformation zones.

Brief characterizations of the bedrock in and adjacent to the brittle zone ZFMA2 are given for the remaining six boreholes (KFM01B, 01C, 2A, 2B, 5A and 10A). For each of the seven boreholes, a compiled structural geologic log which also contains hydrogeological data is provided.

The hydrogeological borehole measurement used is the Posiva Flow Log (PFL; Öhberg and Rouhiainen 2000) and noted are all locations along the boreholes with indicated flow (the magnitude of the flows is not considered in the present study).

The only geophysical data used in this chapter of the report are obtained by the borehole radar measurements. The borehole data are used to support orientation of structures, for example, water-conductive structures.

In the discussion chapter (Chapter 4), a comparison between geological and geophysical data from another borehole (KFM09A) located in the north-western part of the Forsmark site is made. This is done in order to test the distribution of fracture clusters against the outcome of the statistical analysis (cluster analysis) applied on borehole geophysical data in order to detect brittle deformation zones (Sträng et al. 2010 and Tirén et al. 2009).

Investigated area – structures and boreholes

Most of the boreholes used in this study are relatively closely located within the southern part of the SKB target area, where also the gently zone is situated, while the separation between these boreholes and the two borehole located southeast of the modelled area are greater (> 1 km, cf. Fig. 3-3). Two steeply inclined zones (Table 3-1) interfere with the gently inclined zone in the investigated borehole sections and these zones intersect the boreholes at relatively shallow levels (Figs. 3-4, 3-6 and 3-7).

Zone ZFMA2 outcrops in the Forsmark area (although not exposed) and is intersected by seven boreholes from shallow levels to slightly above repository depth at about -400 to -500 m a.s.l. (Figs. 3-1 and 3-3 and Tables 3-1). When possible, the bedrock 50 m (borehole length) above and below the SKB zone ZFMA2 is described together with the character of the zone intersection in boreholes; investigated borehole sections varies from 65 to 150 mbl. (shorter borehole sections where the zone is intersected by bore holes at shallow levels, cf. Table 3-1).

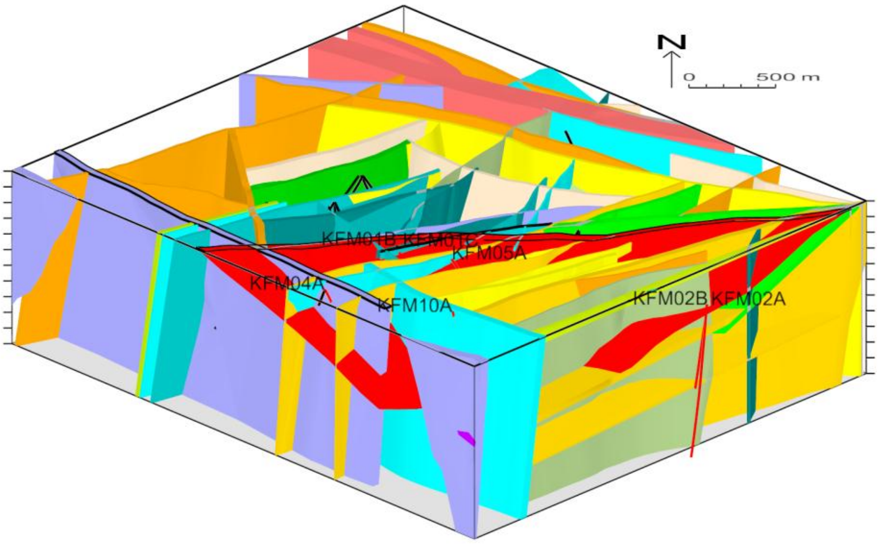


Figure 3-1. Model of brittle deformation zones in the local SKB area at Forsmark (SKB RVS data, Cf. SKB 2008). The dimension of the model is 3780 x 3200 x 1100 meter and it is viewed from south. The seven boreholes involved in this study are given (the actual boreholes are drawn in red, cf. Fig. 3-3). Surface traces of structures intersecting the investigated borehole sections in the seven boreholes are drawn with black contours (cf. Table 3-1).

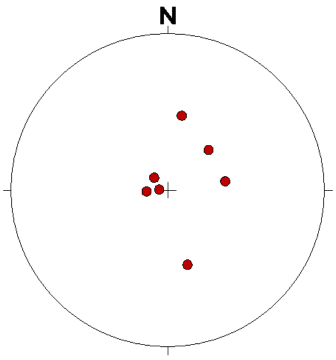


Figure 3-2. Orientation of cored boreholes KFM01B, 1C, 2A, 2B, 4A, 5A and 10A (SKB SICADA data; cf. Figs. 3-3 to 3-7 and Table 3-1). All stereograms are lower-hemisphere equal area (Schmidt) plots, if not something else is stated.

Table 3-1: Borehole data, location of investigated borehole sections and zones, Forsmark area (positions in boreholes (from-to) are given in metre borehole length).

Borehole IDKFMXXY	Borehole Orientation[1]		Investigated borehole sections (mbl.) (depth interval[2])		Intersection of deformation zones (SKB DZ[3]) in boreholes (mbl.)		Deformation zone in the SKB Geological Site Descriptive Model[4]		
	trend	plunge	from	to	from	to	Zone ID[2]	from	to
01B	267.6	79.0	15	120					
			(-12	-114)					
					16	64	ZFMA2	16	53
					107	135	(not modelled)		
01C	165.3	49.6	0	150					
			(-6	-110)					
					23	48	ZFMA2	23	48
					23	48	ZFMENE1192	23	48
					62	99	ZFMA2	62	99
					120	124	(not modelled)		
02A	275.8	85.4	350	490					
			(-342	-480)					
					417	520	ZFMA2	417	442
							ZFMF1	476	520
02B	313.1	80.3	360	480					
			(-349	-466)					
					411	431	ZFMA2	411	431
					447	451	(not modelled)		
					462	473	ZFMF1	462	472
04A	45.2	60.1	160	280					
			(-132	-237)					
					160	176	ZFMNW1200	110	176
					202	213	ZFMA2	202	213
					232	242	ZFMA2	232	242
05A	80.9	59.8	100	165					
			(-83	-137)					
					102	114	ZFMA2	102	114
10A	10.4	50.0	350	500					
			(-248	-338)					
					430	449	ZFMA2	430	449
					478	490	ZFMA2	478	490

[1] Cf. Fig. 3-2. [2] Depth interval according to elevation system RHB70 (meters above sea level; m a.s.l.). [3]According to data files in SKB database SICADA (p-eshi-KFMXXY.xls); Extended geological Single Hole Interpretation of deformation zones (DZ). [4] Stephens et al. 2007 and 2008.

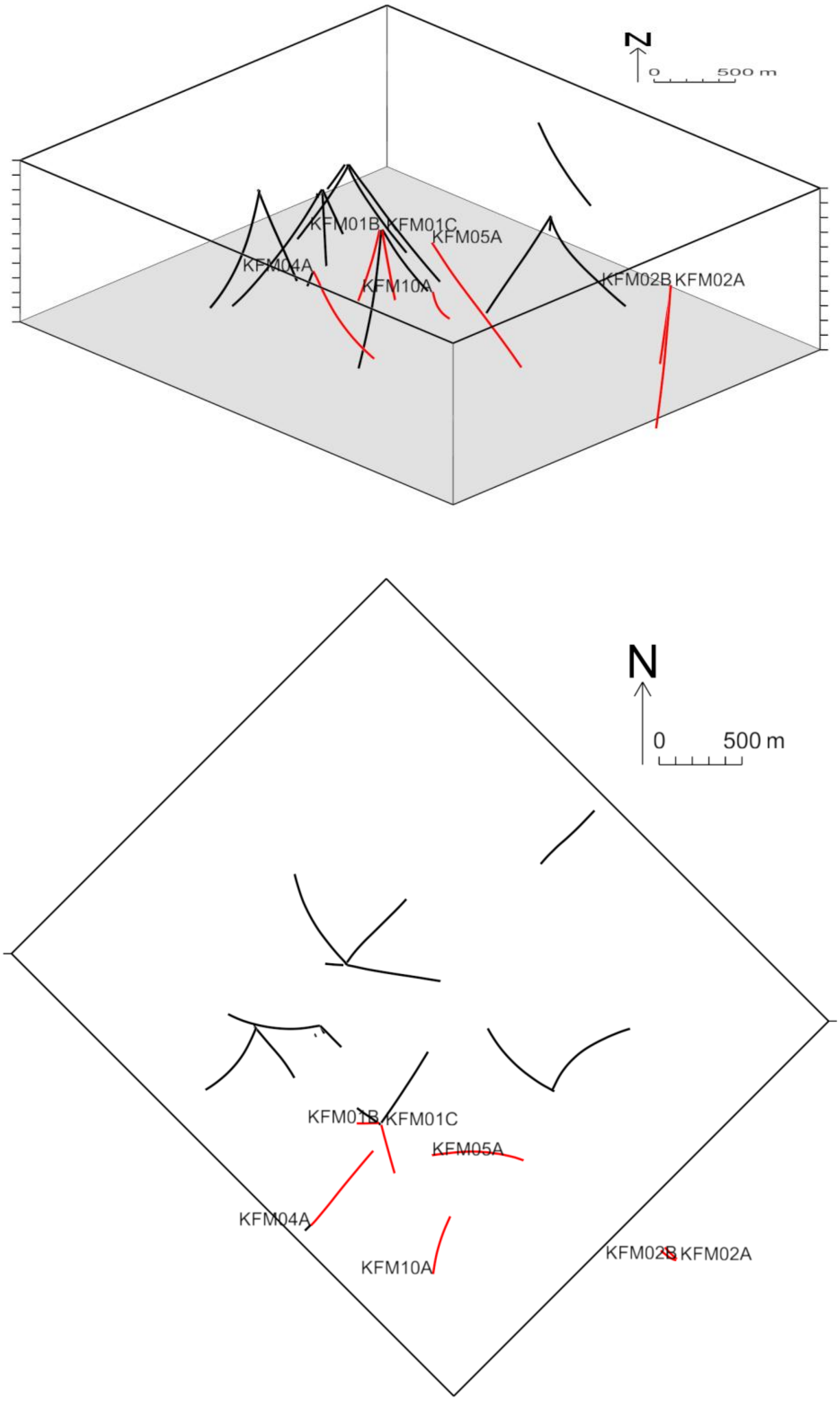


Figure 3-3. Location of cored boreholes in the SKB Forsmark area (SKB RVS data). Boreholes included in the present study are given ID's (KFM01B, 01C, 02A, 02B, 04A, 05A and 10A) and indicated by red lines. Borehole IDs are located where the boreholes start at the surface. Boreholes KFM02A and 02B are located just outside the model.

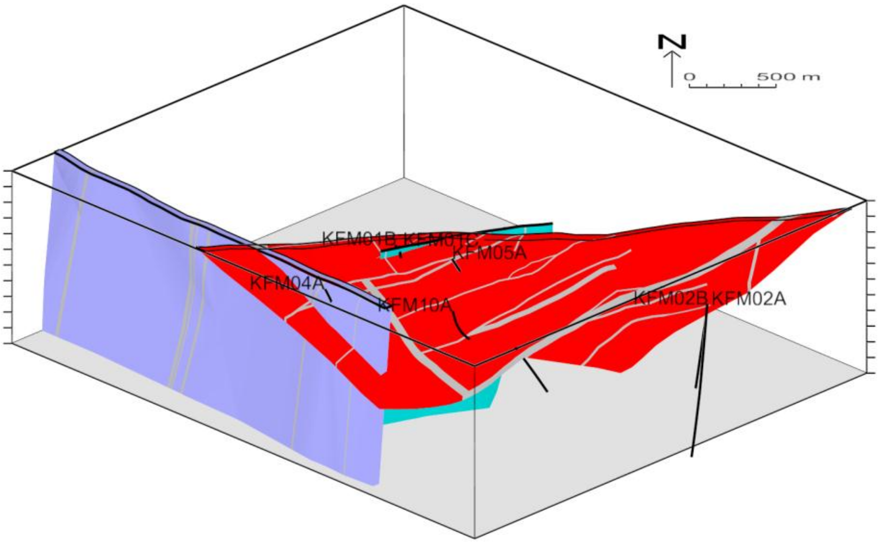


Figure 3-4. Location of investigated boreholes and deformation zones (SKB RVS data): Zone ZFMA2 (oriented 80/24; 9 to 45 m thick, cf. Fig 3-5) in red, zone ZFMNW1200 (oriented 138/85; 10 to 64 m thick, cf. Fig. 3-6) in purple and zone ZFMENE1192 (oriented 64/88; 3 to 45 m thick, cf. Fig 3-7) in green. The grey lines drawn on the surfaces of the zones represent zone to zone intersections.

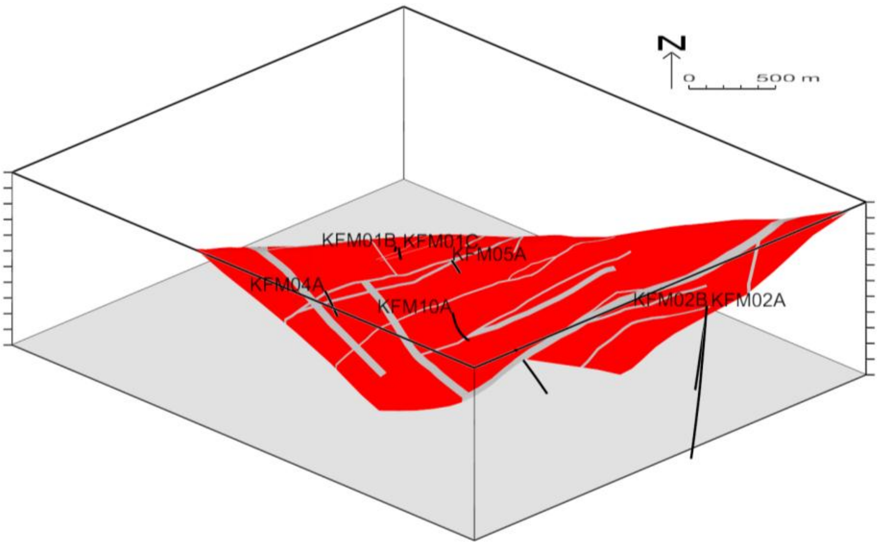


Figure 3-5: Zone ZFMA2 (SKB RVS data) is investigated by seven boreholes and dips southwards (Table 3-1). The intersection between boreholes KFM02A, 2B and the zone is not given as the boreholes are located outside the model volume. The grey lines drawn on the surfaces of the zones represent zone to zone intersections.

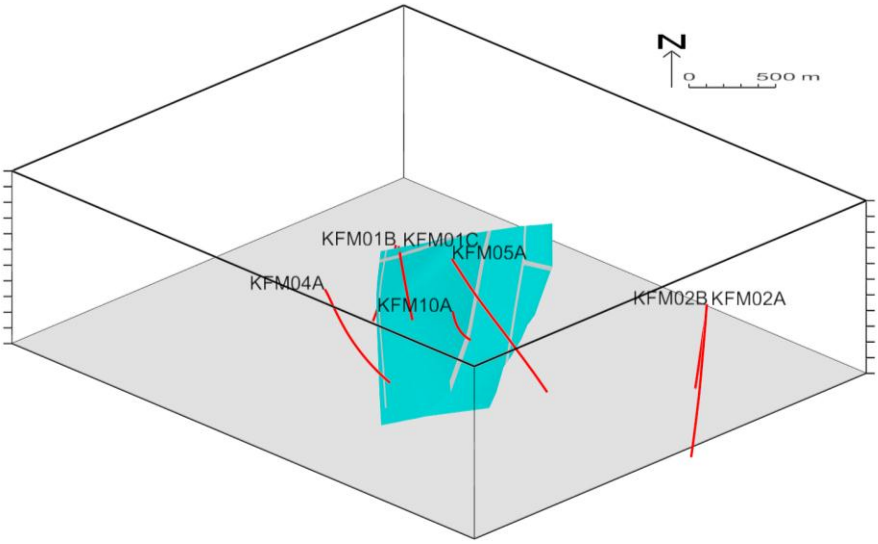


Figure 3-6: Zone ZFMENE1192 (SKB RVS data) is in this study investigated by one borehole (Table 3-1) and the zone is sub-vertical. However, the zone to borehole intersection in borehole KFM01C is interfering with the intersection of zone ZFMA2 (cf. Fig. 3-4 and Table 3-1). The grey lines drawn on the surfaces of the zones represent zone to zone intersections.

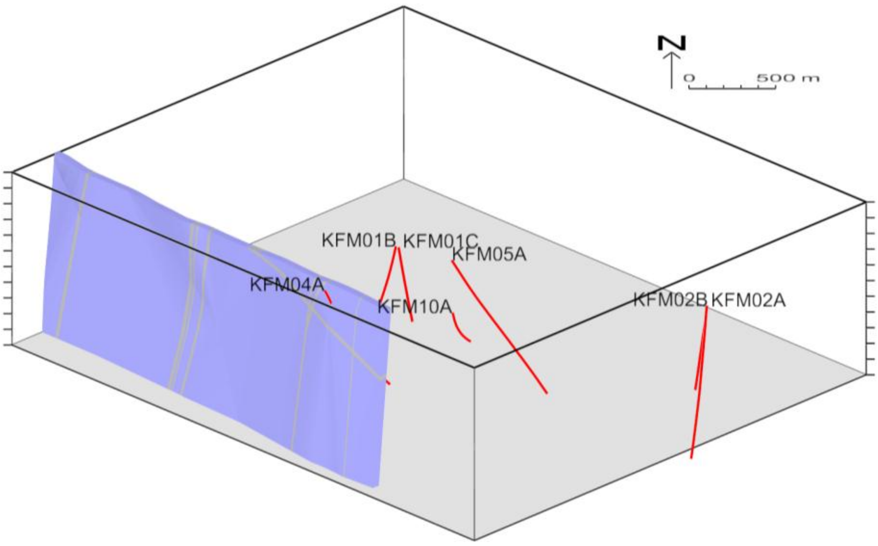


Figure 3-7: Zone ZFMNW1200 (SKB RVS data) is investigated in this study by one borehole (Table 3-1) and the zone is steeply inclined south-westwards. The grey lines drawn on the surfaces of the zones represent zone to zone intersections.

Character of studied borehole sections

Fractures described in following sections consider discrete borehole fractures unless stated otherwise. For each investigated borehole section, a short presentation of the general character of the bedrock is given.

KFM01B - section 15 to 120 m borehole length

Borehole KFM01B is located in the central southern part of the local Forsmark area (Fig. 3-3) and the borehole is steeply plunging westwards (267/79; swings northwards with increasing depth).

Rock type and general structure elements

The dominant rock types in the shallow part of borehole KFM01B (borehole length 15.5-120 m: the corresponding range in absolute altitude is from about -12 to -115 m a.s.l.) are gneisses with granitic-granodioritic-tonalitic composition containing bands of granitoids and meta-basic rocks.

Lithological contacts, especially those of thinner layers/bands commonly conform to the foliation, which is steeply inclined and trends NW-SE to N-S (NE-SW trends also occur, Fig. 3-8).

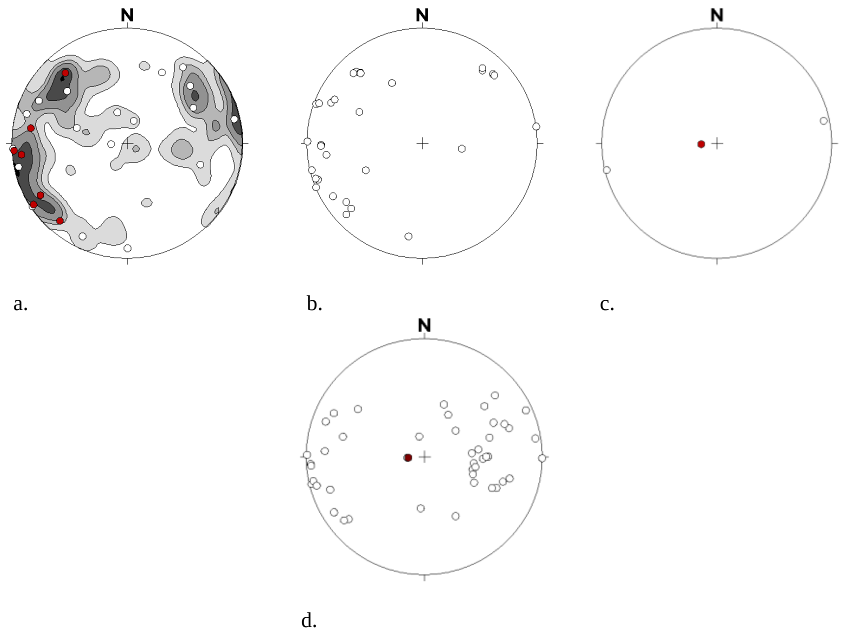


Figure 3-8: Structural elements in the shallow parts of the cored borehole KFM01B (12.5-120 mbl.):

a. White dots are the orientation of the contacts of the main lithologies (wider than 1mbl., N=18), contoured[12] are the contacts of thinner lithologies (shorter than 1mbl. and given with both upper and lower contacts, N=81) and red dots are the orientation of the foliation in the gneissic rock (N=7).

b. Orientation of amphibolite bands/layers, N=30 (upper and lower contacts of 15 bands with range in width from 0.02 to 0.92 mbl.).

c. Orientation of upper and lower of a ductile shear zone, N=2 (1 zone).

d. Orientation of section with altered rock, N=47, and the red dot (Fig. 3-8 c and) is the orientation of borehole KFM01B.

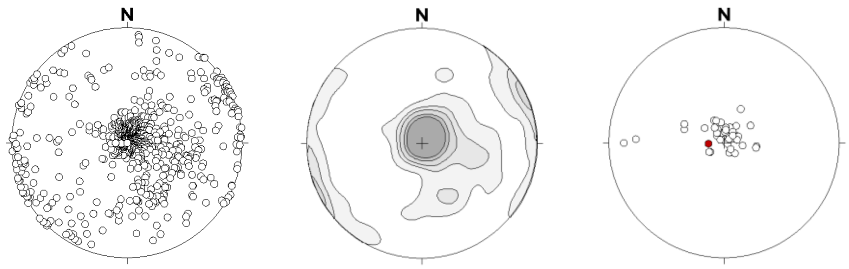
[12] Contours generally represent 1, 2, 3 and 5%. Occasionally contours representing 7 % are given.

Altered sections of the borehole

Close to 50 percent of the investigated borehole section (47 %); total 50 mbl., has been affected by alteration, primarily by oxidation. However, it is beyond the scope of this investigation to relate rock alteration to tectonic structures, although such a correlation is indicated (cf. Fig. 3-8d and 3-8a). The altered sections are frequent and relatively short, ranging in width from 0.03 to 4.11 mbl. and dominated by oxidation /44 sections; mean and median values are 1.1 and 0.6 mbl., respectively. Standard deviation is 1.2 mbl.) / and there are also a few thin sections (<0.1 m wide) with chloritization /2/ and epidotization /1/).

Brittle structures

The overall fracture pattern in the shallow parts of KFM01B consists of two sets of fractures (Fig. 3-9 and text below); sub-horizontal fractures and sub-vertical fractures trending NNW-SSE. Sections of crushed rock are dominated by sub-horizontal to gently inclined fractures and there are also a few sections with vertical fractures trending N-S (Fig. 3-9c).



a. b. c.

Figure 3-9: Fractures in the shallow parts of cored borehole KFM01B:

a-b. All fractures in section 15.5 to 120 mbl.; N=772 (+6 without notated orientation).

c. Orientation of sections with crushed rock in the drill core (N=21; upper and lower contacts of crushed rock are plotted giving 42 pole points, the sections are 0.1 to 0.58 m wide and the mean width is 0.10 mbl. and the median width is 0.05 mbl.). Orientation of borehole KFM01B is given in Fig. 3-9c (red dot).

Core loss

Two sections (0.09 and 0.15 m wide, respectively) with core losses occur at about 47 mbl.

Network of sealed fractures

A minor portion of the core (about 4 %, 61 sections, 0.01-0.40 mbl. wide) consists of sections with sealed networks of fractures (Fig. 3-10). The orientation of sections with sealed networks of fractures conforms to the orientation of sealed fractures containing epidote and also to sealed fractures having oxidized walls.

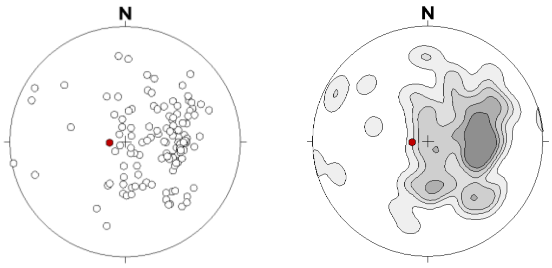


Figure 3-10: Orientation of upper and lower contact of sections with sealed network of fractures in borehole KFM01B, section 12.5-120 mbl., N=122 (61 sections).

Fractures

In the SKB core log, fractures are classified as open, partly open or sealed. Several other fracture characteristics, for example fracture minerals, geometry of the fracture surface (orientation and form) and alteration are also given in the SKB fracture log. All fracture characteristics reflect the history of the fractures, for example the fracture minerals indicate the condition during their growth. The alteration should reflect the relation to the fracture fill (whether it predates the fracture fill, is synchronous with the fracture fill or postdate the fracture fill). However, it is not always obvious how much the description of alteration of fractures also regards the wall rock. Open fractures in the drill core may either be fresh (indicating mechanical breakage caused by drilling or during the handling of the core) or be altered (have a dull lustre) caused by contact with ambient groundwater (open fracture). Across an open fracture the core pieces should have at least a minor misfit.

In the shallow parts of borehole KFM01B the relative occurrences of sealed, partly open and open fractures are 44.6, 8.1 and 47.3 percent, respectively. The proportions of open and sealed fractures, respectively, are fairly similar. However, there are some notable differences regarding the orientation of the three categories/groups of fractures. For instance, the sealed fractures have a distinct set of fractures oriented NW-NNW/sub-vertical and very few fractures with orientations NE-NNE/sub-vertical orientations. Notable is that the sealed and partly open fractures have a subdominant set of fractures trending EW and are dipping moderately northwards. All three categories of fractures have sub-horizontal fractures and the sealed fractures have also a fair amount of gently inclined fractures dipping west-northwestwards.

Fractures oriented NW-NNW/sub-vertical are, as mentioned previously, in most cases sealed (50 out of 52) and the fracture fills are dominated by epidote (found in 34 fractures; all unbroken). Subdominant is quartz (16 fractures, 14 together with epidote; all unbroken) and common are halos of oxidized host rock surrounding the fractures (along 25 fractures; all unbroken and 18 contain epidote). A plot of all fractures along the upper part of borehole KFM01B that contain epidote shows that they conform to fractures that have oxidized walls (Figs. 3-12 and 3-13). It is also indicated that these two categories of fractures also deviate in orientation from the open fractures, especially for the gently inclined fractures (cf. Figs. 3-12, 3-13 and 3-17).

However, a plot of sealed fractures (Fig. 3-11) that neither contains epidote, quartz, laumontite nor have oxidized walls (all these four types of parameters are related to fractures that have a very high percentage of sealed/unbroken fractures; Figs. 3-14 and 3-15) shows that such group of fractures has a dominance of sub-horizontal fractures similar to the open fractures. The difference in orientation between sealed fractures with or without epidote, quartz, laumontite and oxidized walls may reflect the existence of different sets of fractures within the geological history of the area (implying that no or limited reactivation of discrete older fractures have occurred). Alternatively, it may reflect a bias in the fracture mapping (the difficultly to map fracture fills in thin sealed fractures). The latter seems less probable as both fractures parting (classified as sealed though) and not parting the core (broken and unbroken fractures according to the SKB SICADA nomenclature[13], Figs. 3-14 and 3-15), without epidote, quartz, laumontite or having oxidized walls, have fairly the same orientations.

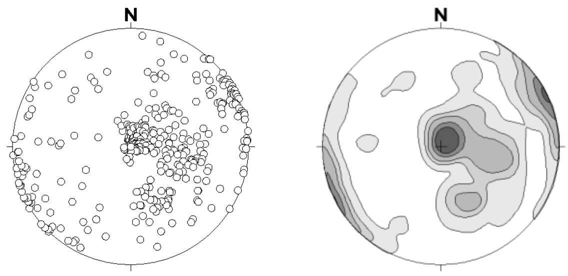


Figure 3-11: All sealed fractures in borehole KFM01B, section 12.5-120 mbl., N=344 (+ 3 without noted orientation).

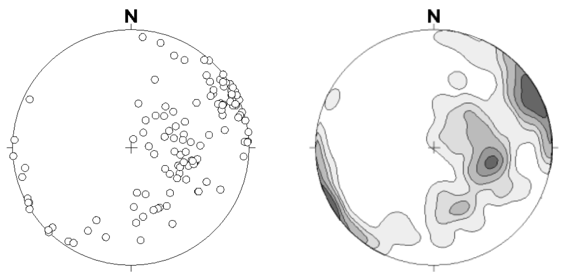


Figure 3-12: Sealed fractures with epidote in borehole KFM01B, section 12.5-120 mbl., N=118 (all but 3 with epidote fractures are sealed).

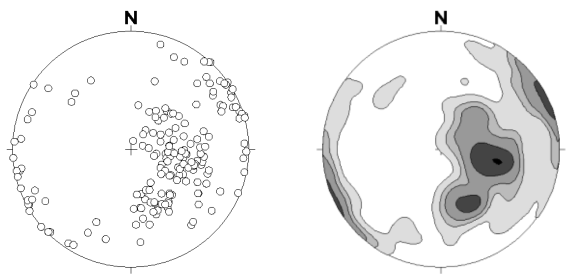


Figure 3-13: Sealed fractures with oxidized walls in borehole KFM01B, section 12.5-120 mbl., N= 178 (1 fracture with oxidized walls is open).

13. The nomenclature broken and unbroken fractures used in the SKB data base SICADA denotes whether the core is parted or not along a fracture. Unbroken fractures indicate that the rock is solid and has withstand drilling and the general handling of the core. The drill core is parted along a broken fracture. The fracture may initially be open or have a low degree of cohesion or may have been broken during drilling or by the handling of the core. Partly open fractures are generally unbroken (not the standard usage in early boreholes). All open fractures are broken. Fresh fractures that are broken may represent fractures that originally are sealed. However, such fractures may represent very late natural fractures or unconnected fractures. Altered broken fractures have a high probability to represent fractures with low to no cohesion.

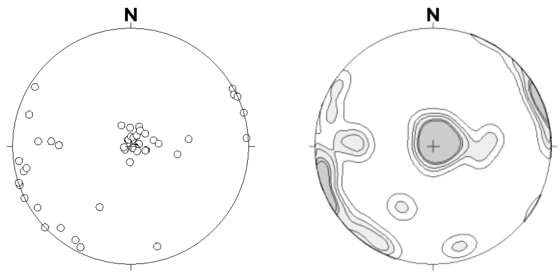


Figure 3-14: Unbroken fractures with no epidote, quartz, laumontite or oxidized walls, in borehole KFM01B, section 12.5-120 mbl., N=50.

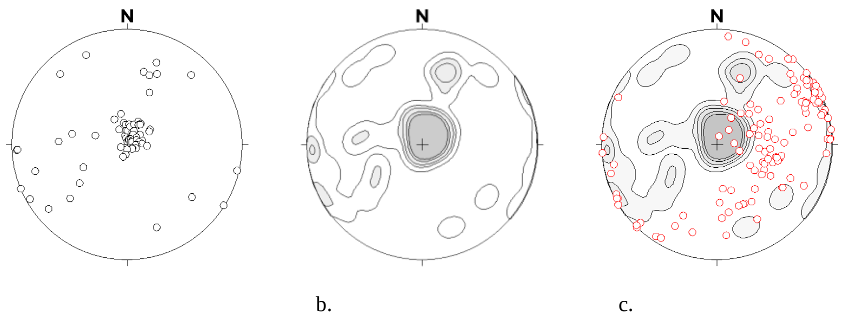


Figure 3-15: a-b Broken sealed fractures in borehole KFM01B, section 12.5-120 mbl.:
a-b: With no epidote, quartz, laumontite or oxidized walls, N=72 (+ 2 without orientation).
c. Fig. 3-15b with orientation of epidote bearing fractures added (red circles).

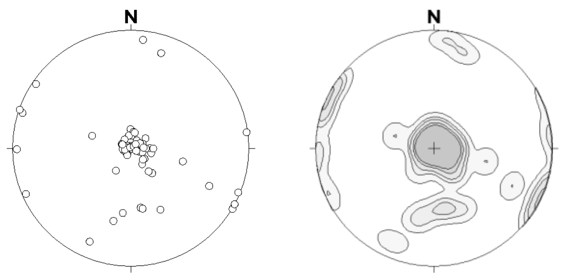


Figure 3-16: All partly open fractures in borehole KFM01B, section 12.5-120 mbl., N=63.

The partly open fractures are fairly similar to the open fractures in orientation, although they also have also similarities to the orientations of all sealed fractures.

The open fractures are dominated by horizontal to gently inclined fractures with subdominant vertical fractures trending NE-SW (Fig. 3-17). If all fresh fractures are subtracted from the group of open fractures, the relative distribution of fracture according to the orientations remains the same and the result reflects the system of weaker structures in the rock. A comparison the populations of broken-sealed-fresh fractures (i.e. fractures interpreted to be mechanically broken, Fig. 3-20) and broken open-fresh fractures (i.e. fractures that may to some extent represent broken partly open fractures, Fig. 3-19, cf. Fig. 3-16) shows that there is a tendency for the former to have sealed fractures and the latter to have sealed/partly sealed fractures. Both types may represent fractures of relatively good cohesion. Broken-sealed-fresh fractures form a subdominant part of all sealed fractures and, except for the sub-horizontal fractures, they have scattered orientations (Fig. 3-20), although there is a minor, unique group of fractures dipping steeply south-southwest. A general analysis of all mapped fractures (Fig. 3-9) and a sub-set consisting of open altered fractures (i.e. broken-open-altered fractures, Fig. 3-18) is also performed for the other boreholes.

The rock stress is mainly horizontal and oriented in NW-SE and the dominant trend of vertical fractures is NNW-SSE to NW-SE (cf. Fig. 3-9). However, the dominant orientation of open vertical fractures is NE-SW (Fig. 3-17), i.e. at a high angle to the regional stress field.

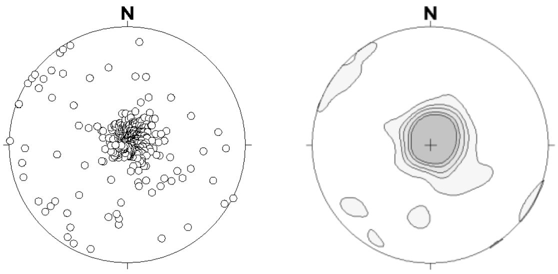


Figure 3-17: All open fractures in borehole KFM01B, section 12.5-120 mbl., N=365 (+ 3 fractures without noted orientation).

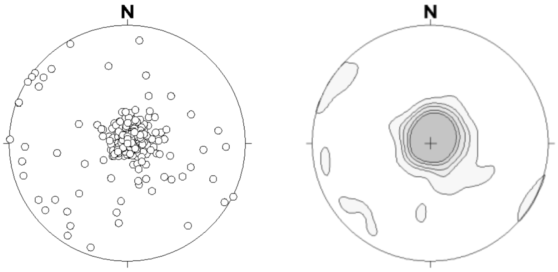


Figure 3-18: Broken-open- altered fractures in borehole KFM01B, section 12.5-120 mbl., N=286 (+3 without orientation).

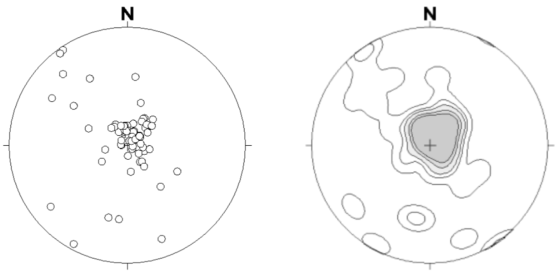


Figure 3-19: Broken-open-fresh fractures in borehole KFM01B, section 12.5-120 mbl., N=79.

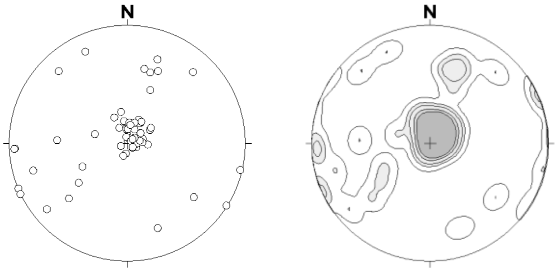
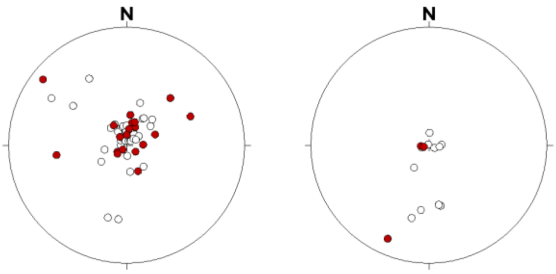


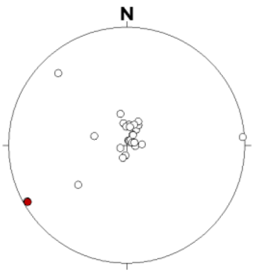
Figure 3-20: Broken-sealed-fresh fractures in borehole KFM01B, section 12.5-120 mbl., N=63 (+2 fractures with no noted orientation).

Overview of fracture fills

Fracture fills and alterations of the wall rock are two fracture characteristics that reflect the structural history of the area. Parts of the evolution has already been touched upon in the previous section regarding sealed fractures with mineral and wall rock alteration characteristic for tight fractures.



a. b.



c.

Figure 3-21: Fractures with no fracture fill notated in borehole KFM01B, section 12.5-120 mbl.:

a. Open fractures, $N_{\text{no fill, open}}$=58 (open circles; + 2 with no orientation) and $N_{\text{altered, no fill, open}}$ =19 (red dots).

b. Partly open fractures, $N_{\text{no fill, partly open}}$=14 and $N_{\text{altered, no fill, partly open}}$=3 (red dots).

c. Sealed fractures, $N_{\text{no fill, sealed}}$=26 and $N_{\text{altered, no fill, sealed}}$=1 (red dot)

It is obvious from the results of the core mapping of borehole KFM01B that certain fracture minerals are more common than others. The core is parted along fractures, containing certain types of fills while along other fractures, containing specific fracture fills, the core is generally unbroken (cf. Table 3-2). Fractures that have a potential to be soft or to connect water are those containing chlorite, calcite, clay minerals, iron hydroxides, asphaltite, pyrite, hematite and fractures without any infill (cf. Fig. 3-21). The relative occurrence of fractures (in percent of the population of all fractures containing a certain fill) classified as open varies from c. 50 percent (chlorite, calcite, no infill) to more than 90 percent (iron hydroxide, pyrite). Fractures with hematite are few and 50 percent are classified as open.

Fractures that have a potential to be stiff and tight contain epidote, quartz, laumontite or have oxidized walls (red stained). Typical for these fractures is that they do not constitute surfaces along which the core is parted. Open fractures with such fracture fills constitute 0.1 percent of all fractures.

There are some accessory minerals, having very low presence in the core log. Such minerals may be overlooked, i.e. they are not fully represented or they are mistaken for another mineral.

Fracture minerals - Alteration of fractures

In the SKB SICADA data base, the descriptions of fracture presented in the fracture file (e.g. p_fract_core-KFM01B) generally considers the fracture surface and the fracture fills as well as oxidation of the wall rock. However, other types of alteration of the wall rock and the general alteration of the host rock are given in a separate data file (e.g. p_rock_alter-KFM01B.xls).

The classification of the degree of alteration used in the fracture files applies a scale with four degrees: from fresh (no visible alteration), via slightly altered and moderately altered to highly altered. The degree of alteration is a function of several parameters such as time, temperature, pressure and transport and chemistry of altering fluids.

Alteration of open fractures is most frequent along sub-horizontal fractures. Early alteration is indicated by oxidation of the fracture walls and fractures with such alteration have similar orientations as fractures with epidote. Since these fractures generally are tight, late alteration is not to be expected. However, moderate alteration of steep fractures trending N-S and NW-SE may occur close to junctions with moderately and highly altered horizontal to gently inclined fractures (Fig. 3-22). Moderately to highly altered fractures occur in clusters along the borehole at about 18.5 (3 fractures), 28.0 (3 fractures), 37.5 to 44.5 (15 fractures) and 50.5 mbl. (3 fractures), respectively. However, identification of alteration of sealed fractures (unbroken fractures) without fracture fill is difficult (cf. Fig. 3-21).

Table 3-2: Relation between all, open and partly open fractures and their fracture fills and wall rock alteration in the shallow parts of cored borehole KFM01B, section 15.5 to120 m borehole length (number of sealed fractures = all fractures – (open + partly open fractures)).

	Fractures – number of observations			In percent of total number of fractures (778)		
Fracture fill	**All fractures**	**Open fractures**	**Partly open fractures**	**All fractures**	**Open fractures**	**Partly open fractures**
Fractures that have a potential to be soft or connect water						
Chlorite	232	146	18	29.8	18.8	2.3
Calcite	213	130	13	27.4	16.7	1.7
Clay minerals	151	126	11	19.4	16.2	1.4
Iron hydroxide	138	101	22	17.7	13.0	2.8
Asphaltite	57	47	6	7.3	6.0	0.8
Pyrite	23	22	0	3.0	2.8	0
Hematite	8	4	0	1.0	0.5	0
No infill	100	60	0	12.9	7.7	0
Fractures that have a potential to be stiff and tight						
Oxidized walls	180	1	0	23.1	0.1	0
Epidote	120	0	0	15.4	0	0
Quartz	36	0	0	4.6	0	0
Laumontite	7	0	0	0.9	0	0
Accessorial mineral						
Prehnite	3	1	0	0.4	0.1	
Red feldspar	3	0	0	0.4	0	0
Zeolite	1	1	0.1	0.1		
Kaolinite	1	1	0.1	0.1	0.1	0.1

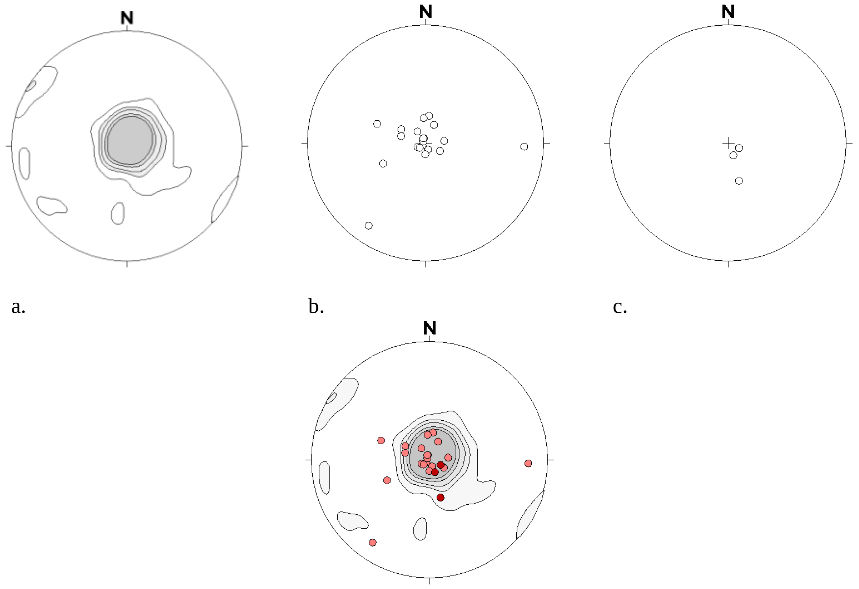
A comparison of the alteration of fractures with types of fracture fills shows some observable patterns (cf. Figs. 3-22 to 3-27, Table 3-2). For example, fractures with asphaltite occur in fractures with variable degree of alteration, relatively common in slightly altered fractures dipping moderately northwestward, and there is only small spread in orientation of altered fractures with pyrite, which occur primarily in two sets oriented sub-horizontal and NE/vertical.

All open fractures are classified as broken in the SKB database SICADA and all partly open fractures as unbroken. The broken fractures constitute more than half of all mapped fractures (56.7 %; 441 out of 778) and consist of 16.5 percent (73) sealed fracture and 83.5 percent of open fractures (368). Nearly half of the population of mapped fractures in borehole KFM01B are noted as altered (43.6 %; 339 out of 778) and 12.4 percent of the altered fractures are noted as unbroken fractures (42 out of 339). The majority of the unbroken fractures (32) are partly open.

Amongst the open fractures 21 percent are classified as fresh (79), i.e. neither the fracture surface nor the fills display any alteration. The most common fills in fresh open fractures are chlorite and calcite. However, close to half of all the open fresh fractures (38) have no fill or fills consisting of asphaltite (6), clay mineral (4), or pyrite (2). Most of these fills (except for clay minerals) are found in shallow parts of borehole KFM01B, i.e. above 50 mbl.

The degree of alteration of fractures in borehole sections mapped as crushed rock (21 section; SICADA files p_fract_crush-KFM01B.xls) varies; two sections with unaltered fractures (crushed during drilling?), seven with slightly altered fractures, ten with moderately altered fractures and two with highly altered fractures. One of the crushed sections with highly altered fractures is bounded by north-south trending fractures dipping steeply eastwards and the remaining sections are dominated by gently inclined to sub-horizontal fractures (Fig. 3-9c). All altered sections with crushed rock contain fracture fills consisting of clay minerals and/or chlorite, while iron hydroxide/hematite is found in six sections and asphaltite is found in one section.

Of special interest for the characterization of brittle deformation zones, as they appear today, are the open altered fractures, i.e. fractures mapped as discrete fractures and fractures in sections mapped as crushed rock. However, late reactivation and formation of fractures may give fracture with “fresh” surfaces.



d.

Figure 3-22: Orientation of open (broken) altered fractures (fresh fractures excluded) in cored borehole KFM01B, section 15.5 to 120 mbl.:

a. All slightly altered fractures, N=266.

b. All moderately altered fractures, N=20 (light red in Fig. 3-22d).

c. All highly altered fractures, N=3 (dark red in Fig. 3-22d).

d. Combined plot; slightly altered fractures are contoured, light red are moderately altered fractures and red are highly altered fractures.

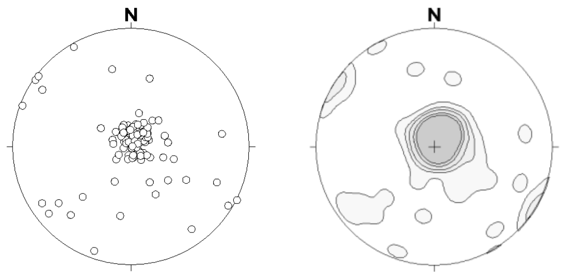


Figure 3-23: Open slightly altered fractures containing chlorite in cored borehole KFM01B, section 0 to 120 mbl., N=128.

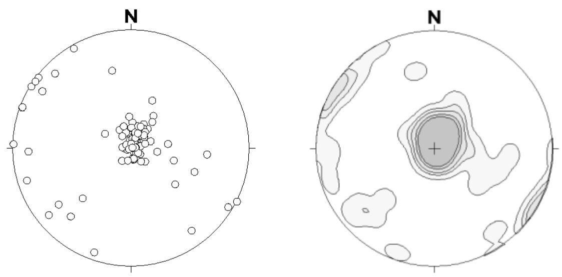


Figure 3-24: Open slightly altered fractures containing calcite in cored borehole KFM01B, section 0 to 120 mbl., N=96

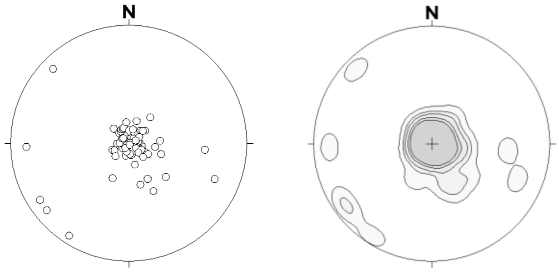


Figure 3-25: Open slightly altered fractures containing iron hydroxide in cored borehole KFM01B, section 0 to 120 mbl., N=86.

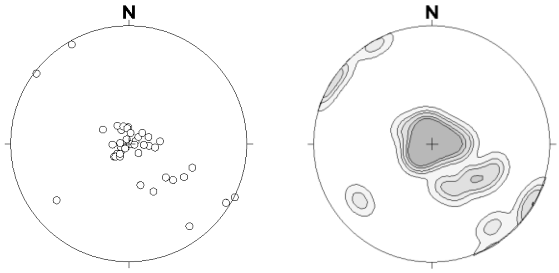


Figure 3-26: Open slightly altered fractures with asphaltite in cored borehole KFM01B, section 0 to 120 mbl., N=43.

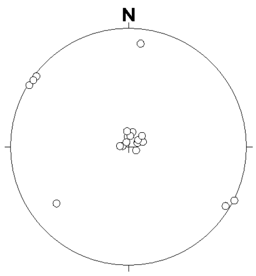


Figure 3-27: Open slightly altered fractures containing pyrite in borehole KFM01B, 0 to 120 mbl., section N=19.

Fracture distribution with respect to inclination and alteration

In the previous sections different fracture characteristics have been discussed. The SKB SICADA data base contains several additional parameters, related to bedrock structures, not treated in this report. One such parameter is the morphology of fractures (e.g. fracture roughness/shape and type of host rock). Other parameters, such as the occurrence of shear zones and sealed network of fractures (many time related to the general alteration of the rock) and the general alteration of the bedrock rock have been considered in this study but are not explicitly described (cf. Figs. 3-48, 3-61, 3-72, 3-87, 3-103 to117 and 3-132).

One important parameter in the structural interpretation of geological data is the location of observations, for example in identification of deformation zones and their extensions. Another is the spatial distributions of structural features in relation to their orientations. In this section the variation in fracture density for different groups of fractures along the upper 120 m of borehole KFM01B is described. This is done on two scales:

1. By fracture density distribution diagrams (0.5 mbl. intervals).
2. For three sub-sections in the upper part of the borehole.

Fracture distributions according to their separation along the borehole (clusters containing four or more fractures with mutual separations corresponding to fracture densities greater than 10 and 5 fractures per metre, c.f. the fracture densities in the core and damage zones of a brittle deformation zone as defined by Munier et al. 2003) are treated in separate sections (Characterization of brittle deformation zones) for each borehole.

The fracture density varies strongly along the upper part of borehole KFM01B (Fig. 3-28) and the highest densities are found in the shallow parts of the borehole with twelve peaks (10 or more fractures per 0.5 mbl.) in the borehole section 28 to 49 m. Sections with similarly high fracture density are found also in the lower parts of the studied borehole section, including three sections in the interval 108.5 to 115.5 mbl. Most of these peaks represent clusters thinner than 0.5 m and they are predominately much thinner.

The number of fractures mapped as open (Figs. 3-29) constitutes nearly half of the total number of all mapped fractures (47.3 %). The relative distribution of open fractures is generally higher in sections where the overall fracturing is increased.

Amongst the fresh open fractures, forming 10.2 percent of all fractures, 72.2 percent are low angle fractures (inclination <20°; 57 out of 79; Figs. 3-30 and 3-34).

Open fractures with altered fracture surfaces (Fig. 3-31) constitute 78.5 percent of the open fractures and 37.2 percent of all mapped fractures. Amongst these fractures 75.8 percent are low angle fractures (219 out of 289; cf. Fig. 3-35).

The number of moderately to highly altered open fractures are few (23; i.e. forming 3 percent of all mapped fractures) and they all occur in the more shallow parts of the borehole (to a borehole length of 52 m; Fig. 3-32). Furthermore, the occurrence of such fractures is not in a simple way related to the density of all fractures. Fracture densities of 2 to 3 moderately to highly altered fractures per 0.5 mbl. occur in borehole sections with a total fracture density of six or more fractures per 0.5 mbl. However, there are 33 0.5 mbl. sections in the investigated upper part of borehole KFM01B having a density of all fractures that is greater than 5 fractures per 0.5 mbl. and they do not contain any moderately to highly altered fractures. Sections with a single moderately or highly altered fracture occur in sections having a range in total fractures density from 2 to 9 per 0.5 mbl. Most of the moderately to highly altered fractures are sub-horizontally to gently inclined and just a few of them are steeply dipping and such fractures trend either WNW-ESE or N-S.

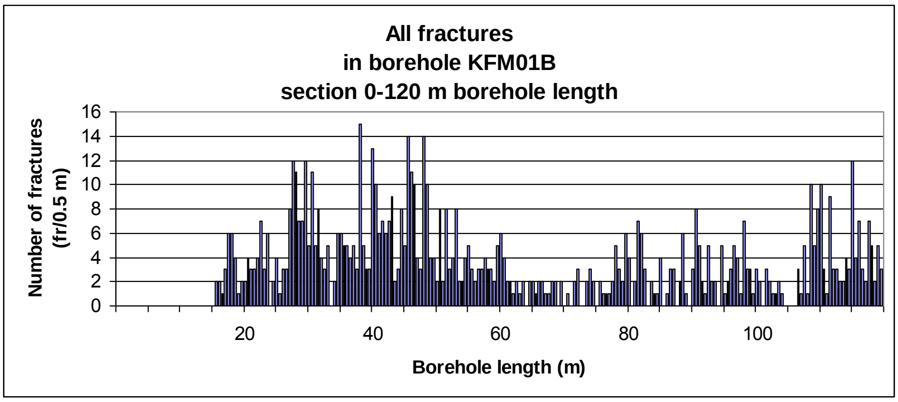


Figure 3-28: Distribution of all mapped fractures along the upper part of the borehole KFM01B, N_{total}=778. The number of fractures is given for 0.5 m wide borehole sections.

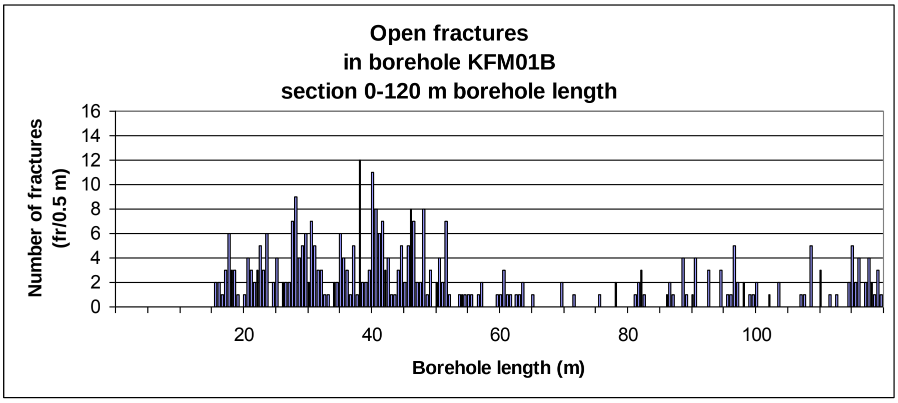


Figure 3-29: Distribution of open fractures along the upper part of the borehole KFM01B, $N_{total\ open}$=368. The number of fractures is given for 0.5 m wide borehole sections.

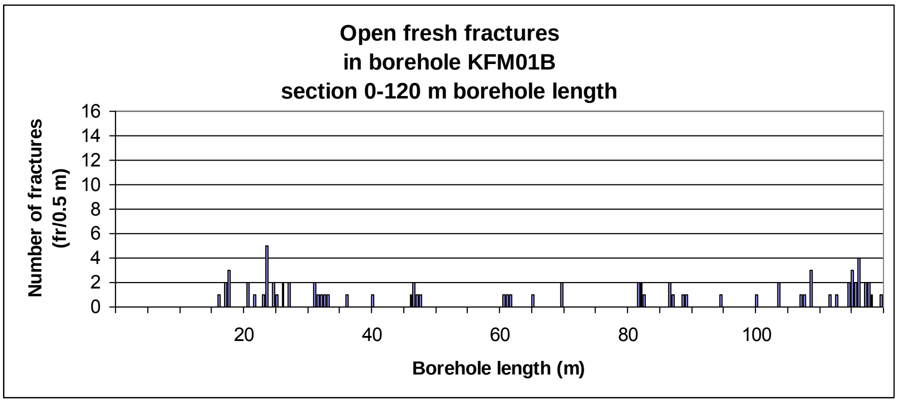


Figure 3-30: Distribution of open fresh fractures along the upper part of the borehole KFM01B, $N_{open\ fresh}$=79. The number of fractures is given for 0.5 m wide borehole sections.

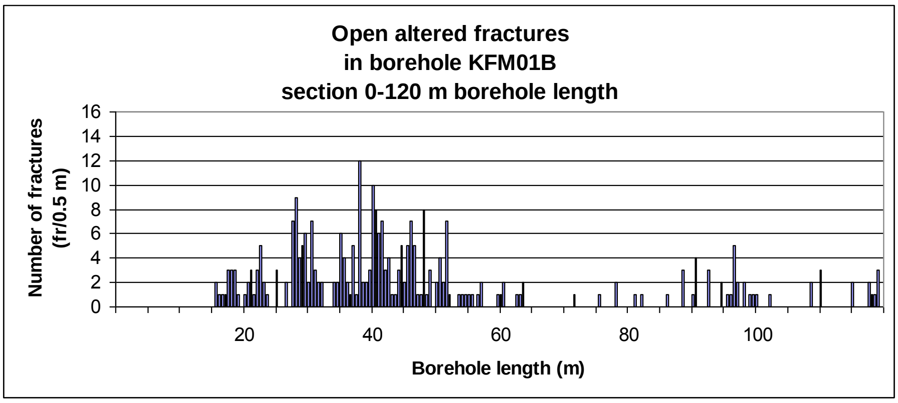


Figure 3-31: Distribution of open altered fractures along the upper part of the borehole KFM01B, $N_{open\ altered}$=289. The number of fractures is given for 0.5 m wide borehole sections.

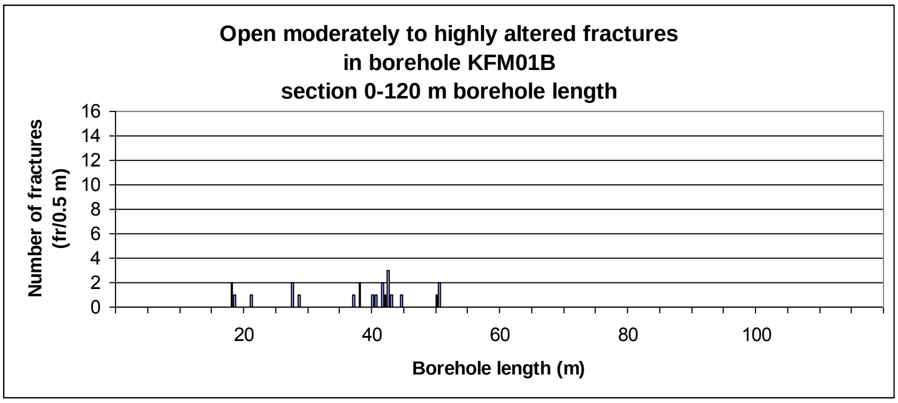


Figure 3-32: Distribution of moderately to highly altered fractures along the upper part of the borehole KFM01B, $N_{open\ mod.+highly\ altered}$=23 (2 moderately altered fractures are partly open and remaining fractures are open). The number of fractures is given for 0.5 m wide borehole sections.

Low-angle fractures (inclination<20°; Fig. 3-33) are dominant (50.9 % of all fractures). They occur primarily in the more shallow part of the borehole and 14.4 percent of the low-angle fractures are classified as fresh. These fractures are mainly randomly distributed along the borehole except for a minor cluster in the lower part of the investigated section (at 114 to 118 mbl.; Fig. 3-34). Open altered low-angle fractures (37.5 % of all fractures and 78.5 % of the open fractures) are primarily found in the upper part of the borehole (above 65 mbl.) and also in a minor accentuated cluster in the lower part of the borehole (90 to 102 mbl.; Fig. 3-35).

A comparison the distribution of low angle fractures and gently inclined fractures (10°<inclination<20°, 28.8 % of all fractures; Fig. 3-36) shows that it is obvious that low-angle fractures (inclination<10°) are very common. A minor part of the gently inclined fractures are open and altered (13.6 %; Fig. 3-39) and such fractures are most common in the upper part of the investigated section (at about 27.5 to 32.5 mbl.; maximum 2 fractures per 0.5 mbl.) and occur as scattered single fractures in other parts of the investigated borehole section.

Steeply inclined fractures (inclination> 60°) are relatively homogeneously distributed along the borehole (Fig. 4-40) and form a subdominant part of the

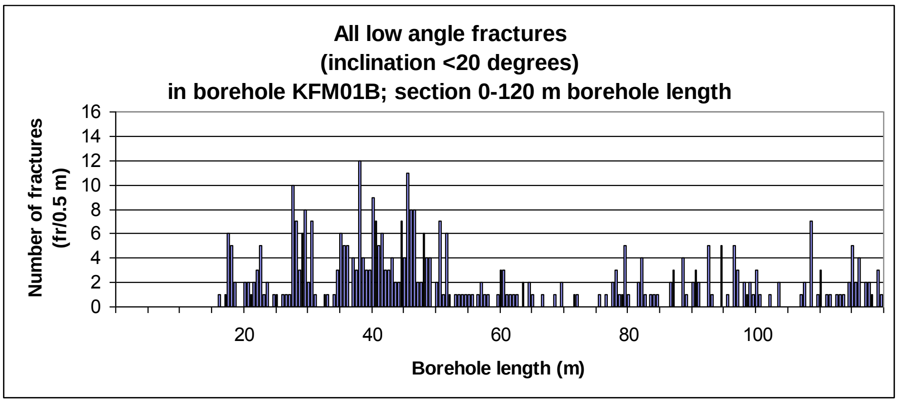


Figure 3-33: Distribution of all low angle fractures along the upper part of the borehole KFM01B, $N_{hor.\ to\ gentle\ inclined}$=397. The number of fractures is given for 0.5 m wide borehole sections.

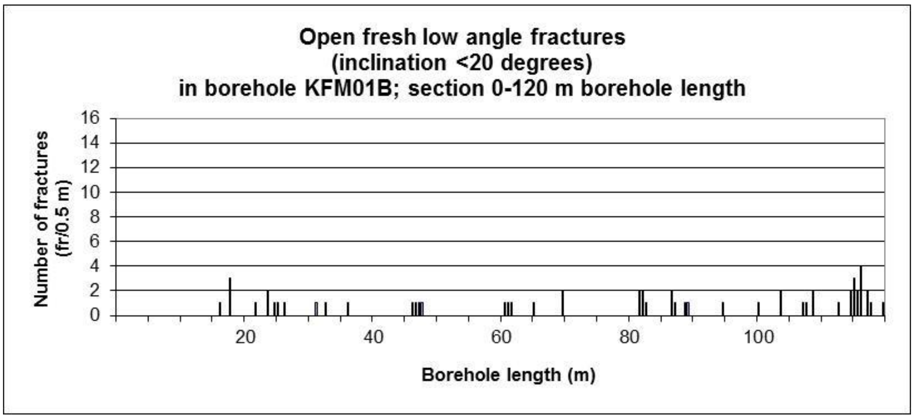


Figure 3-34: Distribution of open fresh low angle fractures along the upper part of the borehole KFM01B, $N_{open\ fresh\ hor.\ to\ gently\ inclined}$=57. The number of fractures is given for 0.5 m wide borehole sections.

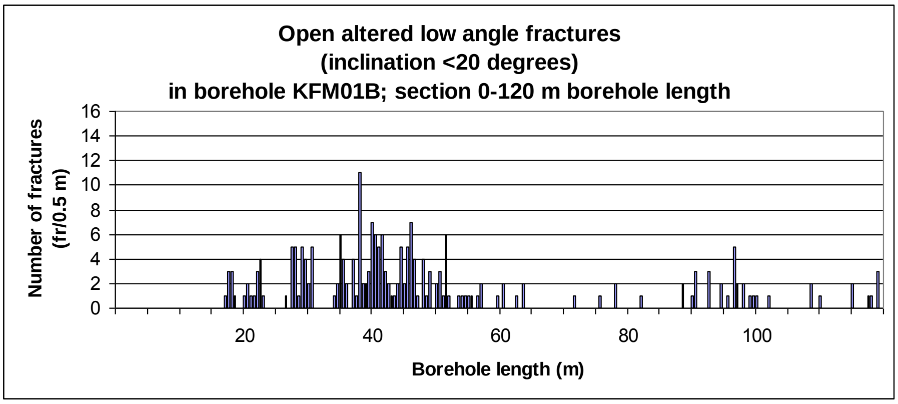


Figure 3-35: Distribution of open altered low angle fractures along the upper part of the borehole KFM01B, $N_{open\ alt.\ hor.\ to\ gently\ inclined}$=219. The number of fractures is given for 0.5 m wide borehole sections.

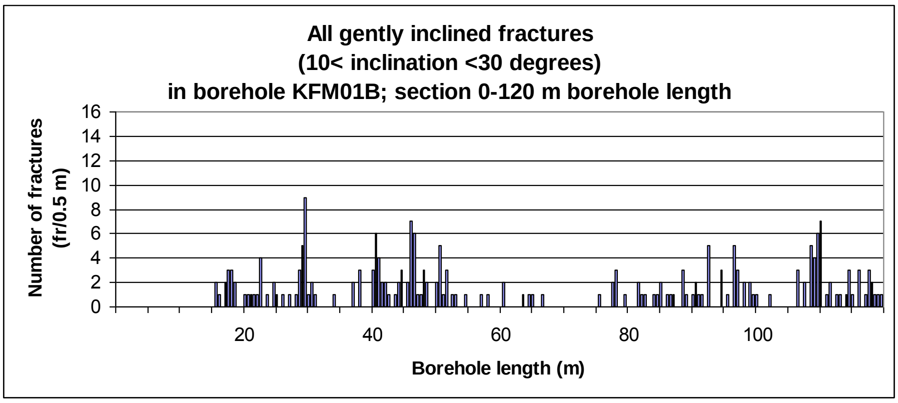


Figure 3-36: Distribution of gently inclined fractures along the upper part of the borehole KFM01B, $N_{subhor\ to\ mod.\ inclined}$=224. The number of fractures is given for 0.5 m wide borehole sections. This figure and Figure 3-35 have a 10° overlap in fracture orientation.

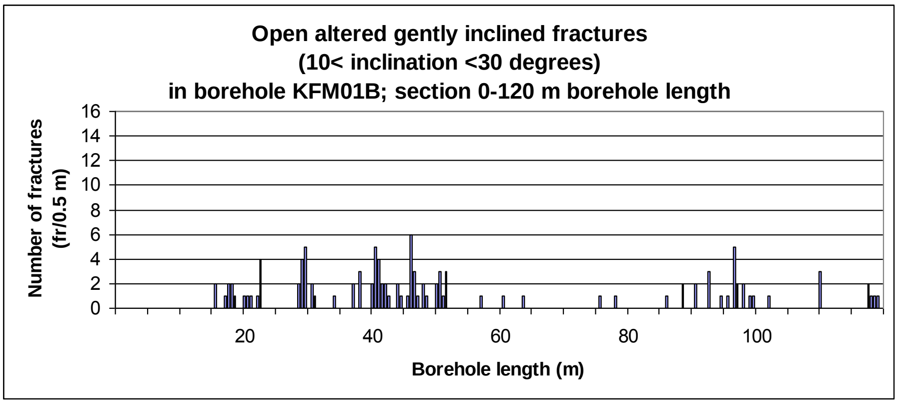


Figure 3-37: Distribution of gently inclined open altered fractures along the upper part of the borehole KFM01B, $N_{alt.\ subhor\ to\ mod.\ inclined}$=113. The number of fractures is given for 0.5 m wide borehole sections. This figure and Figure have an overlap in fracture orientation.

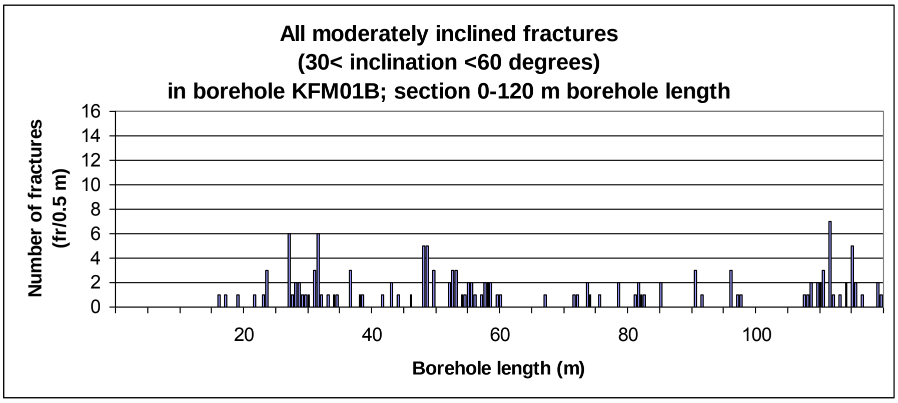


Figure 3-38: Distribution of all moderately inclined fractures along the upper part of the borehole KFM01B, $N_{moderately\ inclined}$=140. Number of fractures is given for 0.5 m wide borehole sections.

total fracture population (23.1 % of all fractures). Open altered steeply inclined fractures form a minor part (15.0 % of all steep fractures) and such fractures are only found in the upper part of the investigated section of borehole KFM01B (above 52 mbl., Fig. 3.41).

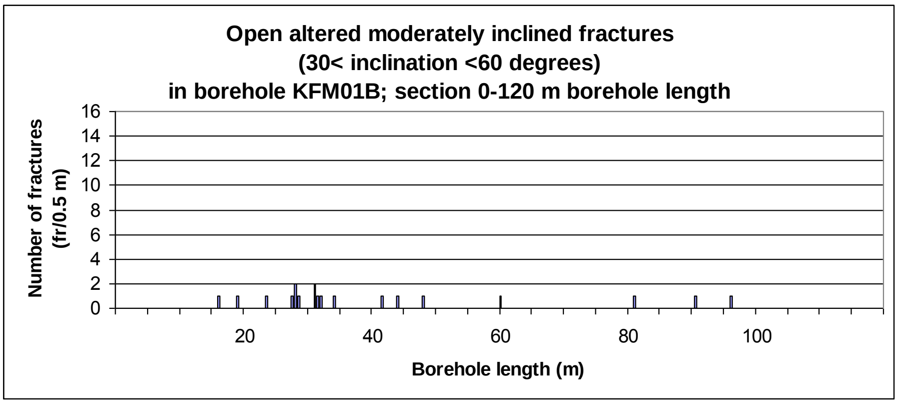


Figure 3-39: Distribution of moderately inclined open altered fractures along the upper part of the borehole KFM01B, $N_{op.\ alt.\ moderately\ inclined}$=19. Number of fractures is given for 0.5 m wide borehole sections.

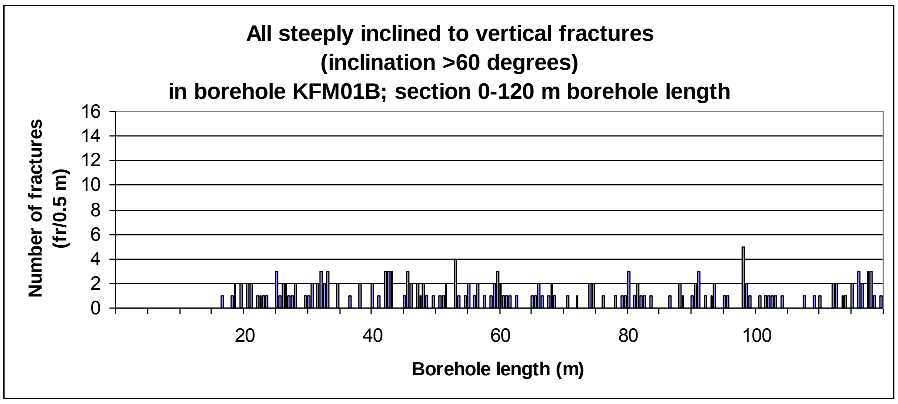


Figure 3-40: Distribution of all steeply inclined to vertical fractures along the upper part of the borehole KFM01B, $N_{steeply\ inclined}$=180. Number of fractures is given for 0.5 m wide borehole sections.

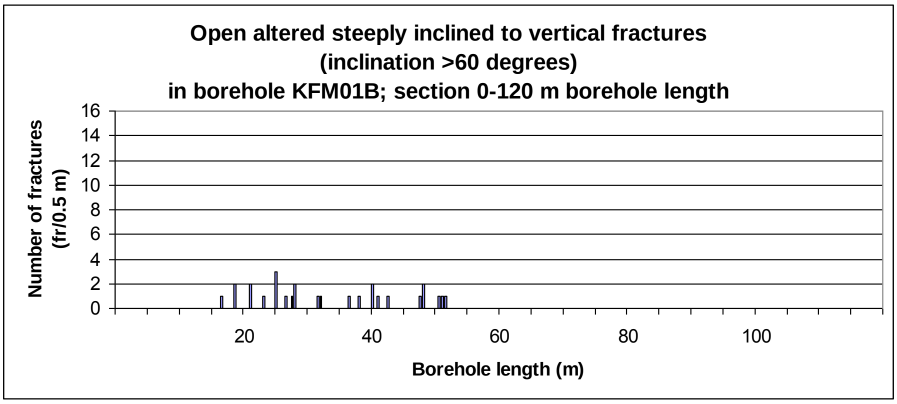


Figure 3-41: Distribution of sub-horizontal to gently inclined open altered fractures along the upper part of the borehole KFM01B, $N_{op.\ alt.\ steeply\ inclined}$=27. Number of fractures is given for 0.5 m wide borehole sections.

The investigated section of borehole KFM01B (12.5-120 mbl.) can be divided into three parts (sub-sections) according to the density of fractures and also to the character of fractures with respect to orientation (dip) and the relative percentage of open and open altered fractures (Figs. 3-29 to 3-43, and Table 3-3). The sub-sections are:

1. Sub-section 1 (S1): 15.5 mbl (start of core) to 52.0 mbl.
2. Sub-section 2 (S2): 52 to 108.5 mbl.
3. Sub-section 3 (S3): 108.5 to 120 mbl.

As a reference to the presented data on fracture densities within the three sub-sections (Table 3-3), some data on the average fracturing within the investigated upper section of borehole KFM01B are given. The mean fracture densities along the borehole for all fractures, open fractures and open altered fractures are 7.46, 2.47 and 2.14 fr/mbl.[14], respectively.

In the following text, some trends expressed in the fracture populations within the three sub-sections of borehole KFM01B are discussed. Data on fracture densities along the borehole, without considering the orientation bias, are given in Table 3-3.

Going from the upper sub-section (S1) to the lower sub-section (S3) there is a marked contrast between the middle sub-section (S2) and the other two sub-sections regarding the fracture densities for all fractures. The fracture densities in the upper and lower sub-sections are close to or slightly more than twice the density in the middle section. However, the percentage of open fractures is fairly similar for S2 and S3 (28.1 and 31.9 % of all fractures) while the number is more than double for S1 (64.2 %). However, the percentage of open altered fractures is highest for S2 (70.3 % of the open fractures) while the corresponding numbers for S1 and S3 are lower (55.5 and 39.9 %). The density of altered fractures is most accentuated in S1 (6.16 fr/mbl.) compared to S3 (1.22 fr/mbl.) and S2 (0.92 fr/mbl.).

Low-angle fractures are common in all sub-sections, especially in S1 and S2 while in S3 gently inclined fractures dominates and is even more common than in S1. The relative proportions of open altered fractures amongst the low-angle and the gently inclined fractures are high in S1 (90.6 and 85.7 %, respectively) and the proportions decrease strongly with depth (S2: 38.1 and 73.0 %; S3 26.3 and 38.1 %).

Moderately inclined fractures are most frequent in S3 (2.70 fr/mbl.), about 1.7 times higher than in S1 and three times higher than in S2. Very few open altered moderately dipping fractures occur, mainly in S1 and are absent in S3.

Steeply dipping fractures (inclination>60°) are relatively few (S1 and S3 about 2 fr/mbl. and 1.5 fr/mbl. in S2). Open altered steeply dipping fractures occur only in S1 (0.8 fr/mbl.).

[14] fr/mbl. = fractures per metre borehole length.

Table 3-3: Fracture densities in three sub-sections of the investigated part of borehole KFM1B, section 12.5 to 120 m borehole length. Given numbers are not corrected for orientation biases.

Group	Dip	Type	Fracture density along borehole (fr/mbl.[1])		
			Sub-section 1 (S1) 15.88-52.00 m	Sub-section 2 (S2) 52.00-108.5 m	Sub-section 3 (S3) 108.5-120.00 m
All fractures	0-90°	All	11.10	4.65	9.83
		Open	7.13	1.31	3.13
		Open fresh	0.97	0.39	1.91
		Open altered	6.16	0.92	1.22
Low angle	< 20°	All	6.63	2.09	3.30
		Open	5.00	1.19	2.43
		Open fresh	0.47	0.39	1.57
		Open altered	4.53	0.80	0.87
Gently inclined	10-30°	All	3.12	1.19	3.83
		Open	2.51	0.65	1.83
		Open fresh	0.36	0.18	1.13
		Open altered	2.15	0.48	0.70
Moderately inclined	30-60°	All	1.60	0.90	2.70
		Open	0.64	0.07	0.00
		Open fresh	0.22	0.00	0.00
		Open altered	0.41	0.07	0.00
Steeply inclined	>60°	All	2.04	1.47	2.00
		Open	0.91	0.00	0.09
		Open fresh	0.17	0.00	0.09
		Open altered	0.75	0.00	0.00

[1] fr/mbl.= number of fractures per metre borehole length.

Amongst fractures mapped as open, the sub-sections have similar percentages of fractures (20.6 to 29.6 % according to their inclinations /cf. Table 3-3/; highest value for moderately inclined fractures) that are given the attribute fresh; i.e. open fractures "unaffected by alteration". However, such fractures generally have dull fracture surfaces (indication of very weak alteration, e.g. coated by a thin transparent film of clay minerals).

The orientations of fractures in the three sub-sections (S1 to S3) show some minor variations in orientation (Figs. 3-42 and 3-43). Dominant in all three sub-sections are sub-horizontal fractures. The upper sub-section S1 displays the largest spread in fracture orientation and the spread is less for open altered fractures compared to all fractures. With increasing depth, going from sub-section S1 to S3, the orientation of open altered fractures becomes more and more sub-horizontal (Fig. 3-43). For all fractures, the population of moderately inclined fractures displays the largest variation in orientation from having northwesterly dips in S1 to westerly dips in S2 and to northerly in S3 (Fig. 3-42).

In summary, in the investigated section of borehole KFM01B the fracturing is most pronounced in its upper parts (above c. 50 mbl., i.e. above c. - 46 m a.s.l.) and related to a general increase of low-angle fractures (inclination< 20°; with a dominance of sub-horizontal fractures). The relative proportion of open altered fractures in relation to open fractures (fresh and altered) appears to decrease with depth and moderately to steeply dipping open altered fractures are not recorded in the investigated section below 96 mbl. Open altered fractures still occur from 108.5 to 120 mbl., but they are few (less than one fracture metre). However, the highest number of open fresh fractures, found in the lowest part of the investigated section of the borehole (108.5 to 120 mbl.), indicates that the rock may either be more fragile (or stiffer) if it has an increased density of sealed fractures compared to rock without any brittle overprint or that stress is released closest to deformation zones, or a combination of both. Furthermore, analysis of the distribution of all fractures in combination with open altered fractures appears to be a good guide to indicate the location of weak brittle structures in the rock. However, determination of the location of brittle deformation zones needs analysis of fracture sets (cf. Fig. 3-102).

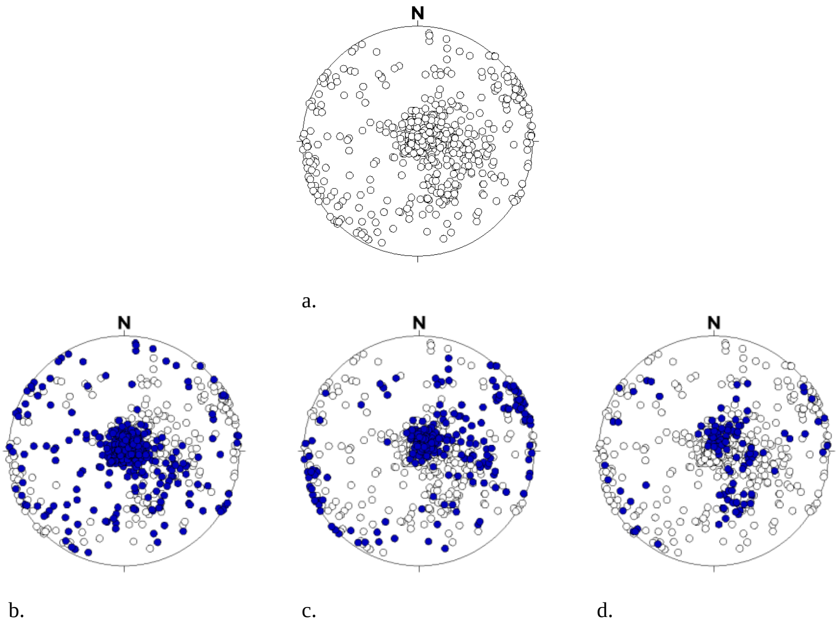


Figure 3-42: All fractures borehole KFM01B, section 15.5 to 120.0 mbl. (Table 3-3; cf. Fig. 3-43 and Figs. 3-28, 3-33, 3-36, 3-38 and 3-40):

a. All fractures, N= 772 (open circles; total 778, 6 fractures without orientation).

b. All fractures in sub-section S1, 15.5-52.0 m, N=400 (blue dots; total 402, 2 fractures without orientation).

c. All fractures in sub-section S2, 52.0-108.5 m, N=259 (blue dots; total 263, 4 fractures without orientation).

d. All fractures in sub-section S3, 108.5-120.0 m, N=113 (blue dots).

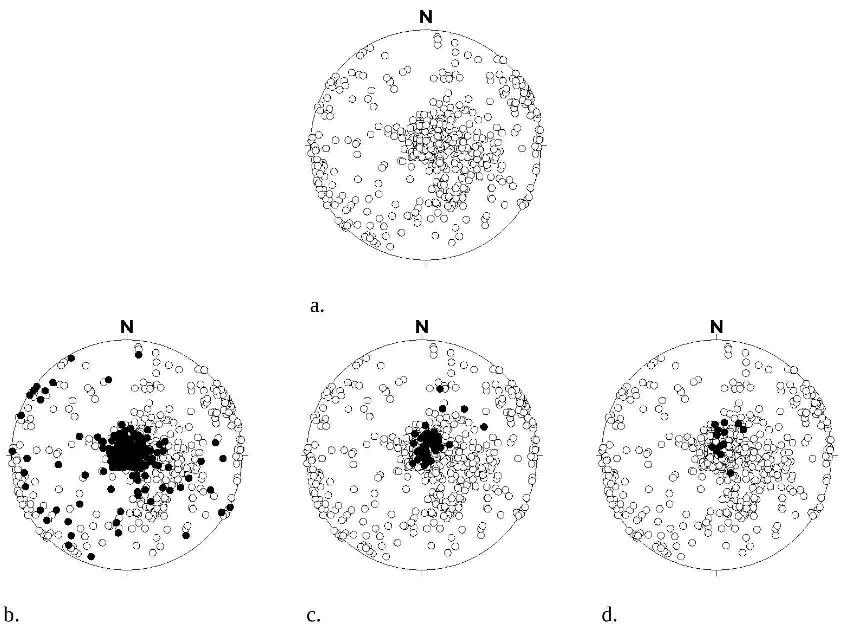


Figure 3-43: Open altered fractures borehole KFM01B, section 15.5 to 120.0 mbl. (Table 3-3); cf. Fig. 3-42 and Figs. 3-31, 3-35, 3-37, 3.39 and 3-41):

a. All open altered fractures, N= 286 (open circles; total 291, 3 fractures without orientations).

b. All open altered fractures in sub-section S1, 15.5-52.0 mbl., N=221 (black dots; total 223).

c. All open altered fractures in sub-section S2, 52.0-108.5 mbl., N=51 (blue dots; total 52).

d. All open altered fractures in sub-section S3, 108.5-120.0 mbl., N=14 (black dots).

Borehole radar reflectors

The borehole radar instrument detected six reflectors with absolute orientation (Fig. 3-44). Five of these are sub-horizontal to moderately inclined and they all have alternative orientations, all gently inclined. The reflectors intersect the borehole between 40 to 98 mbl. For the steeply southwestwards dipping reflector, intersecting the borehole at about 111 mbl., there is no alternative orientation presented.

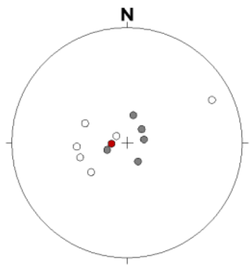


Figure 3-44: Radar reflectors intersecting borehole KFM01B between 0 to 120 mbl. , $N_{first\ alternative\ orientation}$=6 (open circles) and $N_{second\ alternative\ orientation}$=5 (grey dots). The orientation of the borehole is given by the red dot.

Water-conductive fractures

No measurements with the Posiva Flow Log have been performed in the cored borehole KFM01B.

Brittle deformation zones in the SKB model

In the shallow parts of the cored borehole KFM01B, two brittle deformation zones are distinguished (Stephens et al. 2007) at borehole lengths 16 to 64 m (DZ1) and 107-135 m (DZ2). The upper zone (DZ1) is interpreted to be the intersection of a gently inclined zone (ZFMA2; 16-64 mbl. and oriented 080/24) in the SKB geological model of the Forsmark site, while the second zone intersection (DZ2) is not correlated with any extensive tectonic structure/zone and therefore not incorporated in the SKB site model.

The objective of the present study of cored borehole KFM01B is to study the character of zone ZFMA2 (DZ1) in relation to structures in the surrounding host rock (up to at least 50 mbl. away from the zone) and in this case the borehole section 0 to 120 m was selected.

Sub-horizontal shears along NS/sub-vertical fractures are noted in DZ1. Fault cores in DZ1 are noted at 39.5 to 42.20 mbl. and at 46 to 47 mbl., respectively. However, neither any kinematic indicator related to deformation along zone ZFMA2 nor any fault core in DZ2 was identified (Nordgulen and Saintot 2006).

Character of brittle deformation

The brittle deformation in the uppermost part of borehole KFM01B is dominated by horizontal to sub-horizontal fractures. This is typical for the area and found in most boreholes drilled in the Forsmark area (cf. Stephens et al. 2007). The question is if it is possible to distinguish gently inclined brittle deformation zones in an environment strongly dominated by horizontal to gently inclined fractures; such features might represent a mix of fractures with tectonic and non-tectonic (sheet joints) origin.

Of special interest is to find geological characteristics that are distinguishable, both regarding the structural evolution of the zone and the present character of fractures. This has to be performed as a filtering process of available borehole data as the present author does neither have any direct field observations of gently inclined zones in the Forsmark area nor have any experience gained from mapping drill cores from Forsmark.

Generally, steeply dipping fractures may not be related to the formation of any open brittle deformation zone in the upper part of borehole KFM01B as steeply dipping fractures are relatively homogeneously distributed along the borehole (cf. text above and Fig. 3-40). However, the steeply dipping fractures belong to at least three sets of fractures trending approximately NW to NNW, NE to ENE and EW (cf. Fig. 3-42). These three sets may form local clusters. However, the steeply dipping fractures are all sealed at levels below approximately 50 mbl., while a minor part of these fractures are open within the first 50 m of the borehole (cf. Fig. 3-41). This implies that they affect the ground water flow and the competence of the shallow part of the bedrock and thereby also affect the local character of the gently inclined zone ZFMA2.

The degree of fracture alteration reflects the amount of time the fracture has been in contact with flowing groundwater and it is also strongly related to geological history of the fracture, i.e. past and present state of parameters such as temperature, pressure, groundwater chemistry and type of wall rock. Fractures mapped as moderately to highly altered are only found in minor sections in the uppermost part of the investigated section of the borehole (12.5-120 mbl.), e.g. at 37.4 to 45.0 mbl. (the longest section with more intensely altered fractures comprising 15 fractures having a mutual separation from 0.01 to 1.72 mbl.; two of the fractures are highly altered). The section of moderately to highly altered fractures extends some metres outside (beneath) the SKB zone ZKFMA2. No moderately to highly altered fractures are mapped within the investigated part of SKB zone DZ2 (i.e. 107-120 mbl).

The borehole section 37.4 to 45.0 m is here chosen as an example in order to describe the structural environment within which the more altered fractures occur. The fractures are dominantly sub-horizontal. By dividing the section into three separate sub-sections and by plotting each sub-section separately, a distinct pattern is displayed (Fig. 3-45):

1. All fractures in the upper sub-section (6 fractures; 37.4 to 40.5 mbl.) are sub-horizontal (inclination less than 10° towards N or S) and have EW:ly trends (Fig. 3-45b).
2. Fractures in the middle sub-section (5 fractures; 40.5 to 42.7 mbl.) are gently to moderately inclined (18 to 33°) and easterly dips dominate (Fig. 3-45c).
3. Fractures in the lower sub-sections (4 fractures; 42.7 to 45.0 mbl.) are sub-horizontal (Fig 3-45d).

The dominant fracture fills in the moderately to highly altered fractures are clay minerals (13) and iron hydroxides (12). Subordinate fracture minerals are chlorite (3), aspaltite (2) and pyrite (1). The interpretation of this is that the moderately to highly altered fractures were all connected and they do not form parts of reactivated early structures (i.e. characterized by fills containing ±epidote ± laumontite and ± quartz and/or with oxidized walls) as only 4 fractures with epidote ± oxidized wall and no fracture with quartz or laumontite are found. The epidote ± oxidized wall fractures are all sealed and generally moderately to steeply inclined (about 60°).

A comparison of the populations of open altered and all fractures within moderately highly altered fractures in borehole section 37.4 to 45.0 mbl. (containing zone ZFMA2) shows the pattern to be similar to that for the more altered fractures (Figs. 3-46 and 3-47). The middle section has the highest density considering both open altered fractures and all fractures (12.2 and 15.0 fr/mbl.). Notable is also that the middle section has the highest relative proportion of open altered fractures; 81.8 percent of all fractures. The upper section is also densely fractured; 14.5 fractures per meter borehole metre and 73.4 percent of these are open altered fractures. The lower subsection is less fractured; 10.9 fracture per metre borehole length and only 44.0 percent of these fractures are open and altered.

In conclusion, the section 37.4 to 45.0 mbl. constitutes a core zone according to the definition of brittle deformation zones given by Munier et al. (2003) regarding to the fracture density of all fractures (>10 fr/m). The fracture population in the three sub-sections are dominated by sub-horizontal to gently inclined fractures. A minor proportion consists of steeply dipping fractures (13 to 28 % all fractures) of which 20 to 50 percent represent open altered fractures trending NE-SW, N-S and NW-SE (Fig. 3-46).

Minor sections of moderately to highly altered fractures are also found in KFM01B at the following borehole lengths: 18 (3 moderately altered), 21 (1 moderately altered), 28 (2 moderately altered and 1 highly altered) and 50.5 (3 moderately altered) mbl. They have similar sets of fracture fill as in the previously described section (37.4 to 45.0 mbl.). However, there are also moderately altered sections with only chlorite (2) and one fracture has no fill.

The detailed description given above may be used as a guide how to interpret the fracture pattern in the upper part of borehole KFM01B; a duplex configuration within a brittle shear zone.

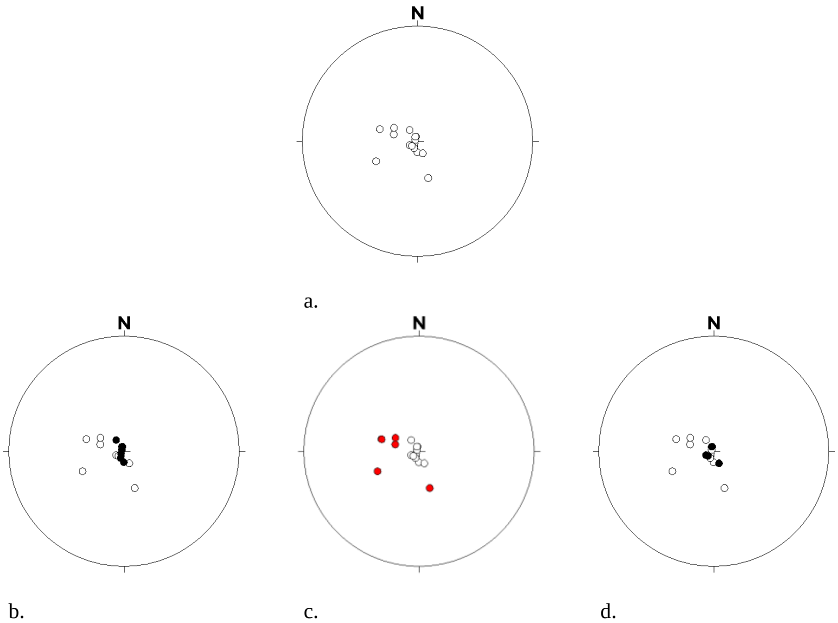


Figure 3-45: Moderately to highly altered fractures borehole KFM01B, section 37.4 to 45.0 mbl.:

a. All fractures, N=15.

b. Altered fractures in the upper part of the section, 37.4 to 40.5 mbl., N=6 (black dots).

c. Altered fractures in the central part of the section, 40.5 to 42.7 mbl.. N=5 (red dots).

d. Altered fractures in the lower part of the section, 42.7 to 45.0 mbl., N=4 (black dots).

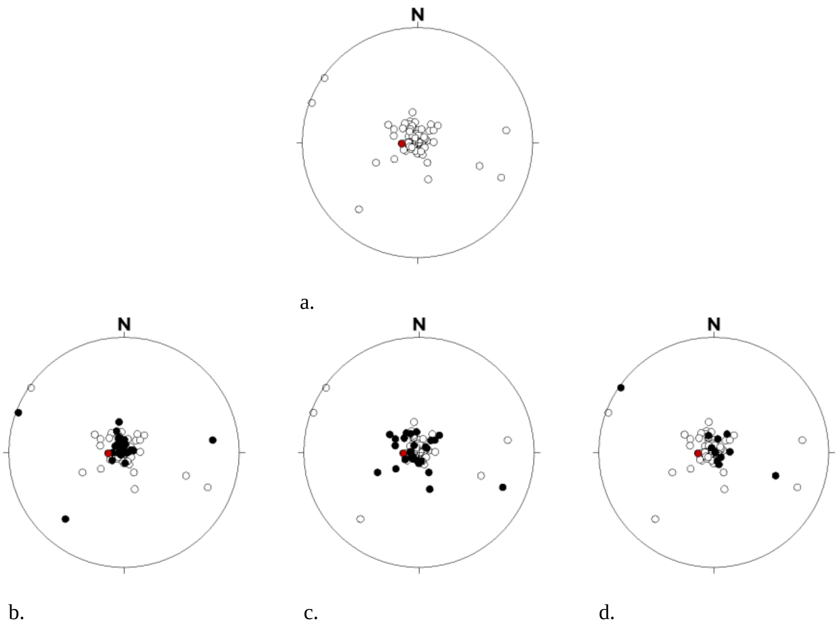


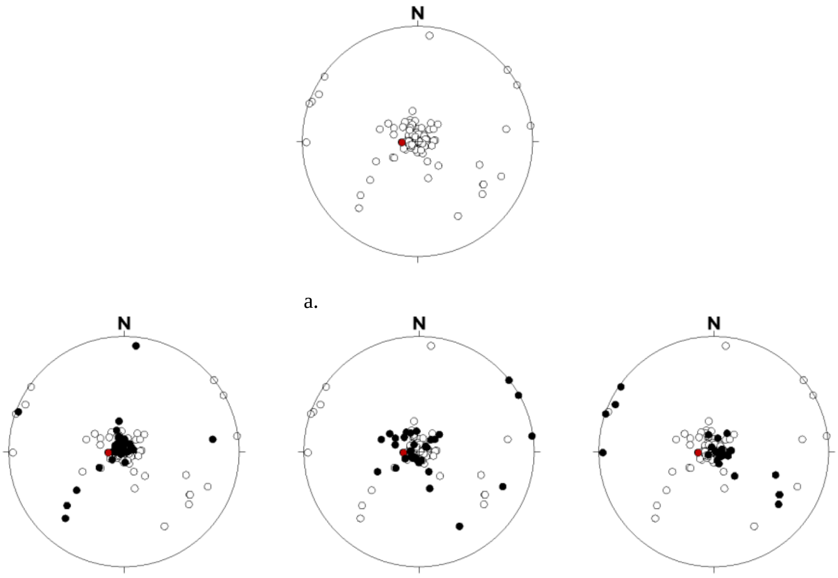
Figure 3-46: Open altered fractures borehole KFM01B, section 37.5 to 45.0 mbl.:

a. All open altered fractures, N=71 (open circles; red dot is the borehole, 267/79).

b. Open altered fractures in the upper part of the section, 37.4-40.5 mbl., N=33 (black dots).

c. Open altered fractures in the central part of the section, 40.5-42.7mbl., N=27 (black dots).

d. Open altered fractures in the lower part of the section, 42.7-45.0 mbl., N=11 (black dots).



a. b. c. d.

Figure 3-47: All fractures borehole KFM01B, section 37.5 to 45.0 mbl.:
a. All fractures, N= 103 (open circles; red dot is the borehole, 269/79).
b. All fractures in the upper part of the section, 37.4-40.5 mbl., N=45 (black dots).
c. All fractures in the central part of the section, 40.5-42.7 mbl., N=33 (black dots).
d. All fractures in the lower part of the section, 42.7-45.0 mbl., N=25 (black dots).

Location of brittle deformation and zones of weakness

Geological data indicating structural features that may represent zones of weakness in the rock and relation between such structures and their imprint on the rock for borehole section 12.5-120 m along borehole KFM01B is compiled in Figure 3-48. Data presented in Figure 3-48 give how fractures are clustered and how the clusters are related to other geological core log data:

- Clustering of all fractures and open altered fractures.
- Sections with core loss.
- Sections with crushed rock.
- Sections with ductile shear zones.
- Sections with network of sealed fractures.
- Sections with breccia.
- Sections with altered host rock.

SKB’s interpretation of brittle deformation zones (cf. Stephens et al 2008) is also given in Figure 3-48; i.e. the location of the gently inclined zone ZFMA2 (SKB DZ1: 16 to 64 mbl.), and a not modelled zone intersection (SKB DZ2: 107 to 135 mbl.).

The clustering of all fractures and open altered fractures have been classified according to the mutual separation of fractures along the borehole (Table 3-4 and Figs. 3-40a to 3-40d; the applied methodology is described in Chapter 2).

The relative high density of fractures in the upper section (0 to 120 mbl.) of borehole KFM01B, 7.5 fr/mbl., is reflected in the high percentages of fractures embraced by clusters (Table 3-4; 1B:1, > 10 fr/mbl. – c. 54 % and 1B:2, >5 fr/mbl. – c. 74 %). The total length of 1B:2 clusters is about 2.5 times larger than the total length of 1B:1 clusters and the two types of clusters occur together in three intervals of the borehole: about 17 to 61, 78 to 99 and 107 to 120 mbl. The 1B:1 clusters have in many cases the same width as 1B:2 clusters. Exceptions from this occur, for example where 1B:1 clusters are densely located in interval 26 to 53 mbl.

Clusters of open altered fractures occur primarily in the upper part the investigated borehole section (Table 3-4; 1B:3, >10 fr/mbl., from 27 to 52 mbl., and 1B:4, >5 fr/mbl., from 18 to 52 mbl.). The occurrences of clusters of open altered fractures start at the same level as clusters outlined by all fractures but ends at a higher level. For the remaining parts of the investigated borehole sections, clusters composed of open altered fractures exist at two levels: about 90 and 96 mbl. The lower part of the investigated borehole section has no clusters of open altered fractures.

Borehole sections mapped as core loss (Fig. 3-48e) or crushed rock (Fig. 3-48f) are excluded in the data files with discrete fractures. In most cases these types of structural features are associated with sections of increased fracturing (all fractures cluster 1B:2, except for at 70 m, and all open altered fractures cluster 1B:3, except for at 70 and 78 mbl.). In the upper part of the borehole section (17 to 52 mbl.), crushed rock form four clusters 1.5 to 3.7 m wide along the borehole having separations of 5.0 to 9.8 m along the borehole. In the upper part of the lowest of these clusters core losses are recorded (at about 47 mbl.). Sections with breccias (Fig. 3-48i) are found in the lower part of the upper section with increased general fracturing (clusters 1B:2, at 55 mbl.) and in the middle section with increased general fracturing (clusters 1B:2, at 83, 88 and 90 mbl.). A ductile shear zone (at 90 mbl.) is located below a section with breccia (Fig. 3-48g).

Sections with networks of sealed fractures (Fig 3-48h) correlate well with altered rock. Altered rock is common in the three sections with general increased fracturing, although also found outside these sections. However, there is no general correlation between clusters of open altered fractures and networks of sealed fractures.

The section extending from 18 to 52 mbl. is the mechanically weakest part of the investigated section of borehole KFM01B. This section contains nearly half of all fractures and three quarters all open altered fractures mapped in the upper 120 m of the borehole (49.9 % and 73.7 %, respectively). About 66.3 percent of all fractures are open and amongst the open fractures a dominant part are altered (88.1 %; cf. Fig. 3-49g and h).

The highest densities of sub-horizontal fractures (inclination ≤10°) are found in the section from 18 to 52 mbl. (39.1 % of all fractures, cf. Fig. 3-49) and a major part of the fractures are open (70.2 %; 106 out of 151) and nearly all open fractures are altered (94.3 %; 100 out of 106). Partly open fractures are relatively few (14.7 % of all fractures), about half of them are altered (50.9 %) and the main part are sub-horizontal (Figs. 3-49e-f). Sealed altered fractures are relatively few (3.9 %; 15 out of 388, Fig. 3-49d) and half of them are sub-horizontal (7 out of 15).

Character of SKB DZ

The section 18 to 52 m along the borehole KFM01B (Fig. 3-48) constitutes the upper and central parts of SKB's deformation zone ZFMA2 (16 to 64 mbl.; Stephens et al. 2007). This indicates that the brittle deformation zone is inhomogeneous, i.e. the zone may be partly sealed or partly reworked (a matter of view).

Comments

In summary, the investigated upper section of borehole KFM01B has three intervals with increased brittle deformation 17 to 61 mbl., 78 to 99 mbl. and 107 to 120 mbl. However, open altered fractures that form clusters are almost exclusively found in the section 18 to 52 mbl. and the fractures are dominantly sub-horizontal to gently inclined. A high proportion of open fractures are altered and amongst these are sub-horizontal to gently inclined fractures the most commonly occurring ones (fractures sub-parallel to the gently inclined SKB zone ZFMA2). Steeply dipping fractures are not related to the gently inclined zone, while moderately dipping fractures may to some extent be related to, or re-activated during the formation of, gently inclined brittle deformation zones. However, it is not proven that all of the low-angle open altered fractures are related to zone ZFM02A, although it is indicated that the rock contains sealed structures/sections representing tight and stiff deformation zones, i.e. they are sealed.

Table 3-4. Character of clusters of fractures in borehole KFM01B section 0 to 120 m borehole length (cf. Fig 3-48). Two groups of fractures are treated: all fractures and open altered fractures. Identification of clusters is based on two criteria: 1. the minimum mutual separation between fractures, 0.10 and 0.20 m (corresponding to minimum fracture frequency of 10 and 5 fractures per metre borehole length, respectively) and 2. the minimum number of fractures to outline a cluster (4 fractures).

Cluster				Borehole KFM01B					
ID[2]	Group of fractures	Criterion to identify clusters		Borehole section 15.7 to 120 m borehole length					
		Minimum number of fractures to outline a cluster[1]	Minimum fracture frequency (fr/mbl.)[3]	Number of clusters	Length of clusters (mbl.)	Length of clusters in percent of section length (%)	Mean fracture frequency in section (fr/mbl.)	Mean fracture frequency in clusters (fr/mbl.)	Fractures in clusters in percent of fractures in section (%)
1B:1	*All*	4	10	61	12.7	12.2	7.5	28.1	53.6
1B:2		4	5	52	31.3	30.0	7.5	16.7	73.8
1B:3	*Open and altered*	4	10	18	2.9	2.8	2.8	37.3	33.2
1B:4		4	5	17	11.9	11.5	2.8	13.7	62.3

[1] Minimum number of fractures to outline a cluster; 4 fractures = 3 core pieces. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of clusters).

[2] ID of group of clusters.

[3] fr/mbl. = fractures per metre borehole length.

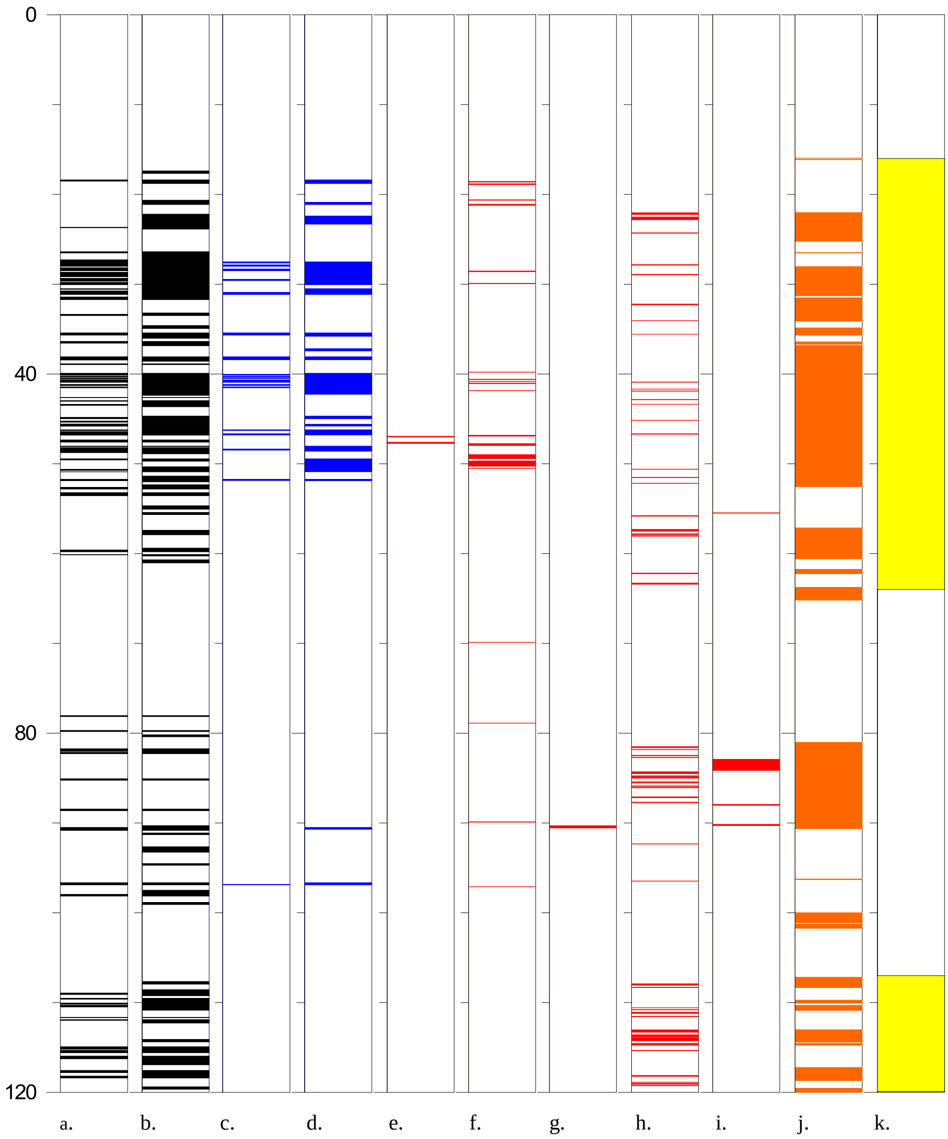


Figure 3-48. Borehole KFM01B section 16.5 to 120 mbl.; Clusters of fractures (Table 3-4), tectonic structures and location of SKB ESHI (incl. zone ZFMA2):

a. All fractures (cluster 1B:1), fracture separation less than 0.10 m (fracture frequency>10 fr/mbl.).

b. All fractures (cluster 1B:2), fracture separation less than 0.20 m (fracture frequency>5 fr/mbl.).

c. Open altered fractures (cluster 1B:3), separation less than 0.10 m (fracture frequency>10 fr/mbl.).

d. Open altered fractures (cluster 1B:4), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

e. Sections with core loss.

f. Sections with crushed rock.

g. Sections with ductile shear zones.

h. Sections with network of sealed fractures.

i. Sections with breccia.

j. Sections with altered host rock, oxidation.

k. SKB's interpreted location of the gently inclined zone ZFMA2 (DZ1: 16 to 64 m), and a not modelled zone intersection (DZ2: 107 to 135 mbl.).

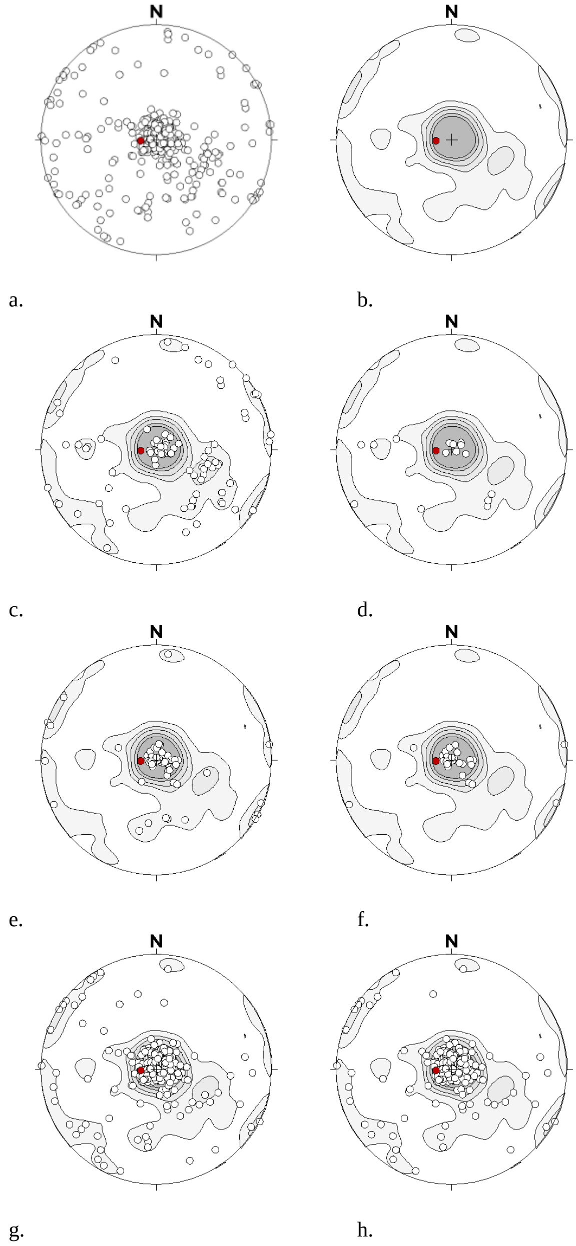


Figure 3-49: Fractures in KFM01B, section 18 to 52 mbl.:

a. All fractures, N=386 (388, 2 fracture without orientation; 11.4 fr/mbl.)

b. All fractures, contoured.

c. Sealed fractures plotted on all fractures, N=87 (2.6 fr/mbl.).

d. Sealed altered fractures plotted on all fractures, N=15 (0.4 fr/mbl.).

e. Partly open fractures plotted on all fractures, N=57 (1.7 fr/mbl.).

f. Partly open altered fractures plotted on all fractures, N=29 (0.9 fr/mbl.).

g. Open fractures plotted on all fractures, N=242 (244, 2 fractures without orientation; 7.2 fr/mbl.).

h. Open altered fractures plotted on all fractures, N=213 (215, 2 fractures without orientation; 6.3 fr/mbl.).

KFM01C - section 0 to 150 m borehole length

Borehole KFM01C is drilled from the same drill site as borehole KFM01B and plunges moderately southwards (165/50; Table 3-1 and Fig. 3-3).

Rock types and general structure elements

Rock types

The main rock type is metamorphic medium-grained granite to granodiorite. Subordinate types comprise pegmatitic granites (about 13 %) and amphibolites (about 6 %). There also some thin bands (> 10 cm wide; dykes) of medium to fine-grained granites (cf. Fig. 3-55).

All fractures

The upper part of the cored borehole KFM01C, 0 to 150 mbl., is strongly fractured (12.02 fr/mbl.) and the fractures constitute two major sets: one sub-horizontal and the other composed of sub-vertical ENE trending fractures dipping NNW (Fig. 3-50). Fractures within a minor third set dip steeply northeastwards.

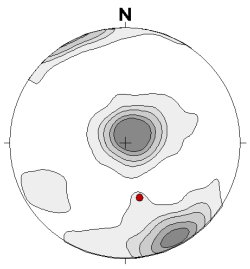


Figure 3-50: All fractures in borehole KFM01C, section 0 to 150 mbl., N=1 645. The red dot gives the orientation of the borehole.

Open altered fractures

The average fracture density of open altered fractures in the upper 150 m of borehole KFM01C is 3.72 fr/mbl. The sub-horizontal fractures are about 1.6 times more frequent than the sub-vertical fractures. The borehole is close to the bisector of the two sets; no correction for orientation bias is made (Fig. 3-51).

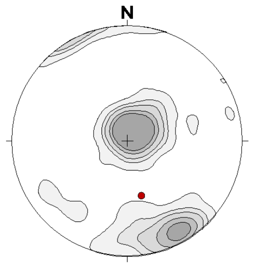


Figure 3-51: Open altered fractures in section in borehole KFM01C, section 0 to 150 mbl., N=509. The red dot gives the orientation of the borehole.

Core loss

Two sections with core losses are noted. The first section is 1.38 m long, located between 84.50 to 85.89 mbl., and coincides with a section of crushed rock in the borehole. The second section is 0.01 mbl. wide and located at 86.2 mbl.

Crushed rock

Four sections with crushed rock are recorded in the upper part of borehole KFM01C and all are sub-horizontal to gently inclined (Fig. 3-52). The three upper sections, at about 40.5 to 43.6 mbl., are more flat and have a range in width from 0.11 to 0.55 mbl. The forth section is about 1.7 mbl., dipping gently south-eastwards and located at a borehole length of 85 m.

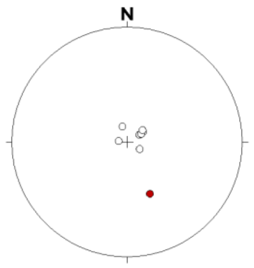


Figure 3-52: Crushed rock in borehole KFM01C, section 0 to 150 mbl., N=8 (upper and lower contacts of 4 sections). The red dot gives the orientation of the borehole.

Sealed network of fractures

Domains with sealed networks of fractures display similar orientations as the discrete fractures and are heterogeneously distributed along the borehole (Fig. 3-53).

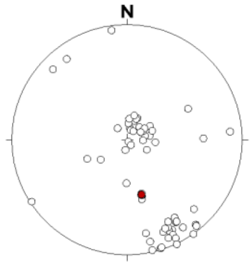


Figure 3-53: Sections with sealed network of fractures in borehole KFM01C, section 0 to 150 mbl., N=76 (upper and lower contact of 38 sections). The red dot gives the orientation of the borehole.

Altered sections of the bedrock

Most of the bedrock in the upper part of borehole KFM01C is altered (about 83 %; different types of alterations may intricate overlaps); oxidation dominates (74 % of the bedrock; maximum, mean, median and standard deviation are 22.7, 1.8, 0.8 and 3.4 mbl., respectively) while subordinate types of alteration are albitization (about 7 %; maximum, mean, median and standard deviation are 4.2, 0.5, 0.3 and 0.9 mbl., respectively) and epidotization (about 3 %%; maximum, mean, median and standard deviation are 1.9, 0.3, 0.1 and 0.6 mbl., respectively). The domains with altered rock have three major orientations (Fig. 3-54). Two sets are similar to the dominant fracture sets while the third is NW/steepNE, i.e. parallel to the minor set of fractures (cf. Figs. 3-50 and 3-51).

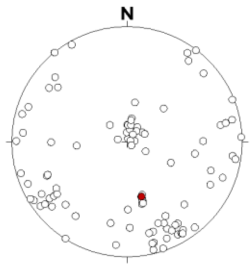


Figure 3-54: Altered section of the bedrock in borehole KFM01C, section 0 to 150 mbl.;, N=105. The red dot gives the orientation of the borehole.

Rock types/lithological contacts

Thin bands of rock are oriented NE/steepNW and NS/vertical to NW/steepNE (Fig. 3-55). The latter two orientations are most common for the contacts between more extensive rock units.

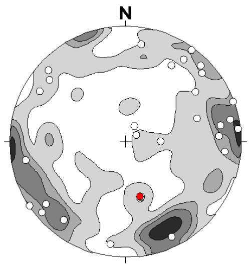


Figure 3-55: Orientation of lithological contacts in borehole KFM01C, section 0 to 150 mbl.; countered are upper and lower contacts of thinner segments/bands of rock (N=300; 150 intercalated bands) and lithological contacts between major rock types are added (N=28 white dots). The red dot gives the orientation of the borehole.

Cataclastic rock

Twelve thin bands of cataclastic rock (mean and median width about 0.01 m) are found (Fig. 3-56). All of the cataclastic bands are steeply dipping to vertical and trend ENE-WSW, i.e. parallel to the dominant orientation of lithological contacts (Fig. 3-55). Five bands are noted at about 33 mbl. in metamorphic granite and three at 121 mbl. in pegmatite. The widest section (0.06 mbl.) is found at a borehole length of 48 metres.

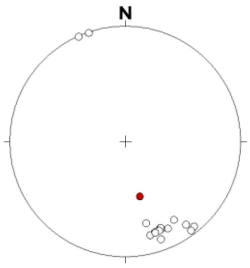


Figure 3-56: Orientation of cataclastic rocks in borehole KFM01C, section 0 to 150 mbl., N= 24 (12 bands, upper and lower contacts). The red dot gives the orientation of the borehole.

Brittle-ductile shear zones

The widest brittle-ductile shear zone is located from 74.39 to 75.58 mbl. and it is oriented NW/sub-vertical. However, brittle-ductile shear zones primarily are oriented ENE/steepNW (Fig. 3-57) and they occur in the upper part of the borehole (between 30 to 45 mbl.). These zones are thin (generally less than some centimetres wide; except for one which is about 0.3 m wide).

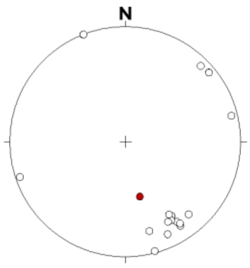


Figure 3-57: Orientation of brittle-ductile shear zones in borehole KFM01C, section 0 to 150 mbl., N=23 (11 zones + one contact). The red dot gives the orientation of the borehole.

Sections with breccias

Sections mapped as breccias (>0.06 mbl.) have similar orientation as bands mapped as cataclastic rock (Fig. 3-58 and 3-56) and the two types are closely related in space. Breccias are located at about 31, 33, 46, 56 and 123 mbl. The latter breccia is the widest (0.06 mbl.) while the other are less than 3 centimetres wide.

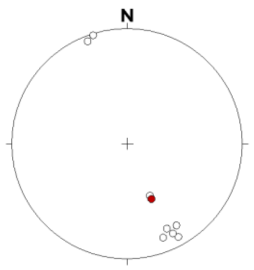


Figure 3-58: Orientation of breccias in borehole KFM01C, section 0 to 150 mbl., N=10 (5 sections; upper and lower contacts). The red dot gives the orientation of the borehole.

Sections with ductile shear zones

The ductile shear zones (Fig. 3-59) occur in the lower part of the investigated section; located between 113 to 122 mbl. The orientations of the ductile shears are NW/steepNE (3) and EW/steepN (1).

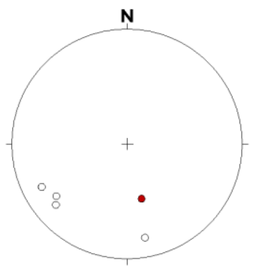


Figure 3-59: Orientation of ductile shear zones in borehole KFM01C, section 0 to 150 mbl., N= 6 (three bands; upper and lower contacts). The red dot gives the orientation of the borehole.

Foliation

The bedrock is in the upper part of borehole KFM1C foliated and the dominant orientation is NS/steep (Fig. 3-60).

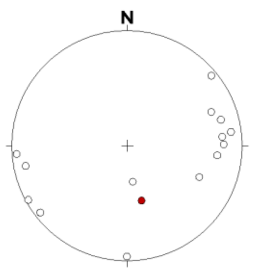


Figure 3-60: Orientation of foliations in borehole KFM01C, section o to 150 mbl., N=14. The red dot gives the orientation of the borehole.

Water-conductive fractures

Logging with the Posiva Flow Log (PFL) has not been performed in borehole KFM01C.

Borehole radar

The borehole radar has not been used in borehole KFM01C.

Fracture minerals

Minerals precipitated in fractures may form mono-minerals or mineral assemblages. Mineral formed in a fracture may be formed during a large time interval and the character of the fracture minerals (textural and structural relations) reflect their geological history, which requires microscope studies to unravel. In this simplified study, the relation between single fracture minerals and certain characteristics of the fractures are studied; to what extent are fractures containing a certain mineral open, partly open or sealed? As a fracture may contain several minerals, the fracture may appear repeatedly in the statistic of fracture minerals presented in Table 3-5.

The most common fracture mineral is calcite (48.6 % of all fractures) followed by chlorite (31.1 %). These two minerals often occur together and the relative occurrence of open fracture with calcite is 45.7 percent and with chlorite 56.8 percent. Similar relative numbers when considering all possible fractures that could conduct water (open plus partly open fractures) are 53.3 and 63.1 percent, respectively. Other common fracture minerals include clay minerals and hematite (both in about 21 % of all fractures) and the relative percentage of open together with partly open fractures are 73.9 and 90.9 percent, respectively. Fractures containing pyrite and asphaltite are relatively few (found in 3.4 and 7.2 % of all fractures) although the relative percentage of such fracture that are open or partly open are very high (89.3 and 84.7 %). Epidote is found in 3.3 percent of all fractures and 61.1 percent of such fractures are open or partly open.

A fracture characteristic typical for fractures that are mainly sealed is oxidized walls. Such fractures are common (32.5 % of all fractures) and the relative proportion of open together with partly open fractures is 23.4 percent. Fracture minerals that are relatively common (10 to 14 % of all fractures) are adularia and laumontite and their proportions of open plus partly open fractures are relatively low (25.4 and 45.0 %, respectively).

Accessorial fracture minerals are all found in open or partly open fractures. Fractures lacking descriptions of fracture minerals (not noted and not detected; cf. Table 3-5) are relatively common (6.5 % of all fractures) and are typically sealed (76.4 %).

Table 3-5: Relation between all, open and partly open fractures and their fracture fills and wall rock alteration in the shallow parts of cored borehole KFM01C, section 12 to150 m borehole length (number of sealed fractures = all fractures – (open + partly open fractures)).

	Fractures – number of observations			In percent of total number of fractures (1645)		
Fracture fill	**All Fractures**	**Open fractures**	**Partly open fractures**	**All fractures**	**Open fractures**	**Partly open fractures**
Fractures that have a potential to be soft or connect water						
Calcite	799	365	61	48.6	22.2	3.7
Chlorite	512	291	32	31.1	17.7	1.9
Clay minerals	350	255	63	21.3	15.5	3.8
Hematite	341	194	58	20.7	11.8	3.5
Asphaltite	118	78	22	7.2	4.7	1.3
Pyrite	56	49	1	3.4	3.0	0.1
Epidote	54	28	5	3.3	1.7	0.3
Fractures that have a potential to be stiff and tight						
Oxidized walls	535	97	28	32.5	5.9	1.7
Laumontite	231	90	14	14	5.5	0.9
Adularia	169	28	15	10.3	1.7	0.9
No detected mineral[1]	54	5	18	3.3	0.3	1.1
No notation of fill[1]	52	2	0	3.2	0.1	
Accessorial mineral						
Iron hydroxide	9	8	1	0.5	0.5	0.1
Prehnite	6	4	0	0.4	0.2	
White feldspar	6	5	1	0.4	0.3	<0.1
Chalcopyrite	2	2	0	0.1	0.1	
Zeolite	2	2	0	0.1	0.1	
Quartz	2	2	0	0.1	0.1	

[1] In the SKB SICADA file p_fract_core-KFM01C.xls fracture minerals are not given for some fractures while "NO DETECTABLE MINERAL" are noted for others.

Brittle deformation zones in the SKB model

Deformation zones (DZ) according to SKB are located within following sections in the upper part of borehole KFM01C:

1. DZ1: 23 to 48 mbl. (brittle deformation zones ZFMA2 and ZFMENE1192; Stephens et al. 2007, Stephens et al. 2008).

2. DZ2: 62 to 99 mbl. (brittle deformation zone ZFMA2; Stephens et al. 2007, Stephens et al. 2008).
3. DZ4: 121 to 124 mbl. (SKB database SICADA file p_eshi-KFM01C.xls; the extended geological single-hole interpretation).

In the upper section of borehole KFM01C the structural relation is intricate as DZ1 represent both the intersection between a gently inclined zone dipping southwards (80/24; zone ZFMA2) and a steeply dipping zone (64/88; zone ZFMENE1192). The DZ2 zone represents a lower branch of the gently inclined brittle deformation zone ZFM02A (described but not visualised in the deterministic geological model). DZ1 contains three core zones (crushed rock extending 0.03 to 0.55 m along the borehole at about 40.5, 41 and 43 mbl.) while DZ2 contains one core zone (1.71 metres length of crushed rock at about 84 mbl.). Dip-slip is indicated along some gently inclined fractures in DZ1 and DZ2 (Saintot and Nordgulen 2007). The zone DZ4 is not described (zone DZ3 235-250 mbl. is located below the investigated section).

Characterization of brittle deformation

Brittle deformation zones display spatial variation in their character. The reason for this may be related to natural variability of the internal geometrical configuration of fractures in the zones, to variation in the character of the rock within which the structures are formed or to the imprint of crossing structures. Deformation zones are also modified by reactivation, which may be partial. The present character of a brittle deformation zone is the result of its structural history, the accumulated re-working and sealing of structures.

The zone ZFMA2 in the upper part of borehole KFM01C display some characteristics due to the intersection with a ENE-WSW trending steeply dipping zone (ZFMENE1192): the forking of the zone into two branches and the existence of general sub-horizontal to gently inclined fracturing in the shallow part of the bedrock.

Location of brittle deformation and zones of weakness

Geological data indicating structural features that may indicate zones of weakness in the rock and relation between such structures and their imprint on the rock for borehole section 0-150 m along borehole KFM01C is compiled in Figure 3-61. The text is focused on discrete fractures (fractures mapped as single structures); how they are clustered (all fractures and sets of fractures) and how they are related to other geological observations. These observations concern:

- Sections with core loss.
- Sections with crushed rock.
- Sections with ductile shear zones.
- Sections with mylonite.
- Sections with network of sealed fractures.
- Sections with cataclastic rocks.
- Sections with breccia.

- Sections with altered host rock.

The general fracturing in the upper part of borehole KFM01C (0-150 metres borehole length) is relatively high, 11.9 fr/mbl. The fracture population consists mainly of two sets: low-angle fractures and steeply dipping fractures trending NE to ENE. The fracture frequencies for these two sets are 5.6 and 3.4 fr/mbl. (no orientation bias correction is made), respectively. As the borehole has an orientation close to the bisector of the two fracture sets, it can be stated that low-angle fractures (dip≤ 35°) are dominant.

The clustering of all fractures and open altered fractures have been classified according to the mutual separation of fractures along the borehole (Table 3-6 and Figs. 3-61a to 3-61d; the applied methodology is described in Chapter 2).

Identification of brittle deformation zones based on the distribution of all fractures would indicate that the main part of borehole KFM01C, from about 17 to 128 mbl., is a brittle deformation zone as clusters with minimum separation of fractures less than 0.2 mbl. are strongly dominant in this part of the borehole and are most prominent in section 32 to 42 mbl. (Fig. 3-61b and Table 3-6: 1C:2). Examples of other sections with increased fracturing are found at about 48, 72, 78, 87, 98, 108, 120 mbl.

The clustering of open altered fractures (Figs. 3-61c and 3-61d) indicates that the weakest part of the investigated section of the borehole is at a shallow level, at about 31 to 43 mbl., where there are sub-horizontal bands with crushed rock (Fig. 3-52) as well as cataclastic rocks (Fig. 3-61h). The latter are steeply dipping and trending ENE (Fig. 3-56). Clusters of open altered fractures are relatively evenly distributed from 43 to 140 mbl. with more prominent clustering at about 48, 78, 87, 98, 109 and 120 mbl.

Low-angle open altered fractures are also most frequent in section 33 to 43 mbl. and clusters (Fig. 3-61f; 1C:6 in Table 3-6) are relatively evenly distributed in the section between 72 to 110 mbl. A peak of fracturing, isolated from other sections with increased general fracturing, represented by a two decimetre wide cluster of low angle fractures occurs at a borehole length of 140 m (cf. Figs. 3-61a to 3-61f).

Open altered steeply dipping fractures occur primarily in the borehole interval between 34 to 39 mbl. and there are also decimetre wide sections (0.4 to 0.6 m wide clusters; type 1C:8 Table 3-6) at the following borehole lengths: 31, 44, 78, 82 and 120 m. Most of these sections, except for the wide section from 34 to 39 mbl., appear not to be associated with any increase of sub-horizontal fractures. All of these clusters with steeply dipping fractures may represent minor zones (some decimetre wide).

The widest section mapped as crushed rock (1.7 mbl. wide) is located at 85 m mbl. and associated with a section of intense general fracturing in the rock. Open altered low-angle fractures occur predominantly just beneath the crushed rock; loss of drill core indicates that this section is soft.

Sections displaying bands with brittle-ductile deformation are generally thin (< 1 dm wide) and are primarily associated with the upper section with increased fracturing (29 to 46 mbl.) and occur also at about 72, 74 and 78 mbl. Ductile shear zones are scarce and only found at about 114 mbl. (2 bands; widest is 0.6 m) and 122 mbl. (0.02m). There is no apparent relation between the occurrence of ductile shear zones and fracturing in the rock. Sections with mylonite, cataclastic rock, breccias are all thin (centimetre to decimetre wide; Figs. 3-61e, 3-61g, and 3-61h) and these type of structures occur both inside and outside clusters of open altered fractures.

Networks of sealed fractures are primarily found between 30 to 48 mbl. and 70 to 98 mbl., i.e. in the sections with enhanced density of open altered fractures. Rocks in the main part of the investigated borehole KFM01C are altered and the relations between general fracturing in the rock, sealed networks and alteration of the rock are not fully obvious.

Character of SKB DZ

In the upper part of borehole KFM01C there are three sections identified by SKB as brittle deformation zones (DZ1/23 to 48 mbl./, DZ2/62 to 99 mbl./ and DZ4/121 to124 mbl./; Fig 3-61j). A comparison the location of these deformation zones with the occurrence of clusters with open altered fractures, as defined in this study, shows that:

For the upper SKB zone (DZ1):

- In the upper part of DZ1 (23 to 31 mbl.) there is an absence of clusters with open altered fractures.
- Clusters of open altered low-angle fractures occur preferentially in the central part of DZ1 (about 33 to 43 mbl.) and there are also some clusters below DZ1 (to about 53 mbl.).
- Gently inclined zones of crushed rocks are found together with clusters of open altered low-angle fractures.
- Clusters of open altered fracture orientated ENE-NE/steep are mainly found in the central part of DZ1.
- There are no obvious relations between alterations of the bedrock and the location of DZ1 or between rock alteration and the distribution of clusters of open altered fractures. However, DZ1 contains several sections with sealed networks of fractures (they are rare outside DZs).

For the middle SKB zone (DZ2):

- In the upper part of DZ2 (62 to 72 mbl.) there is an absence of clusters with open altered fractures.
- Clusters of open altered fractures occur with a fairly regular distribution pattern between 72 to 109 mbl., i.e. the section extends about 10 m beyond zone DZ2.
- A gently inclined zone of crushed rock (about 84 to 86 mbl.) is located just above clusters of open altered low-angle fractures.
- Two clusters of open altered fracture with orientation ENE-NE/steep are found in the central part of DZ2, i.e. at 78 and 82 mbl. (cf. previous item).

- There are no obvious relations between alterations of the bedrock and the location of DZ2 or between rock alteration and the distribution of clusters of open altered fractures. However, DZ2 contains several sections with sealed networks of fractures (they are rare outside DZs).

For the lower SKB Zone (DZ4):

- DZ4 is located within a relative wide section with clusters outlined by the general fracturing in the rock (118 to 127 mbl.).
- DZ4 contain a minor cluster of open fractures (at 123.5 mbl. 0.3 m wide cluster containing 4 fractures; two are gently dipping and two are steeply dipping northwest). However, above DZ4 there is a cluster with ENE-NE trending steeply dipping fractures.
- A thin ductile shear zone (260/71; 0.02 mbl. wide along the core) and a network of sealed fractures are recorded at 122 mbl., i.e. they are located inside DZ4.
- DZ4 is located in a section with alternating thin bands of altered and unaltered rock. Wider borehole sections with oxidized rock occur below DZ4.

Along the borehole the two dominant fracture directions (low angle and ENE-NE/steep fractures) occur in different ways: minor sections dominated by one of the two sets and sections where fractures of the two sets are randomly mixed. However, it is possible that the two sets of fractures are related to two separate sets of deformation zones, gently inclined and sub-vertical brittle deformation zones, both dipping southeast.

Comments

A comparison of characteristics for low-angle fractures (inclination<30°) in section 33 to 43 mbl. (cf. DZ1) with fractures in section 72 to 109 mbl. (cf. DZ2) shows that there are some features that may be expected and some that may not be fully expected (cf. Figs. 3-62 and 3-63; in the figure caption the numbers for all fractures are given):

- All fractures display the same system of fractures in the two sections.
- The total density of low-angle fractures is higher in the upper section and the difference is relatively large (16.9 fr/mbl. in the upper section and 5.3 fr/mbl. in the lower section).
- The density of open fractures and open altered fractures (6.4 and 6.0 fr/mbl.) is higher in the upper section than in the lower section (2.7 and 2.5 fr/mbl.). The ratio between open and open altered fractures is nearly the same in the two sections.
- The density of partly open fractures and altered partly open fractures in the upper section (7.4 and 4.7 fr/mbl.) is much higher than in the lower section (0.6 and 0.5 fr/mbl.).
- The density of sealed fractures and altered sealed fractures in the upper section (3.1 and 1.8 fr/mbl.) is of about the same magnitude as in the lower section (1.9 and 1.5 fr/mbl.).

Table 3-6. Character of clusters of fractures in borehole KFM01C section 0 to 150 m borehole length (cf. Fig 3-61). Two groups of fractures are treated: all fractures and open altered fractures (incl. all, low-angle and NE-ENE/steep open altered fractures). Identification of clusters is based on two criteria: 1. The minimum mutual separation between fractures, 0.10 and 0.20 m (corresponding to minimum fracture frequency of 10 and 5 fractures per metre borehole length, respectively) and 2. The minimum number of fractures to outline a cluster (4 fractures).

Cluster				**Borehole KFM01C**					
ID[2]	**Group of fractures**	**Criterion to identify clusters**		**Borehole section 12.3 to 150 m borehole length**					
		Minimum number of fractures to outline a cluster[1]	**Minimum fracture frequency (fr/mbl.)**[3]	**Number of clusters**	**Length of clusters (mbl.)**	**Length of clusters in percent of section length (%)**	**Mean fracture frequency in section (fr/mbl.)**	**Mean fracture frequency in clusters (fr/mbl.)**	**Fractures in clusters in percent of fractures in section (%)**
1C:1	*All.*	4	10	133	34.4	25.0	12.0	33.0	77.0
1C:2		4	5	88	66.1	48.0	12.0	21.7	92.2
1C:3	*Open and*	4	10	24	4.1	3.0	3.7	27.6	27.0
1C:4	*altered*:All,	4	5	36	17.4	12.6	3.7	13.7	54
1C:5	Dip <35°,	4	10[4]	15	4.7	3.4	2.0	14.7	29.9
1C:6		4	5[4]	22	16.8	12.2	2.0	8.3	57.3
1C:7	NE to	4	10[5]	6	2.0	1.4	1.3	15.1	20.6
1C:8	ENE/steep	4	5[5]	10	5.2	3.8	1.3	9.4	33.7

[1] Minimum number of fractures to outline a cluster – 4 fractures = 3 core pieces. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of clusters).

[2] ID of group of clusters.

[3] fr/mbl. = fractures per metre borehole length

[4] Orientation bias corrections: Minimum separations for 10 fr/mbl. and 5 fr/mbl. are 0.17 and 0.35 metres borehole length, respectively.

[5] Orientation bias corrections: Minimum separations for 10 fr/mbl. and 5 fr/mbl. are 0.16 and 0.32 metres borehole length, respectively.

It is not apparent from the fracture data if healing processes are more strongly developed in the fractured upper section than in the lower section (indicated by, for example, the higher density of partly open fractures in the upper section).

The position of brittle deformation zones in KFM01C needs complementary work.

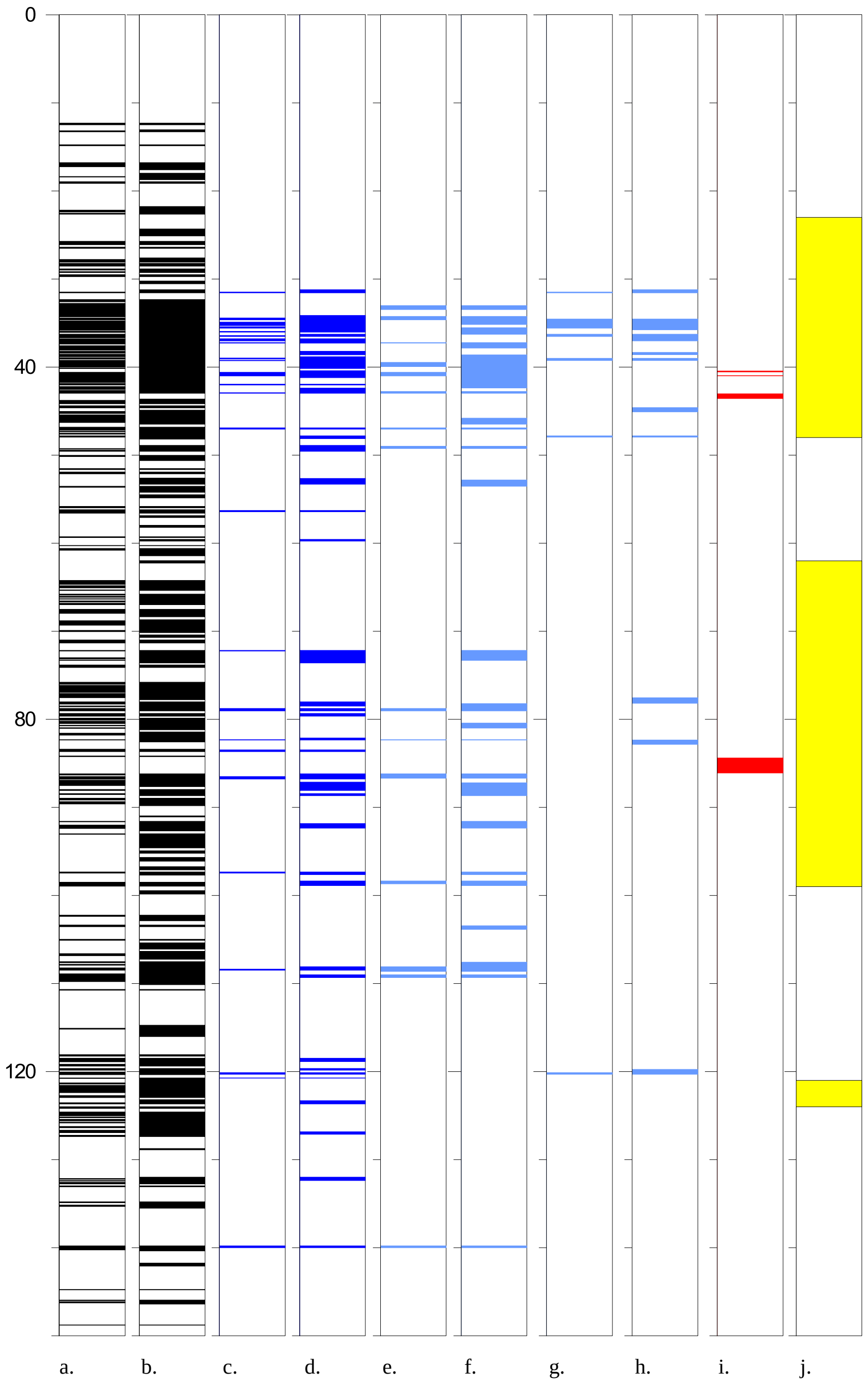


Figure 3-61: Borehole KFM01C section 0 to 150 mbl.; brittle deformation (cf. Table 3-6) and location of SKB ESHI (incl. SKB zone ZFMA2):

a. All fractures (cluster 1C:1), fracture separation less than 0.10 m (fracture frequency>10 fr/mbl.).

b. All fractures (cluster 1C:2), fracture separation less than 0.20 m (fracture frequency>5 fr/mbl.).

c. Open altered fractures (cluster 1C:3), separation less than 0.10 m (fracture frequency>10 fr/mbl.).

d. Open altered fractures (cluster 1C:4), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

e. Open altered fractures inclined less than 35° (cluster 1C:5), separation less than 0.17 m (fracture frequency>10 fr/mbl.),

f. Open altered fractures inclined less than 35° (cluster 1C:6), separation less than 0.35 m (fracture frequency>5 fr/mbl.),

g. Open altered ENE-NE/steep fractures (cluster 1C:7), separation less than 0.16 m (fracture frequency >10 fr/mbl.),

h. Open altered ENE-NE/steep fractures (cluster 1C:8), separation less than 0.32 m (fracture frequency >5 fr/mbl.,

i. Sections with crushed rock.

j. SKB's interpreted location of the gently inclined zone ZFMA2 (DZ1: 23 to 48 m and DZ2: 62 to 99 m), ZFMENE1192 (DZ1: 23-48 m) and a not modelled zone intersection (DZ4: 121 to 124 mbl.).
(To be continued.)

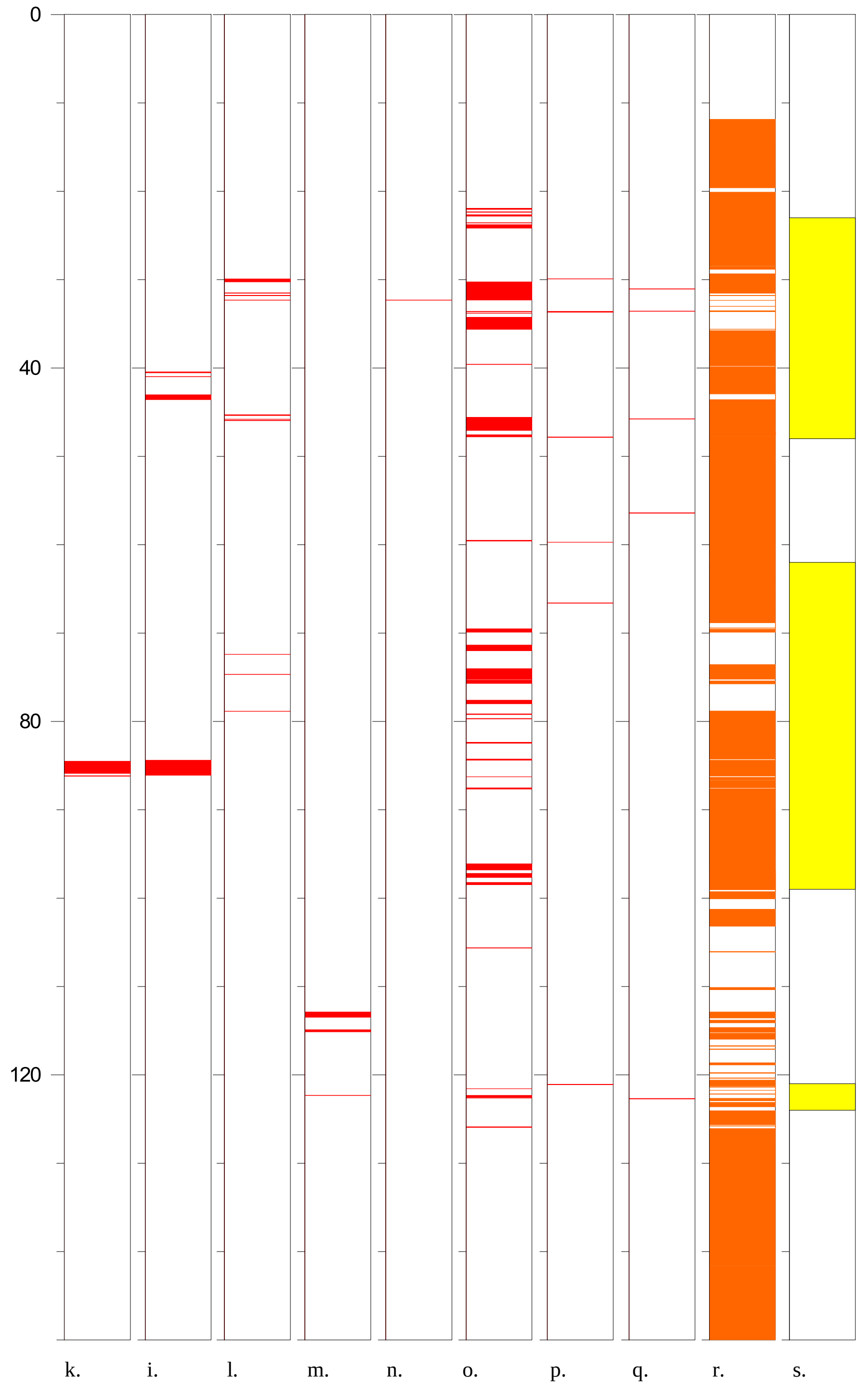


Figure 3-61 (continued): Borehole KFM01C section 0 to 150 mbl.; structures, alteration and location of SKB ESHI (zone ZFMA2) (cf. Figs.3-56 to 3-59):

k. Sections with core loss.

i. Sections with crushed rock (also presented on previous page).

l. Sections with brittle-ductile shear zones.

m. Sections with ductile shear zones.

n. Section with mylonite.

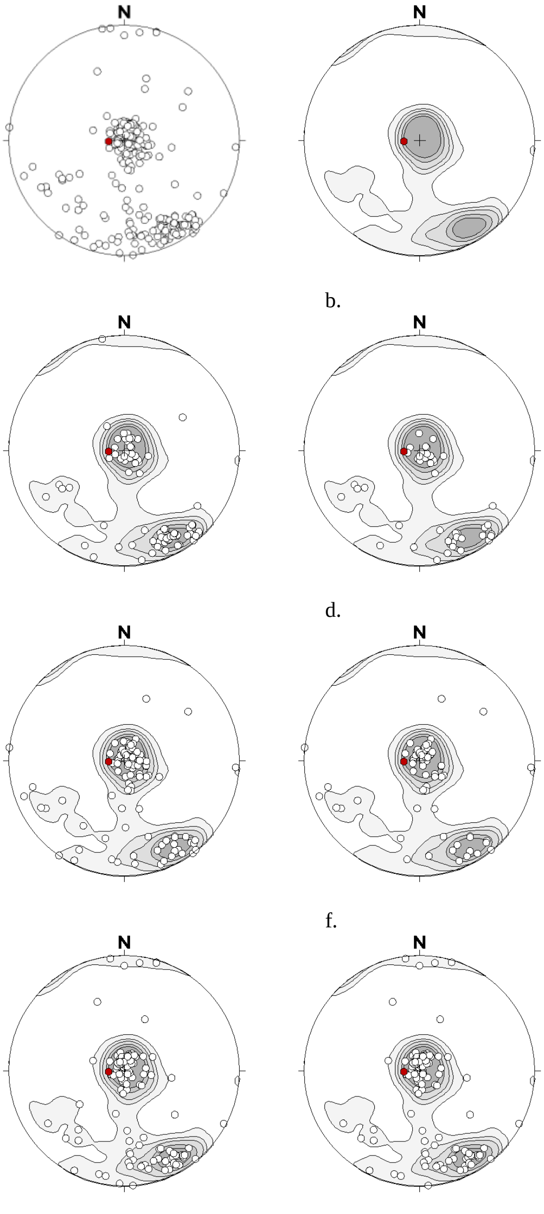
o. Sections with network of sealed fractures.

p. Sections with cataclastic rock.

q. Sections with breccia.

r. Sections with altered host rock, oxidation.

s. SKB's interpreted location of the gently inclined zone ZFMA2 (DZ1: 23 to 48 m and DZ2: 62 to 99 mbl.), ZFMENE1192 (DZ1: 23-48 metres borehole length) and a not modelled zone intersection (DZ4: 121 to 124 metres borehole length).



a. b. c. d. e. f. g. h.

Figure 3-62: Fractures in KFM01C, section 33 to 43 mbl.:

a. All fractures, N=318 (31.8 fr/mbl.).

b. All fractures, contoured.

c. Sealed fractures plotted on all fractures, N=80 (8.0 fr/mbl.).

d. Sealed altered fractures plotted on all fractures, N=43 (4.3 fr/mbl.).

e. Partly open fractures plotted on all fractures, N=115 (11.5 fr/mbl.).

f. Partly open altered fractures plotted on all fractures, N=73 (7.3 fr/mbl.).

g. Open fractures plotted on all fractures, N=122 (12.2 fr/mbl.).

h. Open altered fractures plotted on all fractures, N=113 (11.3 fr/mbl.).

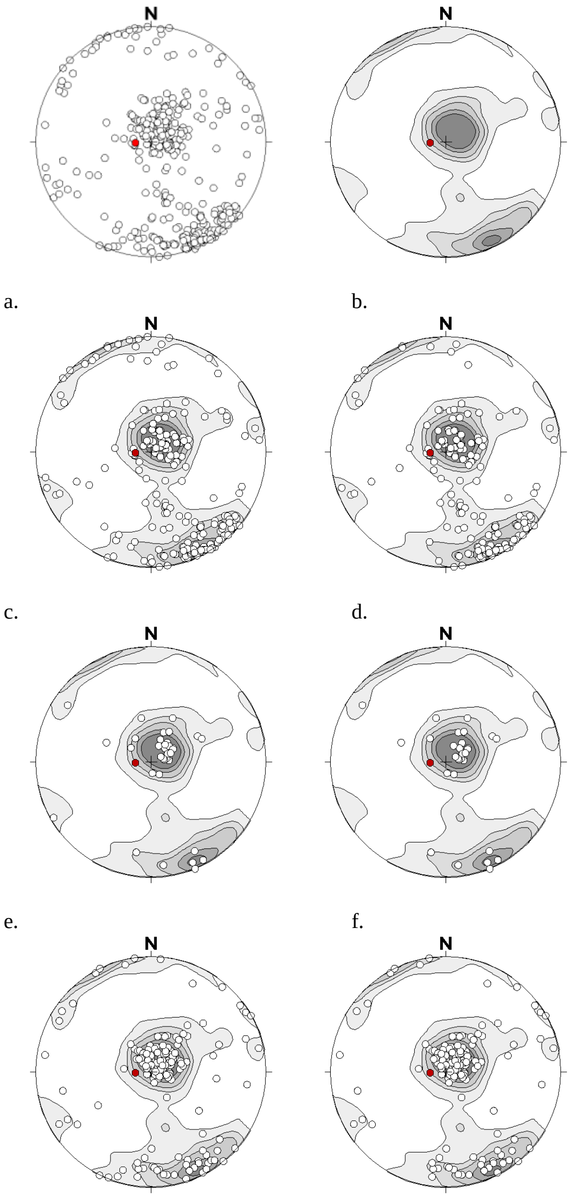


Figure 3-63: Fractures in KFM01C, section 72 to 109 mbl.:

a. All fractures, N=422 (11.4 fr/mbl.)

b. All fractures, contoured.

c. Sealed fractures plotted on all fractures, N=215 (5.8 fr/mbl.).

d. Sealed altered fractures plotted on all fractures, N=163 (4.4 fr/mbl.).

e. Partly open fractures plotted on all fractures, N=37 (1.0 fr/mbl.).

f. Partly open altered fractures plotted on all fractures, N=31 (0.8 fr/mbl.).

g. Open fractures plotted on all fractures, N=170 (4.6 fr/mbl.).

h. Open altered fractures plotted on all fractures, N=151 (4.1 fr/mbl.).

KFM02A - section 350 to 490 m borehole length

Borehole KFM02A is drilled from a drill site located southwest of the SKB local model area and plunges steeply westwards (276/85; Table 3-1 and Fig. 3-3).

Rock type and general structure elements

Rock types

The main rock types in section 350 to 490 mbl. are metamorphic granitoids, generally medium grained. There is a minor section with amphibolite (about 2.5 m wide). There are also thin bands of medium to fine-grained granitoids, pegmatites and amphibolites (cf. Fig. 3-67).

All Fractures

The density of fractures in section 350 to 490 mbl. is 3.5 fr/mbl. (Fig. 3-64). The fracture density is generally higher in the lower part of the section, from about 417 to 490 mbl. There are two main sections of increased fracturing (417.5 to 427.5 m and 437 to 442 mbl.; 11.2 and 10.0 fr/mbl., respectively) and there are also some peak values (at 455, 463, 484 and 486 mbl.).

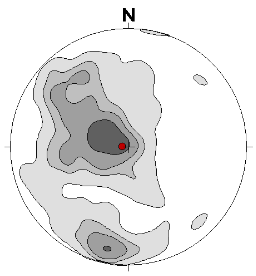


Figure 3-64: All fractures in borehole KFM2A, section 350-490 mbl., N=403 (total number of recorded fracture is 496; 18.75 % missing orientation). The red dot gives the orientation of the borehole.

Open altered fractures

The relative percent of open altered fractures in relation to all noted fractures is 5.85 percent and 7.20 percent in relation to all fractures with noted orientation. The main orientation of open altered fractures is NS/gentleE and subdominant is NNE/moderateSE (Fig. 3-65) and they occur primarily within sections 416 to 427.5 mbl. The fracture density of open altered fractures is only 1.8 fr/mbl. in the section. Minor peaks (2 to 3 fractures) within sections of 0.5 m width occur at 480 and 486 mbl. There are no sections with open altered fractures that have a mutual separation less than 0.20 mbl. for a sequence of four fractures.

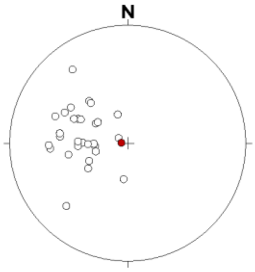


Figure 3-65: Open altered fractures in KFM02A, section 350 to 490 mbl., N=29 (all are oriented). The red dot gives the orientation of the borehole.

Core loss

Core loss is not detected in borehole KFM02A.

Crushed rock

No sections with crushed rock are noted within the interval 350 to 490 mbl. in borehole KFM02A**.**

Sealed networks of fractures

Sections with networks of sealed fractures were not mapped in borehole KFM02A (not included in the core logging activity at the time of logging boreholes KFM01A, 02A and 03A).

Altered sections of the bedrock

The type of bedrock alteration found along the borehole KFM02A is oxidation. There are two wider sections with slightly altered rock (4.5 and 11.5 m wide along the borehole) with sub-horizontal and NE/moderateSE orientations. Two other thin sections (0.09 to 0.45 mbl.) are slightly more altered and have more E-W:ly trends (Fig. 3-66).

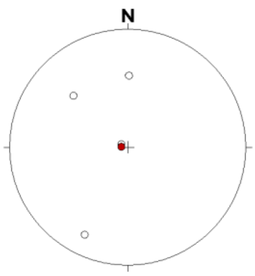


Figure 3-66: Altered sections of the rock in borehole KFM02A, section 350 to 490 mbl., N=4. The red dot gives the orientation of the borehole.

Rock types and lithological contacts

The rock type in the investigated section of borehole KFM02A consists of metamorphosed, mainly medium grained granite to granodiorite.

The orientation of lithological contacts displays two dominant orientations: EW/moderateS and NE/moderate to steepSE (Fig. 3-67). The EW-trends is typical for fine to medium grained granites and pegmatites have commonly NE-trending lithological contacts. Less than 10 percent of the bedrock contains veins and thin rock bands (mean and median widths are 0.11 and 0.05 mbl., respectively).

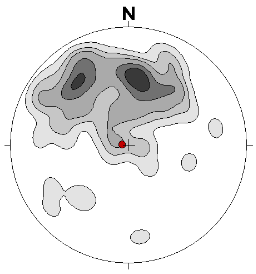


Figure 3-67: Orientation of lithological contacts in borehole KFM02A, section 350 to 490 mbl., N=121 (14 contacts of main rock types + 107 measures of veins and bands of rock /only upper contact given/). The red dot gives the orientation of the borehole.

Cataclastic rocks

No sections with cataclastic rocks are found in section 350 to 490 mbl. in borehole KFM02A.

Brittle-ductile shear zones

No sections with brittle deformation zones are found in section 350 to 490 mbl. in borehole KFM02A.

Sections with breccias

No sections with breccias are found in section 350 to 490 mbl. in borehole KFM02A.

Sections with ductile shear zones

No ductile shear zones are reported for section 350 to 490 mbl. in borehole KFM02A.

Foliation

There are too few data recorded regarding the orientation of the foliation (Fig. 3-68). However, it is obvious from the orientation of lithological contacts that the bedrock does not have a uniform grain (cf. Fig. 3-67).

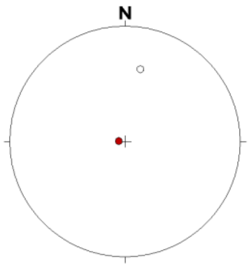


Figure 3-68. Measured foliation in borehole KFM02A, section 350 to 490 mbl., N=1. The red dot gives the orientation of the borehole.

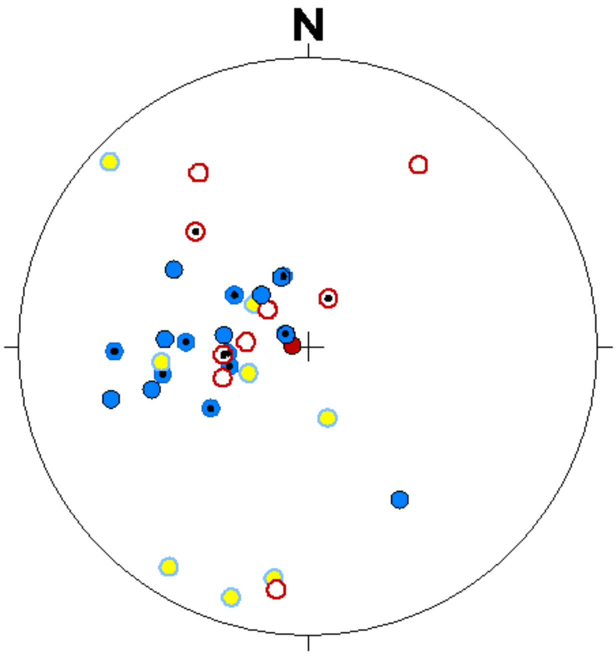
Water-conductive fractures

Water-conductive fractures have been logged by the Posiva Flow Log (PFL; Fig. 3-69) and all indicated flows can be correlated with fractures parting the core (27) or partly open fractures (8; unbroken having voids). However, amongst the fractures mapped as open (18 out of 27), half of them are fresh and half of them are altered. For fracture mapped as sealed (9 out of 27; though breaking the core) most of them are fresh (7) and a couple (2) are altered. All partly open fractures (8) are given the attribute fresh. The altered fractures with indicated flow display a tighter cluster than the fresh fractures with indicated flows do.

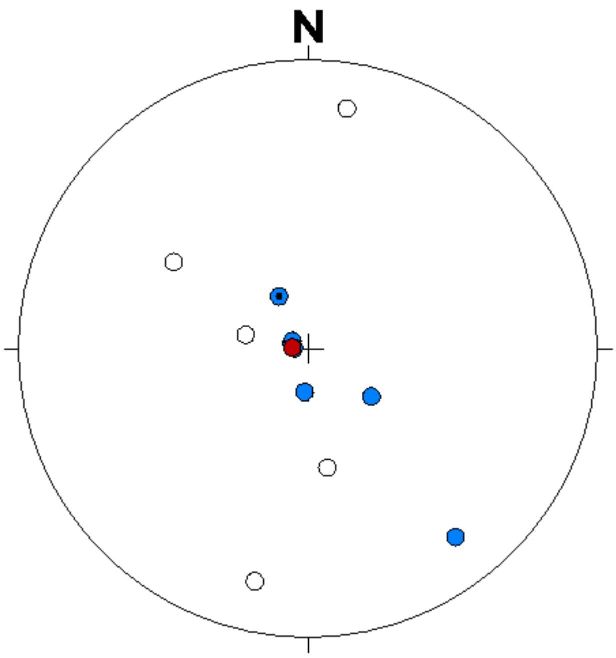
Deviations between the positions of located flow in the borehole and positions of fractures are generally less than 0.1 mbl. (i.e. for 91 % of all correlated fractures), i.e. located within the accuracy of the position for the PFL measurements. However, several (9) of the PFL anomalies could not be correlated with any open or partly open fractures. This matter should be investigated further, but is not within the scope of the present study.

Five radar reflectors intersect the borehole where PFL anomalies are found (at 420, 426, 427, 437 and 484 mbl.) indicating NE-SW trends of the flowing structures with dips varying from sub-horizontal to steeply inclined northwestwards (Fig. 3-69b). However, the orientation of fractures at PFL anomalies deviates from those of the radar reflectors.

The results of the correlation between PFL anomalies and different indications of structures are not uniform. This may be related to scale. Further elaboration on this is beyond the scope of this study.



a.



b.

Figure 3-69: Water-conductive structures indicated by PFL in borehole KFM02A, section 350 to 490 mbl.:

a. Orientation of water-conductive fractures (PFL; N_{PFL}=35);

Blue dots are open fractures, $N_{PFLopen}$= 18 (9 altered),

Yellow dots with light blue rim are partly open fractures, $N_{PFLpartly\ open}$= 8,

Red circles are sealed fractures, $N_{PFL\ sealed}$= 9 (3 altered),

Small central black dots indicates altered fracture, $N_{PFL\ altered}$= 12

Red dot is the orientation of the borehole (276/85).

b. Correlation between PFL anomalies and orientation of borehole radar reflectors (N=5; blue dots, two with alternative orientations /with central black dot; one is hidden by the borehole point, open circles are radar reflectors not related with any PFL anomaly /cf. Fig 3-70/).

Borehole radar

The borehole radar measurements indicate gently inclined to sub-horizontal reflectors (Fig. 3-70) and an approximately E-W trending steeply dipping reflector.

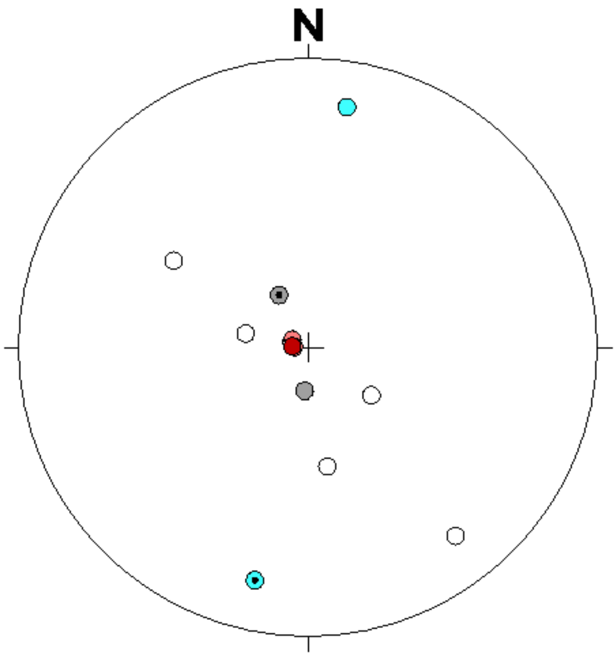


Figure 3-70: Orientation of borehole radar reflectors in borehole KFM02A, section 350 to 490 mbl., N=9. For three reflectors alternative orientations are given. Reflectors with alternative orientations are given by colours and the second orientation is indicated with a black central point. The red dot (orientation of the borehole) covers the pole point for one radar reflector and its alternative orientation.

Fracture minerals

In the borehole section 350 to 490 mbl., 496 fractures are recorded. Of these, 73 are classified as open (14.7 % of all fractures; 29 fractures altered) and 42 as partly open (8.7 % of all fractures; 5 fractures altered).

Fractures without recorded fill are most common (Table 3-7) and constitute about 50 percent of all mapped fractures (250 out of 496). Of these are 13.6 percent altered (34 out of 250; 10 open fractures and 5 partly open). Amongst the sealed fractures without fill, 10.6 percent are altered (19 out of 180). This implies that noted altered sealed fractures without fill are in relative terms the least frequent amongst the sealed fractures compared to open and partly open fractures (30.3 and 13.5 %, respectively). However, in absolute terms the number of altered fractures with no fill is similar for sealed and open plus partly open fractures.

The most common fracture minerals are chlorite (36.5 %) and calcite (23.6 %) and the relative proportions of open altered fractures for fractures with these types of fills are 6.6 and 5.1 percent (12 out of 181 for chlorite and 6 out of 117 for calcite), respectively.

Although the proportion of fractures with clay minerals is small (2.8 %), the relative proportion of open fractures is high (71.4 %). Of the 10 open fractures with chlorite, 6 are altered.

Open fractures with "no fill" (Fig. 3-70) form a distinct cluster at about 418 mbl. (Fig. 3-71). Sealed fractures with "no fill" noted are more spread along the borehole (in the SICADA file "no fill" was either typed in or the field was left blank).

Fractures with oxidized walls or that contain minerals such as prehnite and quartz are mainly cohesive.

Table 3-7: Relation between all, open and partly open fractures, fracture fills and wall rock alteration in cored borehole KFM02A, section 350 to 490 m borehole length (number of sealed fractures = all fractures – (open + partly open fractures)).

	Fractures – number of observations			In percent of total number of fractures (496)		
Fracture fill	**All fractures**	**Open Fractures**	**Partly open fractures**	**All fractures**	**Open fractures**	**Partly open fractures**
Fractures that have a potential to be soft or connect water						
Chlorite	181	32	4	36.5	6.5	0.8
Calcite	118	16	2	23.8	3.2	0.4
Clay minerals	14	10	0	2.8	2.0	
Hematite	20	3	1	4.0	0.6	0.2
No infill	250	33	38	50.4	6.6	7.7
Fractures that have a potential to be stiff and tight						
Oxidized walls	32	3	0	6.5	0.6	
Prehnite	13	0	0	2.6		
Quartz	9	0	0			
Laumontite	4	0	0			
Unknown mineral	5	1	0	1.0	0.2	
Accessorial mineral						
Epidote	3	1	0	0.6	0.2	
Garnet	1	0	0	0.1		

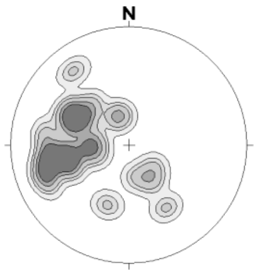


Figure 3-70: Open fractures with no fill in borehole KFM02A, section 350 to 490 mbl., N=33.

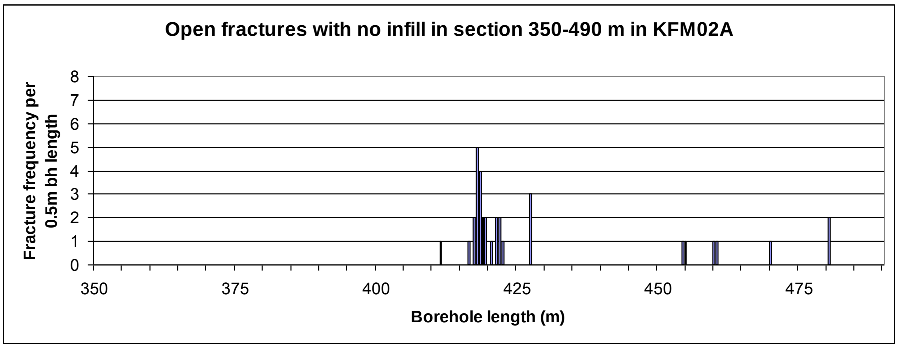


Figure 3-71: Distribution of fractures with “no infill” along borehole KFM02A, sector 350 to 490 mbl. (N=33).

Brittle deformation zones in the SKB model

One deformation zone (DZ: SKB database SICADA file p_eshi-KFM02A.xls) occurs between 350 to 490 mbl. in borehole KFM02A:

- DZ6: 415 to 520 m within which the gently dipping zone ZFMA2 (orientation: 80/24) occupies the borehole section from 417 to 442 mbl. and the sub-horizontal zone ZFMF1 (orientation: 70/10) is located below at 476 to 520 mbl. (Stephens et al. 2007 and Stephens et al. 2008).

The section 442 to 476 mbl. of deformation zone DZ6 is not used in the SKB structural model. The structural relation between zones ZFMA2 and ZFMF1 is not fully clear. However, it is indicated that zones ZFMA2 and ZFMF1 intersect to the southeast of borehole KFM02A.

In a study of the character and kinematics of deformation zones, Nordgulen and Saintot (2006) pointed out that a large part of DZ6 has a very low fracture frequency (430 to 480 mbl.) and they question whether this is part of a deformation zone, i.e. a borehole segment that is somewhat wider than the borehole distance between zones ZFMA2 and ZFMF1. Furthermore, they also pointed out that even in the upper and lower parts of DZ6 there are segments with very few fractures (the thickness of the two SKB zones are less than presented). Two core zones are also given at about 422 to 424.5 mbl. (strong crush along fractures) and 461.5 to 463 mbl. (some steep minor faults). These structures are not explicitly expressed in the core log.

Location of brittle deformation and zones of weakness

Geological data indicating structural features that may point to zones of weakness and brittle deformation zones in the rock (as well as relation between such features and their imprint on the rock for borehole section 350 to 490 m along borehole KFM02A) is compiled in Figure 3-72. The text is focused on discrete fractures (fractures mapped as single structures); how they are clustered and how they are related to other geological observations. These observations concern:

- Sections with altered host rock.
- Locations of water-conductive sections in the borehole (PFL anomalies).

In borehole section 350 to 490 mbl. there are no noted core losses, brittle-ductile shears, ductile shear, breccia, cataclastic rocks or sealed network of fractures.

The general fracturing in section 350 to 450 mbl. in borehole KFM01C is relatively low (3.54 fr/mbl.). The density of open fractures is very low (0.52 fr/mbl.) and for open altered fractures even lower (0.21 fr/mbl.). However, the fracturing along the investigated borehole section is inhomogeneous. The upper part of the investigated section, i.e. 350 to 417 mbl., has low fracture frequencies: 1.26 fr/mbl. for all fractures and one altered fracture at 416 mbl. Corresponding numbers for the lower part of the investigated section in borehole KFM02A, 417 to 490 mbl., are 5.56 fr/mbl. for all fractures and 0.38 fr/mbl. for open altered fractures.

The clustering of all fractures and open altered fractures has been classified according to the mutual separation of fractures along the borehole (Table 3-8 and Figs. 3-72; the applied methodology is described in Chapter 2). Due to the low fracture density of open altered fractures, the clustering is calculated for a minimum of four fractures with maximum mutual separations of 0.5 m corresponding to a fracture frequency of two or more fractures per metre borehole length.

Clustering of all fractures (Figs. 3-72a and 3-72b) occur primarily at borehole lengths below 411 m and the highest density of clusters is located from 417 to 427 mbl. A somewhat shorter borehole section with clusters is located from 436 to 441 mbl. Other clusters of all fractures are relatively evenly distributed in the lower part of the investigated section (below 448 mbl.). A single cluster of fractures is located above 417 mbl., at 377 m.

The few open altered fractures in the investigated section of borehole KFM02A indicate no clusters when applying the definition of clusters given in Chapter 2. However, adjusting the fracture density to two fractures per metre borehole length (minimum separation of 0.5 mbl. for adjacent fractures counted for at least four fractures) results in two minor clusters having widths of about 0.5 mbl. Fractures in the upper cluster (at 421 mbl.) have a relative uniform orientation (NNE to NE/38 to 55SE), while fractures in the lower section (425 mbl.) are all gently to moderately inclined (23 to 35°) mainly with eastward dips.

Table 3-8. Character of clusters of fractures in borehole KFM02A, section 350 to 490 m borehole length (cf. Fig 3-72). Two groups of fractures are treated: all fractures and open altered fractures. Identification of clusters is based on two criteria: 1. The minimum mutual separation between fractures, 0.10, 0.20 and 0.50 m borehole length (corresponding to minimum fracture frequency of 10, 5 and 2 fractures per metre borehole length, respectively) and 2. The minimum number of fractures to outline a cluster (4 fractures).

Cluster				Borehole KFM02A					
ID[2]	Group of fractures	Criterion to identify clusters		Borehole section 350 to 490 m borehole length					
		Minimum number of fractures to outline a cluster[1]	Minimum fracture frequency (fr/mbl.)[3]	Number of clusters	Length of clusters (mbl.)	Length of clusters in percent of section length (%)	Mean fracture frequency in section (fr/mbl.)	Mean fracture frequency in clusters (fr/mbl.)	Fractures in clusters in percent of fractures in section (%)
2A:1	*All.*	4	10	29	5.7	4.0	3.5	25.3	34.7
2A:2		4	5	31	17.7	12.7	3.5	14.7	58.9
2A:3	*Open and altered.*	4	10	0	-	-	0.5	-	-
2A:4		4	5	0	-	-	0.5	-	-
2A:5		4	2[4]	2	1.1	0.8	0.2	5.7	27.6

[1] Minimum number of fractures to outline a cluster – 4 fractures = 3 core pieces. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of clusters).

[2] ID of group of clusters.

[3] fr/mbl. = fractures per metre borehole length.

[4] Clusters formed by fractures with mutual maximum separations of 0.5 mbl.

Altered rock is found within the two sections with increased density of general fracturing at about 422 and 441 mbl.

Water-conductive sections in the borehole (PFL anomalies) are all located below 411 mbl. and about 80 percent of the PFL anomalies are located within clusters of fractures (all fractures; clusters with ≥ 5 fr/mbl., Figs. 3-72b and 3-72e).

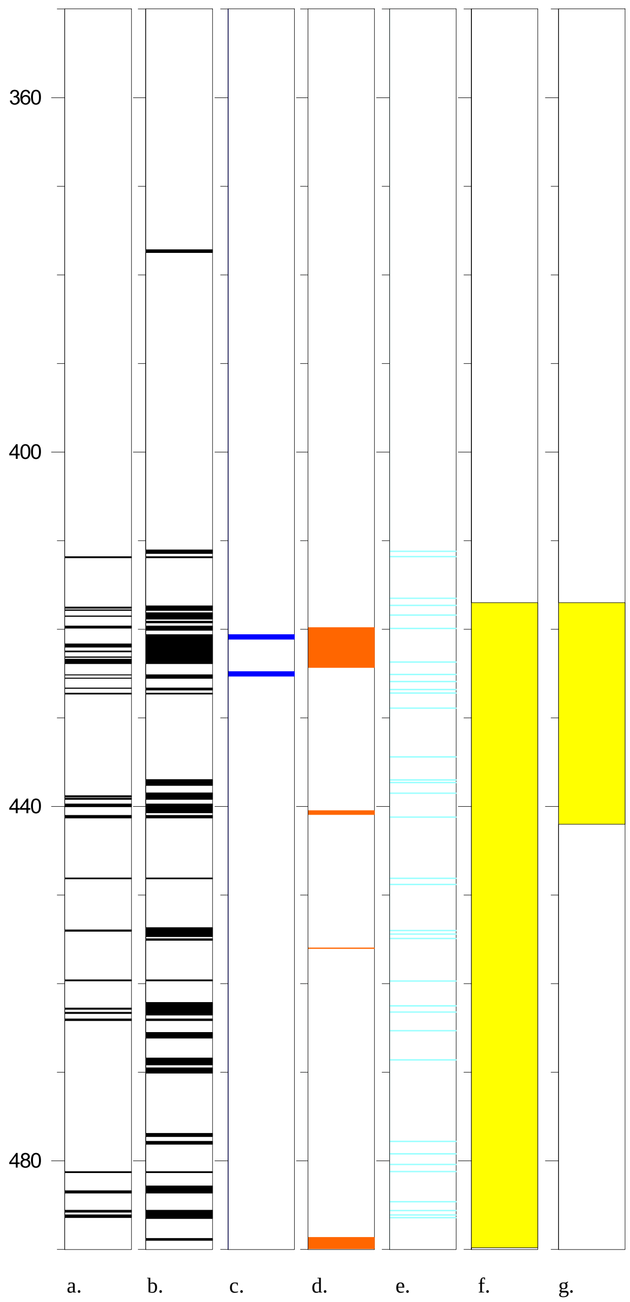


Figure 3-72: Borehole KFM02A section 350 to 490 mbl.; Clusters of fractures (Table: 3-8), core losses, section of crushed rock, PFL and location of SKB ESHI (incl. zone ZFMA2):

a. All fractures (cluster 2A:1), fracture separation less than 0.10 m (fracture frequency>10 fr/mbl.).

b. All fractures (cluster 2A:2), fracture separation less than 0.20 m (fracture frequency>5 fr/mbl.).

c. Open altered fractures (gently to moderately dipping eastwards (cluster 2A:5), separation less than 0.50 m (fracture frequency>2 fr/mbl.).

d. Sections with altered host rock.

e. Indicated water-conductive fractures (PFL, point measurements, here given a width of 0.2 m).

f. SKB's interpreted location of intersection of deformation zones (DZ6: 415-520 mbl. containing SKB zone ZFMA2 between 417 to 422 mbl. and ZFMF1 between 476 to 520 m borehole lenths).

g. Position of the gently inclined zone ZFMA2 (417-442 mbl.)

Fractures and sections with increased fracturing

In a borehole with a low average fracture density for all fractures it may be of interest to compare the orientation of fractures within clusters (cf. Table 3-8, Figs. 3-74 and 3-75) with fractures outside the clusters (Figs. 3-73 and 3-77).

Fractures outside 2A:1 and 2A:2 clusters (Fig. 3-73, cf. Table 3-8 and Fig. 3-72) form several sets. Dominant sets are:

1. Sub-horizontal fractures dipping gently south-eastwards.
2. WNW to EW/steepN.
3. NE/steepSE.

Minor sets are:

- NNW/steepE.
- EW/moderateS.

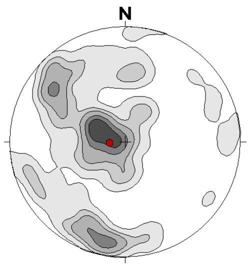


Figure 3-73: Fractures outside clusters (2A:2; >5 fr/mbl.) in borehole KFM02A, section 350 to 490 mbl., N=138 (total noted fractures are 201). The red dot is the orientation of the borehole.

Fractures inside clusters 2A:1 and 2A:2 clusters (≥5 fr/mbl. and ≥10/fr/mbl., Figs. 3-74 and 3-75, cf. Table 3-8 and Fig. 3-72) have similar orientation. Fractures dipping gently southeast dominate and subdominant are sub-vertical fractures trending east-west. However, clusters do not have pronounced numbers of fractures oriented NE/steepSE, NNW/steepE and EW/moderateS.

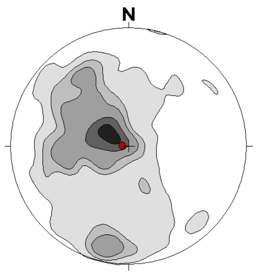


Figure 3-74: Fractures inside clusters (2A:2; with >5 fr/mbl.) in borehole KFM02A, section 350 to 490 mbl., N=265 (total noted fractures is 295). The red dot is the orientation of the borehole.

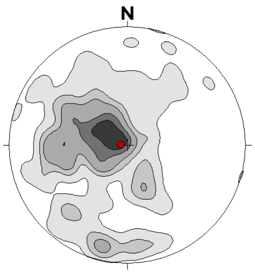


Figure 3-75: Fractures inside clusters with more than10 fr/mbl. in borehole KFM02A, section 350-290 mbl., N=159 (total noted fractures 172, 13 without orientation). The red dot is the orientation of the borehole.

Altered fractures located outside fracture clusters have a dominant moderate dip eastwards (Fig. 3-76) and differs thereby from the general fracturing (Fig. 3-73). Open altered fractures forming clusters have a slight shift in dip direction, dipping more towards southeast (Fig. 3-77).

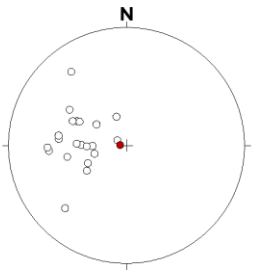


Figure 3-76: Open altered fractures outside section with more than 2 fr/mbl. (2A:5) in borehole KFM02A, section 350 to 490 mbl., N=21. The red dot is the orientation of the borehole.

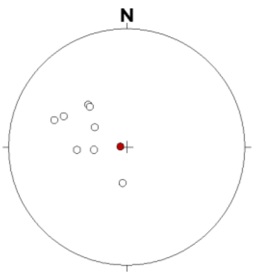


Figure 3-77: Open altered fractures in section with more than 2 fr/mbl. (2A:5) in borehole KFM02A, section 350 to 490 mbl., N=8. The red dot is the orientation of the borehole.

Character of SKB DZ

The mechanically weakest parts of the borehole KFM02A, within the section 350 to 490 mbl., appear to be two 0.5 m wide segments at 221 and 225 mbl., respectively, and the weaknesses consist of a few altered moderately inclined fractures. The main part in between the two segments consists of altered rock. Water-conductive fractures (indicated by the PLF anomalies) are grouped above and below the two segments, which in turn are located in the upper part of the SKB zone ZFMA2 (417 to 442 mbl., Stephens et al 2007; cf. Fig. 3-72). The central part of zone ZFMA2 displays in borehole KFM02A a low fracture density while the lower part of the zone displays a marked increase in fracture density, although most of the fractures are sealed. Furthermore, open fractures inside zone ZFMA2 have orientations that are indicated to differ from the orientation of the zone; in most cases such fractures are steeper. PFL anomalies are relatively randomly distributed within the central and lower part of the investigated section and they correlate fairly well with the general fracturing in the rock (all fractures; cluster with > 5 fr/mbl., 2A:2 in Table 3-8).

However, the core log gives that 80.9 percent of all mapped fracture (401 out of 496 mapped fractures) part the core.

Characterization of the gentle zone ZFMF1 (476 to 520 mbl., Stephens et al. 2007) is not included in this study and it does not appear to be a distinct structure according to data presented in the study.

Comments

In summary, the investigated section in borehole KFM02A may reflect the existence of several structures or branches of structures, of which many are sealed (e.g. sub-vertical structures and also gently inclined structures). The upper part of zone ZFMA2 is indicated as a mechanically weaker part of the rock.

KFM02B - section 360 to 480 m borehole length

Borehole KFM02B is drilled from the same drill site as borehole KFM02A located southwest of the SKB local model area and the borehole plunges steeply north-westwards (313/80; Table 3-1 and Fig. 3-3).

Rock types and general structure elements

Rock types

The rock types in section 360 to 480 mbl. vary along the borehole (Stephens et al. 2008). In the upper part of the investigated borehole section (360 to 392 mbl.) fine to medium-grained granite dominates, followed by a central part with pegmatite and pegmatitic granite (392 to 427 mbl.) and then, in the lower part of the section, metamorphosed medium-grained granite to granodiorite (428 to 480 mbl.).

In the lower borehole section (448 to 466 mbl.) with metamorphosed granitoids there are also two bands of meta-basic rocks (amphibolite and diorite to gabbro, up to some metres wide (1.5 and 4.2 mbl.; the wider at about 464 mbl.). Decimetre-wide granitic bands are common (on average about one to two bands per metre borehole length), most frequent in the upper and lower part of the section (cf. Fig 3-83).

All fractures

The total population of fractures in the interval 360 to 480 mbl. of the cored borehole KFM02B consists of 599 fractures and is dominated by fractures dipping gently north-eastwards and subdominant are fractures steeply dipping eastwards to east-southeastwards (Fig. 3-78).

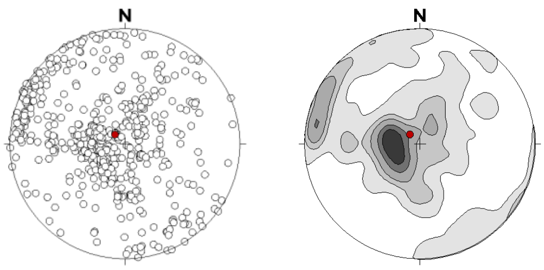


Figure 3-78: All fractures in borehole KFM02B, section 360 to 480 mbl., N=599. Borehole orientation is steep northwest (313/80; red dot).

Open altered fractures

There are 92 open altered fractures in section 360 to 480 mbl. in borehole KFM02B (Fig. 3-79), i.e. they constitute 16 percent of all mapped fractures.

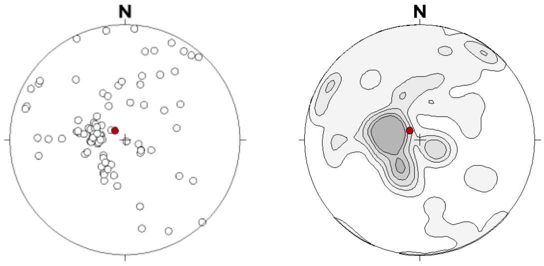


Figure 3-79: Open altered fractures in borehole KFM02B, section 360 to 480 mbl., N=96. Borehole orientation is steep northwest (313/80; red dot).

Dominant are fractures dipping gently east-south-eastwards (15/23) and sub-dominant are two additional gently inclined fracture sets dipping north-north-east-wards and west-north-westwards, respectively. Remaining open altered fractures are scattered in orientation and there are some faint clusters for sub-vertical fractures dipping east-south-eastwards and west-south-westwards.

Core loss

Seven sections are classified as mechanical crushing of the core (caused by drilling) and six of these are noted in the interval 430 to 470 mbl. (0.25 to 0.40 cm wide and the range in separation is 4.5 to 13.5 mbl.).

Crushed rock

Three minor sections of crushed rock (range in width from 0.03 to 0.09 mbl.) have been mapped (Fig. 3-80); one at about 449.5 mbl. and two at about 471.5 mbl.

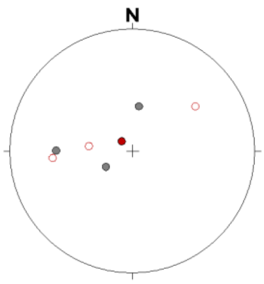


Figure 3-80: Orientation of section with crushed rock in borehole KFM2B, section 360 to 480 mbl., N=3 (open red circles are the upper contacts and grey dots are the lower contact). Borehole orientation is steep north-west (313/80; red dot).

Sealed networks of fractures

Nine sections containing sealed networks of fractures are recorded ranging in width along the drill core from 0.01 to about 0.5 mbl. and they occur mostly in the interval 464 to 466.5 mbl. (4 sections with a total width of 0.82 mbl.). The networks of sealed fractures are either gently inclined or sub-

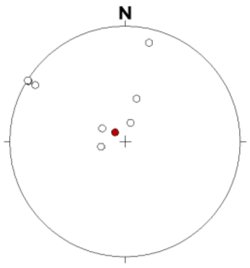


Figure 3-81: Orientation of sealed networks of fractures in borehole KFM2B, section 360 to 480 mbl., N=12. Borehole orientation is steep northwest (313/80; red dot).

vertical (Fig. 3-81). Notable is the set of sub-vertical networks trending northeast-southwest; all three with mutual separations larger than 35 mbl.

Altered sections of the borehole

Sections with altered rocks are commonly relatively thin, less than one metre borehole length (Fig. 3-82). However, there is a wider section from 410 to 427 mbl. with oxidized rock and where the intensity is characterized as weak. Oxidation, the most common type or alteration of the host rock, may also be strong and occur as thin bands (less than 0.05 m wide). Other types of alteration are albitization, saussuritization and argillization. The two latter types may make the rock softer (two bands with widths about 0.1 mbl.). Most of the sections with altered rock dip moderately to steeply eastwards.

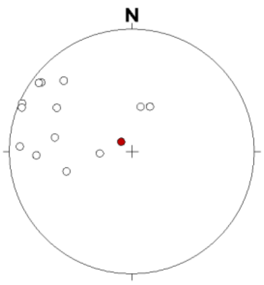


Figure 3-82: Orientations of sections with altered rock in borehole KFM2B, section 360 to 480 mbl., N=13. Borehole orientation is steep northwest (313/80; red dot).

Rock types and lithological contacts

The upper part of the borehole section (360 to 427 mbl.) is characterized by fine to medium-grained granitic and pegmatitic granitic rock, while the lower part of the section is denoted as metamorphic medium-grained granitic to granodioritic rock. The lithological contacts have dominant steep southeast inclinations (Fig. 3-83).

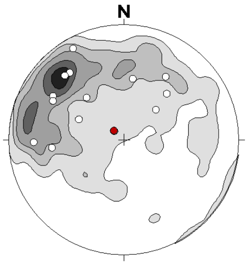


Figure 3-83: Orientations of lithological contacts in borehole KFM2B, section 360 to 480 mbl., N=341 (open circles are orientation of lithological contacts between main rock types and contoured are 326 lithological contacts for minor thinner rock bands /163 bands; upper and lower contacts). Borehole orientation is steep northwest (313/80; red dot).

Cataclastic rock

No cataclastic rocks have been recorded.

Brittle-ductile shear zones

No brittle-ductile shear zones have been recorded.

Sections with breccia

No sections with breccia have been recorded.

Sections with ductile shear zones

No sections with ductile shear zones have been recorded.

Foliation

The tectonic foliation in the rock is uniformly dipping south-westwards. However, there is a banding in the rock with a steep eastward dip (Fig. 3-84).

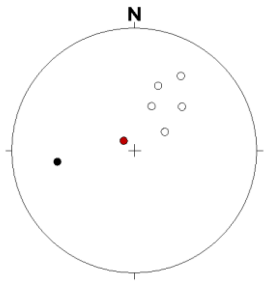


Figure 3-84: Orientations of foliation in borehole KFM2B, section 360 to 480 mbl., N=5+1 (5 measures of the foliation /open circles/ and 1 measure of the banding in the rock /black dot/). Borehole orientation is steep northwest (313/80; red dot).

Water-conductive fractures

Between 360 to 480 mbl. in the borehole KFM02B there are 19 water-conductive features recorded by the Posiva Flow Log (PFL) (Fig. 3-85). These flow indications are generally correlated with open altered fractures (one is not). The separations between these fractures within the interval 410 to 428 mbl. are less than 4.5 m (N=14; mean and median separations are 1.2 and 1.3 mbl., respectively). The largest separations between PFL anomalies (more than 32 mbl.) are found in the upper and lower parts of the investigated section. Most of the fractures that are indicated to be hydraulically connected are gently inclined with dominance for fractures dipping eastwards (Fig. 3-85).

Four PFL anomalies correlate with borehole radar reflectors (cf. below) and for two of these (at 421 and 430 mbl., respectively) the orientation of open fractures agrees with the orientation of the radar reflectors; gently dipping eastwards.

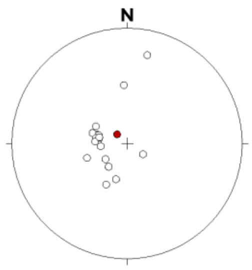


Figure 3-85: Orientations of PFL fractures in borehole KFM2B, section 360 to 480 mbl., N=18. Borehole orientation is steep northwest (313/80; red dot).

Borehole radar

Seven borehole radar reflectors are detected in the investigated sector, 360 to 480 mbl., and for four of the reflectors alternative orientations are presented (Fig. 3-86). Mean and median separations of the reflectors are 16.5 and 18.6 mbl., respectively. Five of the radar reflectors agree with intersections of open altered fractures in the borehole wall; gently inclined eastwards, steeply dipping eastwards and sub-vertical fractures trending northeast-southwest.

Fracture minerals

Table 3-9 presents the distribution of fracture minerals and occurrence of alteration of the wall rock (oxidized or bleached) for all fractures and also for open and partly open fractures.

The most common fracture minerals are chlorite and calcite. These minerals often occur together, but in most cases they occur as single mineral or together with some other minerals, for example clay minerals. Fractures containing calcite, chlorite and clay minerals are dominated by open fractures

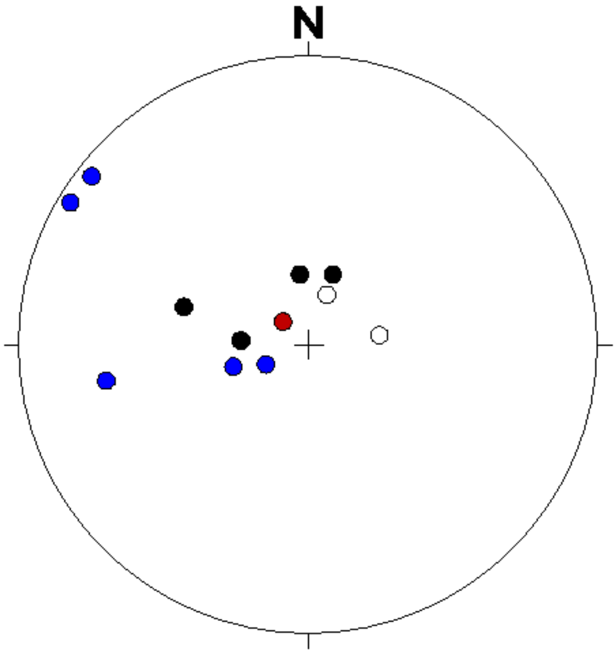


Figure 3-86: Orientations of radar reflectors in borehole KFM02B, section 360 to 480 mbl., N=7 (Blue dots, N=5, are radar reflectors correlated with open altered fractures; circles, N=2, are reflectors with no correlation to open fractures; and black dots are alternative orientation of reflectors, N=4, and none of these are correlated with any open altered fracture). Borehole orientation is steep northwest (313/80; red dot).

(53 to 83 %; highest for fractures containing clay minerals). Open fractures with these minerals have also a high relative percentage of altered fractures (56 to 86 %; highest for fractures with clay minerals). Fractures with no fill are also common (15.2 % of all fractures) and 62 percent of these fractures are open. The latter type is most frequent between 416 and 430 mbl. (cf. borehole KFM02A Fig. 3-71). However, the open fractures with no fill are generally classified as fresh (98 %). Fractures with clay minerals are most frequent at 417, 463 and 471 mbl.

Open fractures with oxidized walls are most frequent between 412 and 421.5 mbl. and most of these fractures contain chlorite and are altered. However, fractures with oxidized walls have a relatively high percent (77.3 %) of sealed fractures. There are several other minerals associated with a high relative percent of sealed fractures (Table 3-9), although such fractures are not frequently occurring.

Table 3-9: Relation between all, open and partly open fractures and their fracture fills and wall rock alteration of cored borehole KFM02B, section 360 to 480 m borehole length (number of sealed fractures = all fractures – (open + partly open fractures)).

	Fractures – number of observations			In percent of total number of fractures (559)		
Type of fracture / Type of fracture fill	**All fractures**	**Open fractures**	**Partly open fractures**	**All fractures**	**Open fractures**	**Partly open fractures**
Fractures that have a potential to be soft or connect water						
Chlorite	178	114	1	31.8	20.4	0.2
Calcite	162	85	1	29.0	15.2	0.2
Clay minerals	53	44	0	9.5	7.9	
No infill	136	85	13	24.3	15.2	2.3
Fractures that have a potential to be stiff or tight						
Oxidized walls	132	30	0	23.6	5.4	0
Prehnite	58	11	0	10.4	2.0	0
Laumontite	47	6	0	8.4	1.1	0
Epidote	35	2	0	6.3	0.4	
Hematite	27	4	0	4.8	0.7	0
Adularia	22	3	1	3.9	0.5	0.2
Quartz	20	7	0	3.6	1.3	0
Accessorial mineral/features						
Pyrite	5	2	0	0.9	0.4	0
Red feldspar	1	0	0	0.2	0	0
White feldspar	1	0	0	0.2	0	0
Red feldspar	1	0	0	0.2	0	0
Polished walls	1	0	0	0.2	0	0
Bleached walls	9	0	0	1.6	0	0

Brittle deformation zones in the SKB model

Three deformation zones (DZ: SKB database SICADA file p_eshi-KFM02B.xls) occur between 360 to 480 mbl. in borehole KFM02B:

1. DZ3: 411 to 431 mbl. corresponding to the gently inclined zone ZFMA2 (orientation: 80/24; Stephens et al. 2007).
2. DZ 4: 447 to 451 mbl. A section not included in the SKB site model.
3. DZ5: 462 to 473 mbl. corresponding to the sub-horizontal zone ZFMF1 (orientation: 70/10; Stephens et al. 2007).

A study of the character and kinematics of deformation zones have been performed in borehole KFM02B (Nordgulen and Saintot 2007). It was found that:

- DZ3 exhibits an increased and relatively uniform frequency of predominantly gently dipping open and sealed fractures. Neither striated faults nor core zones were found in DZ3. However, there is a relatively high percent of fractures without any fill.
- DZ4 has a general increased fracture frequency of variably oriented open and sealed fractures and a 15 cm wide crush zone at the top of an amphibolite (449.50 mbl.). Shear striated fractures are found and also absences of fracture fill in several fractures.
- DZ5 transects the foliation and have increased fracture frequency dominated by gently inclined fractures. The fracture frequency is inhomogeneous, lower in the central part of DZ5 and there is a 0.7 mbl. wide crush zone in the lower part. Displacement is indicated by shear striations.

Location of brittle deformation and zones of weakness

Geological data indicating structural features that may point to zones of weakness and brittle deformation zones in the rock and the relations between such structures and their imprint on the rock for borehole section 360 to 480 m along borehole KFM02B is compiled in Figure 3-87. The text is focused on discrete fractures (fractures mapped as single structures); how they are clustered and how they are related to other geological features. Figure 3-87 displays:

- Clustering of all fractures and open altered fractures.
- Sections with core loss.
- Sections with crushed rock.
- Sections with network of sealed fractures.
- Sections with altered host rock.
- Location of water-conductive sections in the borehole (PFL anomalies).
- Location of SKB zones (see text above).

The general fracturing in section 360 to 480 mbl. in borehole KFM02B is modest, on average 4.7 fr/mbl. The fracture frequency of open fractures is less than half of the frequency for all fractures, i.e. an average of 2.0 fractures per metre borehole. In turn, the frequency of open altered fractures is less than half of the frequency of open fractures, i.e. an average of 0.8 fr/mbl.

Clustering of all fractures (≥10 fr/mbl. and 5≥fr/mbl.; clusters 2B:1 and 2B:2, Table 3-10) displays four wider clusters or sections with gathered clusters: 361.8 to 363.6 mbl., 412.1 to 430.7 mbl., 448.4 to 451.1 mbl. and 463.4 to 473.0 mbl. All fractures consist of two groups (spread in trends too large to define sets): low angle fracture (dip<40°; 53.6 % of all fractures for low-angle fractures and 17.1 % of all fractures for the open altered fractures) and steeply dipping fractures (dip>70°; 28.2 % of all fracture for steeply dipping fractures and 2.7 percent of all fractures for the open altered factures).

Steeply dipping fractures occur primarily as three peaks (364, 370 and 393 mbl.) and in three intervals (396 to 398 mbl., 449 to 451 mbl. and 467 to 473 mbl.). Open altered steeply dipping fractures do not form clusters and pairs of such fractures are found at 370 and 418 mbl., i.e. such fractures may occur outside the clusters formed by all steeply dipping fractures.

Open altered fractures, especially with low to moderate inclination (dip<40°; Figs. 3-87c to 3-87f), are located in the central and lower parts of the investigated section of the borehole, i.e. found as minor sections (0.1 to 0.5 m wide) in the intervals 417 to 426 mbl. and 463 to 471 mbl. The width and location of clusters formed by different types of open fractures (>10 fr/mbl. and >5 fr/mbl.; 2B:3 to 2B:6, Table 3:10 and Fig 3-87c-f) agree, which indicates that the clusters are distinct brittle structures containing mainly low-angle fractures.

Sections with core loss are found outside the clusters of open altered fracture and are in some cases associated with increased general fracturing in the rock (cf. Figs 3-87g and 3-87a-b). Crushed rock are found in three thin section (<0.1 mbl. wide) consistent with increased general fracturing in the borehole. The lower sections with crush rock coincide with a cluster of open altered low-angle fractures at 273.5 mbl.

Sections with networks of sealed fractures (Fig. 3-87k) occur primarily in the borehole sector 464 to 466 mbl. There is no correlation between sealed networks of fractures and alteration of the bedrock (Fig. 3-87l). However, both occur in sections of increased fracturing.

PFL anomalies are dominantly appearing (75 %; 15 out of 20, Fig. 3-87m) in section 411 to 429 mbl., i.e. coinciding with the main segment of altered rock in the investigated section of borehole KFM02B. The PFL anomalies occur as swarms and the correlation between clusters of open altered fractures and PFL anomalies is low. However, three out of the five clusters formed by low angle open altered fractures agree in position with PFL anomalies (Figs. 3-87i and 3-87f).

Table 3-10. Character of clusters of fractures in borehole KFM02B section 360 to 480 m borehole length (cf. Fig 3-87). Two groups of fractures are treated: all fractures and open altered fractures (incl. all and low angle open altered fractures). Identification of clusters is based on two criteria: 1. The minimum mutual separation between fractures, 0.10 and 0.20 m (corresponding to minimum fracture frequency of 10 and 5 fractures per metre borehole length, respectively) and 2. The minimum number of fractures to outline a cluster (4 fractures).

Cluster				Borehole KFM02B					
ID[2]	Group of fractures	Criterion to identify clusters		Borehole section 360 to 480 m borehole length					
		Minimum number of fractures to outline a cluster[1]	Minimum fracture frequency (fr/mbl.)[3]	Number of clusters	Length of clusters (mbl.)	Length of clusters in percent of section length (%)	Mean fracture frequency in section (fr/mbl.)	Mean fracture frequency in clusters (fr/mbl.)	Fractures in clusters in percent of fractures in section (%)
2B:1	*All.*	4	10	34	8.5	7.1	4.7	30.7	58.9
2B:2		4	5	23	25.4	21.9	4.7	16.0	76.7
2B:3	*Open and*	4	10	5	0.9	0.8	0.8	25.5	30.2
2B:4	*altered*:All,	4	5	5	2.0	1.7	0.8	17.1	40.6
2B:5	Dip <40°,	4	10	4	0.7	0.6	0.5	22.8	32.3
2B:6		4	5	5	1.2	1.0	0.5	18.6	41.5

[1] Minimum number of fractures to outline a cluster – 4 fractures = 3 core pieces. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of clusters).

[2] ID of group of clusters.

[3] fr/mbl. = fractures per metre borehole length.

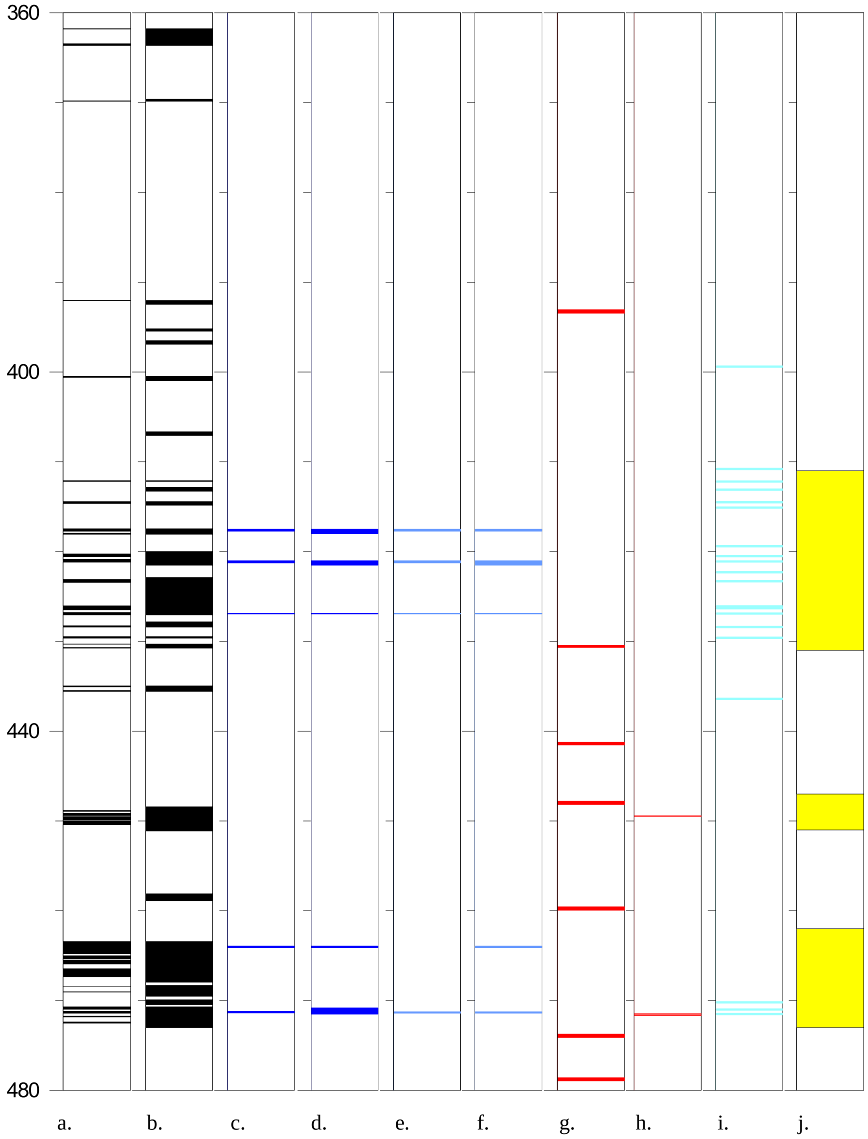


Figure 3-87: Borehole KFM02B section 360 to 480 mbl.; Clusters of fractures (cf. Table 3-10), core losses, section of crushed rock, PFL and location of SKB ESHI (incl. zone ZFMA2):

a. All fractures (cluster 2A:1), fracture separation less than 0.10 m (fracture frequency>10 fr/mbl.).

b. All fractures (cluster 2A:2), fracture separation less than 0.20 m (fracture frequency>5 fr/mbl.).

c. Open altered fractures (cluster 2A:3), separation less than 0.10 m (fracture frequency>10 fr/mbl.).

d. Open altered fractures (cluster 2A:4), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

e. Open altered fractures with dips less than 40° (cluster 2A:5), separation less than 0.11 m (fracture frequency>10 fr/mbl.).

f. Open altered fractures with dips less than 40° (cluster 2A:6), separation less than 0.22 m (fracture frequency>5 fr/mbl.).

g. Sections with core loss (mainly mechanical, caused by drilling).

h. Sections with crushed rock.

i. Indicated water conductive fractures (PFL, point measurements, here given a width of 0.2 m).

j. SKB's interpreted location of the gently inclined zone ZFMA2 (DZ3: 411 to 431 mbl.), a section mot included in the structural model (DZ4: 447-451) and another gently inclined zone ZFMF1 (DZ5: 462 to 473 m). To be continued.

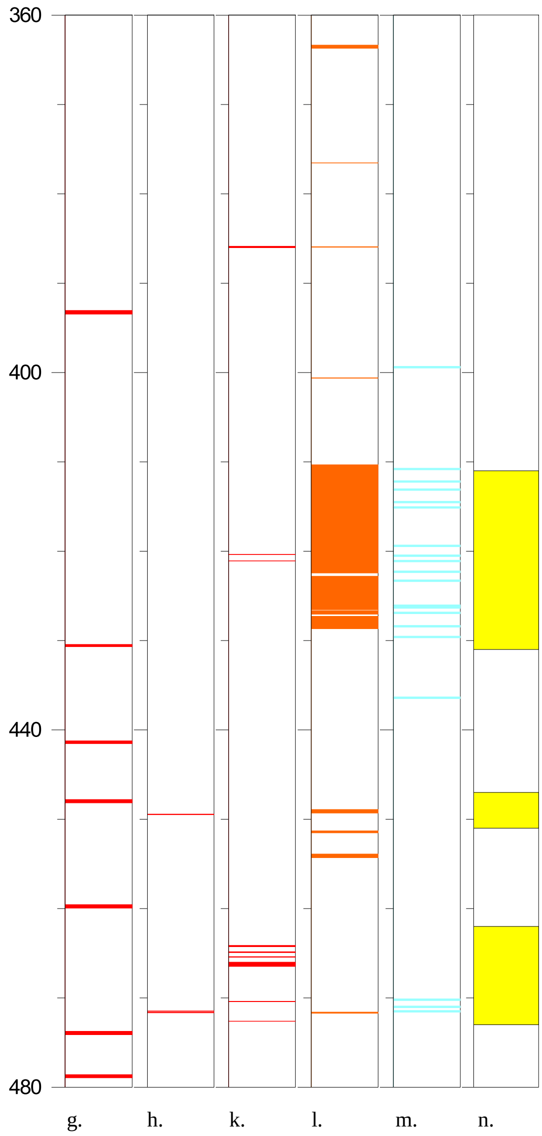


Figure 3-87 (continued): Borehole KFM02B section 360 to 480 mbl.; Fractures, core losses, section of crushed rock, PFL and location of SKB ESHI (incl. zone ZFMA2):

g. Sections with core loss (mainly mechanical, caused by drilling).

h. Sections with crushed rock.

k. Sections with network of sealed fractures.

l. Sections with altered host rock, oxidation.

m. Indicated water conductive fractures (PFL, point measurements, here given a width of 0.2 m).

n. SKB's interpreted location of the gently inclined zone ZFMA2 (DZ3: 411 to 431 mbl.), a section mot included in the structural model (DZ4: 447-451) and another gently inclined zone ZFMF1 (DZ5: 462 to 473 m).

Fractures and sections with increased fracturing

In the investigated part of borehole KFM02B a relative high percentage of all fractures form clusters (78.4 % for all fractures; cluster type 2B:2, Table 3-10), while the corresponding number is about 40 percent for both altered open fractures and altered open low-angle fractures (cluster types 2B:4 and 2B:6).

Fractures outside clusters (Fig. 3-88) form several sets that approximately are located on a great circle in the stereogram and have a fairly regular sepa-

ration in orientation. The trends of the clusters are at a large angle to the regional stress field.
Dominant fracture sets are:

- NNE/sub-verticalE.
- NNE/gentlyE.
- EW/moderateNNW.

Minor fracture sets are:

- NE /steepNW to sub-vertical.
- EW/steepN.

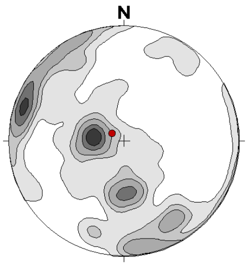


Figure 3-88: All fractures outside clusters (2B:2) in borehole KFM02B, section 360 to 480 mbl., N=127. Borehole orientation is steep northwest (313/80; red dot).

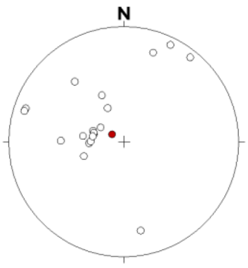


Figure 3-89: Open altered fractures outside clusters (2B:2) in borehole KFM02B, section 360 to 480 mbl., N=19. Borehole orientation is steep northwest (313/80; red dot).

Amongst fractures located outside clusters, 15 percent are open and mainly dipping eastwards (cf. Figs. 3-88 and 3-89).

Gently inclined fractures are most common for fractures included in clusters (Fig. 3-90). Their orientation differs somewhat from the gently inclined fractures outside clusters, i.e. the dip is more towards the northeast. As for fractures outside clusters, the gently inclined fractures have a high proportion of open altered fractures (Fig. 3-91). Sub-vertical fractures are common both inside and outside clusters and the proportion of open sub-vertical fractures is low.

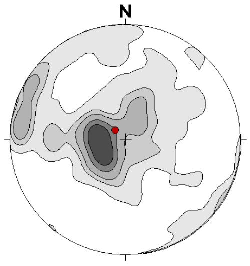


Figure 3-90: All fractures in clusters (2B:2) I borehole KFM02B, section 360 to 480 mbl., N=432. Borehole orientation is steep northwest (313/80; red dot).

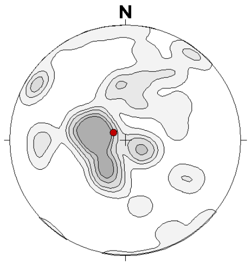


Figure 3-91: Open altered fractures in clusters (2B:4) in borehole KFM02B, section 360 to 480 mbl., N=77. Borehole orientation is steep northwest (313/80; red dot).

Open fresh fractures with no fill are relative frequent between 416 and 430 mbl. Borehole radar reflectors indicate NNE/gentlyE oriented reflectors (about 340/17) intersecting the borehole at about 421 and 429 mbl., i.e. indicating that the gently inclined fractures in clusters are sub-parallel to larger structural surfaces and they form brittle deformation zones.

The gently inclined SKB zone ZFMA2 coincides in borehole KFM02B (411 to 431 mbl., Stephens et al. 2008) with three clusters of PFL anomalies (Figs. 3-87j and 3-87k) located within a section of altered rock which has nearly the same width as the zone. In the adjacent borehole KFM02A there is also a section of altered rock, which, however, constitutes only a minor part of the zone.

There are also some PFL anomalies in the lower part of the gently inclined SKB zone ZFMF1 (070/10), located in the lower part of the investigated borehole section (DZ5 262 to 272 mbl.), and one coincides with a thin weak section (at 471 mbl.) similar to those found in zone ZFMA2. The borehole radar indicates an EW/gently orientation (110/15) for the structure.

Character of SKB DZ

Common for the two boreholes (KFM02A and 02B) is that the weak parts of zone ZFMA2 are focused to two minor sections (in KFM02B at 417.5 and 421 mbl.: 0.2 and 0.5 mbl. wide section containing open altered low angle fractures /4 and 8 fractures, respectively/) with a separation of about three metres. There is also another distinct thin section of similar type (0.1 m wide) at 427 mbl. in KFM02B. All three sections are located in a wider interval where open altered low-angle fractures are common (in KFM02B at

412 to 428 mbl.: average 2.1 fractures per metre borehole length, cf. Fig. 3-87).

The fractured section at 447 to 451 (SKB DZ4) is a 2A:1/2A:2 cluster composite, mainly composed of sealed fractures and there are only a few open altered fractures. The borehole radar indicates an orientation in NS/steepE (350/60) for this structural feature. Fractures in this part of the borehole commonly dip moderately southwards.

Comments

The character of zone KFMA2 in boreholes KFM02A and KFN02B are very similar regarding the general internal fracture distribution, the central location of two narrow sections with increased frequency of open altered fracture and the distribution of PFL anomalies in the boreholes.

KFM04A - section 160 to 280 m borehole length

The cored borehole KFM04 is located inside the detailed study area at its south-western border (Fig. 3-3). The borehole is drilled towards the central parts of the area (45/60).

Rock types and general structure elements

Rock types

The main rock type is foliated and composed of metamorphosed granite to granodiorite, and there are about 250 thin bands dominated by pegmatite and amphibolite mostly located within the foliation. Amongst the minor rock bands, acid volcanic rocks are noted. The bedrock in this borehole is affected by the regional ductile to brittle shear zone located west of and along the southwestern border of the detailed area (Fig. 3-4 and 3-7).

All fractures

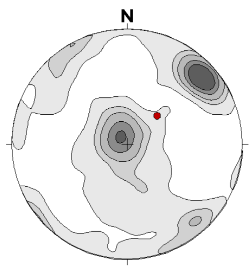


Figure 3-92: All fractures in borehole KFM04A, section 160 to 280 mbl., N=1078 (1078, one fracture missing orientation). The red dot is the borehole (45/60).

The investigated part of the borehole has one dominant set of fractures (NW/sub-verticalSW), one subdominant set (sub-horizontal) and one minor set (NE/sub-verticalNW) of fractures (Fig. 3-92). The NW/sub-vertical fractures conform to the well-developed foliation and ductile and ductile-brittle shear zones (cf. Figs. 3-96 and 3-97).

Open altered fractures

The open altered fractures constitute 19.9 percent of all fractures in section 160 to 280 mbl. in borehole KFM04A. The relative occurrence of open altered gently inclined fractures is increased and as frequent as open altered subvertical fractures trending northwest (Fig. 3-93). Addition orientations of open altered fractures are vertical trending north-northeast and east-northeast.

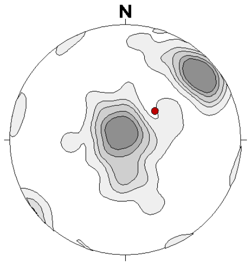


Figure 3-93: All open altered fractures in borehole KFM04A, section 160 to 280 mbl., N=214 The red dot is the borehole (45/60).

Core loss

There is no core loss noted for borehole KFM04A.

Breccias

Breccias are sealed and generally found as decimetre-wide bands, except for in the interval 244 to 247 mbl. where the breccias are up to one metre wide. The orientations of breccias deviate from the foliation (Fig. 3-94, cf. Fig. 3-96b). However, the breccias can be sub-parallel to thin rock bands and lithological contacts of major rock units (cf. Fig 3-96a).

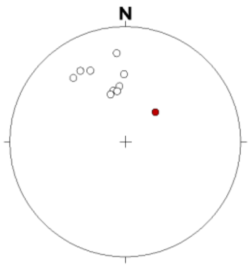


Figure 3-94: Orientation of breccias in borehole KFM04A, section 160 to 280 mbl., N=9. The red dot is the orientation of the borehole (45/60).

Crushed rock

One thin (0.15 mbl. wide) section with crushed rock is noted (at about 232.5 mbl.) and it is sub-horizontal (02/04).

Sealed networks of fractures

The sealed networks show a relative scatter in orientation in the investigated section of borehole KFM04A, 160 to 280 mbl., although some orientations of networks are more pronounced, for example subvertical networks trending west-northwest and northeast (Fig. 3-95).

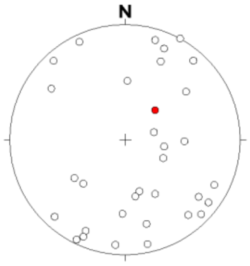


Figure 3-95: Orientation of networks of sealed fractures in borehole KFM04A, section 160-280 mbl., N=32 (upper and lower contacts of 16 sections). The red dot is the orientation of the borehole (45/60).

Altered sections of the bedrock

In the investigated section of the borehole KFM04A the core displays 58 segments with alteration, all except for four show oxidation (Fig. 3-96; oxidation 56.2 mbl. The four sections show epidotization (1.2 mbl.). The orientation of the altered bedrock sections is dominantly NW/steepSW to vertical. More continuous sections with altered rock are found in the middle part of the investigated section of the borehole (Fig. 3-101). There is a correlation between the alteration and the general fracturing in the rock.

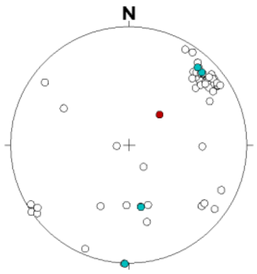
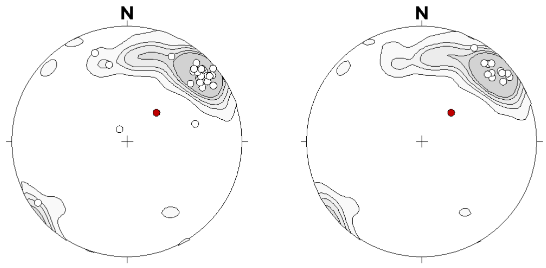


Figure 3-96: Sections with altered bedrock in borehole KFM04A, section 160 to 280 mbl., N=58. Bluish dots are sections with epidotization. The red dot is the orientation of the borehole (45/60).

Foliation and lithological contacts

The rock has a regular fabric with lithological contacts parallel to the foliation reflecting the ductile imprint of rock located at the rim zone of a regional ductile shear zone.

The bedrock is dominated by foliated rocks (gneisses) with granitic to granodioritic composition while amphibolites are subordinate and constitute 6.7 percent of the drill core. The amphibolites consist of two wider bands (widths: 0.8 to 1.0 mbl.) and in between these bands, there are a large number (78) of thin bands (mean width about 0.08 mbl.) parallel to the foliation oriented in NW/steepSW (cf. Fig. 3-96).



a. b.

Figure 3-96: Lithological contacts borehole KFM04A, section 160 to 280 mbl.:

a. Contacts between major rock units (N=26, white dots) plotted on contoured contacts for thinner rock bands (N=496; upper and lower contact for 248 bands).

b. Foliation (N=12, white dots plotted on the contoured for thinner rock bands.

The red dot is the orientation of the borehole (45/60).

Ductile shear zones

Ductile shear zones display uniform orientation, NW/steepSW, and there is a cluster of shears (7) in the upper part of the investigated section (160 to 184 mbl.). The ductile shears are thin (two centimetres to about two decimetres wide) and are not lately reactivated (no open fracture along the shears).

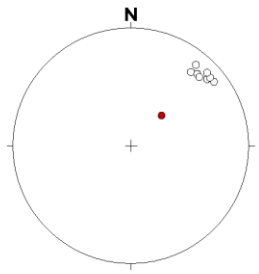


Figure 3-97: Orientation of ductile shear zones in borehole KFM04A, section 160 to 280 mbl., N= 8. The red dot is the orientation of the borehole (45/60).

Mylonites

Mylonites are not recorded in the investigated part of borehole KFM04A. However, there are same metre-wide sections of a relative uncommon fine-grained rock type labelled “felsic to intermediate volcanic rock, metamorphic” recorded in close connection to a ductile shear zone. Meta-volcanic rocks are by no means unexpected in this geological environment. However, their position indicates tectonic mixing or they could represent tectonites.

Water-conductive fractures

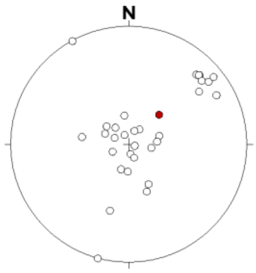


Figure 3-98: Interpreted orientation of fractures related to PFL anomalies in borehole KFM04A, section 160 to 280 mbl., N=31. The red dot is the orientation of the borehole (45/60).

There are 31 water-conductive fractures indicated by the PFL flow log in the analysed section of the cored borehole KFM04A, section 160 to 280 mbl. All but one of the PFL-anomalies can be correlated with open altered fractures including a mapped section of crushed rock (232.58 to 232.73 mbl.). PLF-indicated flows are most common in the upper part of the investigated section of the borehole, i.e. 169.5 to 180 mbl. (12 indicated flows: means and median separations are 0.96 and 0.95 mbl. and the range is 0.041 to 1.91 mbl.). Although the spacing of water-conductive fractures is relative regular in the borehole section the distribution of open altered fractures is inhomogeneous (cf. Fig. 3-101).

The orientation of flowing fractures is dominated by horizontal to moderately inclined fractures and a set of NW/steepSW fractures (Fig. 3-98). There is no apparent correlation in position of interpreted flowing fractures and borehole radar reflectors, although the two show similar orientations (Cf. Figs. 3-98 and 3-99).

Borehole radar

Nine radar reflectors with absolute orientations are indicated in the interval 160 to 280 mbl. in cored borehole KFM04A. The orientations of these reflectors form two sets, gently inclined and NW/steepSW reflectors (Fig. 3-99a). There are additional borehole radar measurements (dipole antenna, Fig. 3-99b) giving the angular relation between reflector and borehole axis (alpha angle) and this type of measurement may investigate the bedrock within an radius up to 3 to 4 times larger compared with the directional antenna. Eleven radar reflectors were detected and the range in alpha angle was 41 to 51° (minimum and maximum values excluded). The alpha angles that correspond to the reflectors detected by the directional antenna indicate that the absolute orientations of the more extensive reflectors are either subhorizontal to gently inclined or oriented in NW/steepSW. The latter coincides with the orientation of lithological contacts, ductile shear zones and the foliation. However, correlation to specific geological structures in the boreholes is indicated only for very few reflectors.

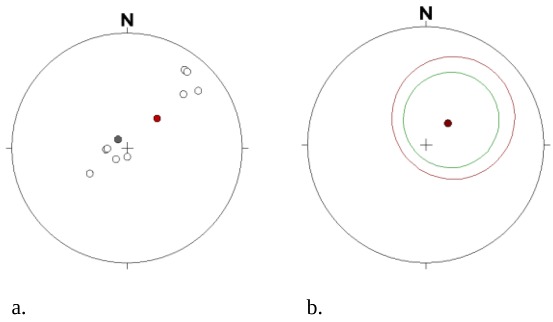


Figure 3-99: Borehole radar reflectors in borehole KFM04A, section 160-280 m:

a. orientation of reflectors (N=9 open circles and one alternative orientation /grey dot/).

b. Wulff projection, small circles with radius equal to alpha angle 41° (green) and 51° (red) show relative positions of 11 radar reflectors detected by the dipole antenna (located between the two small circles).

Fracture minerals

Open and partly open fractures constitute 28.5 and 10.6 percent, respectively, of all fractures in the investigated section of the cored borehole KFM04A, 160 to 280 mbl. The relative proportion of open fractures that are altered is 69.7 percent (214 out of 307) and the corresponding number for partly open altered fractures is 13.2 percent (15 out of 114).

The proportion of open plus partly open fractures containing the three most common fracture minerals (calcite, chlorite and hematite) is about 20 percent of all fractures for each fracture mineral (cf. Table 3-11). Among open fractures containing calcite 71.0 percent are altered (120 out of 169) and for fractures with chlorite and hematite the corresponding numbers are 82.7 and 82.5 percent (167 out of 202 and 127 out of 154, respectively). Alteration of fractures containing pyrite are common while most fractures containing clay minerals are altered (53.3 and 90.5 %; 24 out of 45 and 38 out of 42, respectively). Fractures with quartz have in other boreholes a low relative percent of open fractures but that is not the case for the investigated section of borehole KFM04A (21.4 %) where also the relative percentage of partly open quartz bearing fractures is extreme (33.3 %). However, only two open fractures and none partly open with quartz are altered.

Table 3-11: Relation between all, open and partly open fractures and their fracture fills and wall rock alteration in cored borehole KFM04A, section 160 to 280 m borehole length (number of sealed fractures = all fractures – (open + partly open fractures)).

	Fractures – number of observations			In percent of total number of fractures (1079)		
Type of fracture / Type of fracture fill	**All fractures**	**Open fractures**	**Partly open fractures**	**All fractures**	**Open fractures**	**Partly open fractures**
Fractures that have a potential to be soft or connect water						
Calcite	539	169	54	50.0	14.3	5.0
Chlorite	422	202	48	39.1	17.1	4.4
Hematite	479	154	58	44.4	13.1	5.4
No infill	77	30	22	7.1	2.8	2.0
Pyrite	70	45	6	6.5	3.8	0.6
Clay minerals	47	42	3	4.4	3.6	0.3
Quartz	42	9	14	3.9	0.8	1.3
Fractures that have a potential to be stiff or tight						
Oxidized walls	178	6	5	16.5	0.5	0.5
Laumontite	158	3	9	14.6	0.3	0.8
Prehnite	71	7	2	6.6	0.6	0.2
Epidote	40	1	0	3.7	0.1	0.0
Accessorial mineral/features						
K-feldspar	4	1	0	0.4	0.1	0.0
Iron hydroxide	3	1	0	0.3	0.1	0.0
Red feldspar	1	0	0	0.1	0.0	0.0
Muscovite	1	0	0	0.2	0	0
Zeolite	1	0	0	0.1	0	0

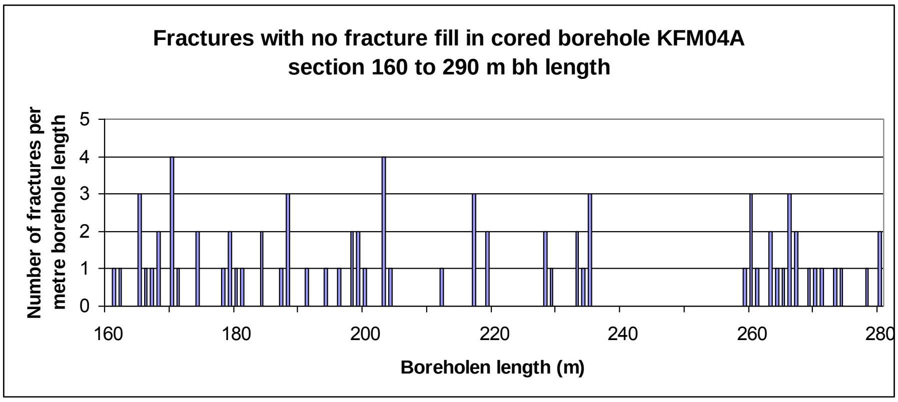
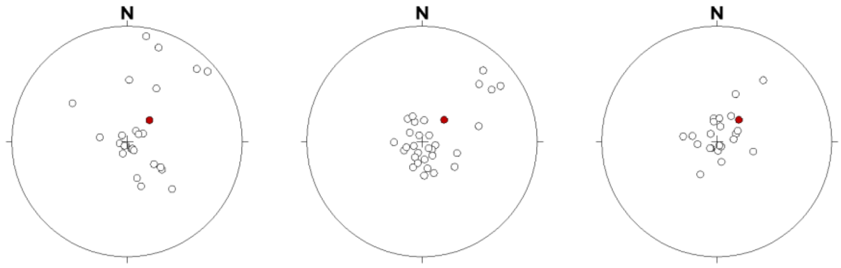


Figure 3-100: All fractures with no fracture fill in borehole KFM04A, section 160 to 280 mbl., N=77.



a. b. c.

Figure 3-101: Fracture with no fill in borehole KFM04A, section 160 to 280 mbl.:
a. sealed fractures with no fill, N=25.
b. open fractures with no fill, N=30.
c. partly open fractures with no fill, N=22.
The red dot is the borehole.

Fractures with no noted fracture fill are relatively common (77; 7 % of all fractures, Table 3-11 and Figs. 3-100 and 3-101) and are randomly distributed along the borehole except for one minor part of the borehole (235 to 259 mbl.) where they are absent. Amongst open fractures with no fill one third are altered (10) having orientations similar to the borehole radar reflectors (cf. Fig. 3-99). Sealed and partly open fractures with no fill are few (1 and 2, respectively).

Small proportions of open and partly open fractures are typical for fractures with oxidized walls (6 %) and fractures with epidote, laumontite and prehnite (3 to 12 relative percent).

Brittle deformation zones in the SKB model

Three deformation zones occur between 160 to 280 mbl. in borehole KFM04A (SKB database SICADA file p_eshi-KFM04A.xls):

- DZ1: 110 to 176 mbl., is a vertical northwest trending zone, ZFMNW1200 (orientation: 138/90; Stephens et al. 2007).
- DZ2: 202 to 213 mbl., is the upper section of the gently inclined zone ZFMA2 (orientation: 80/24; Stephens et al. 2007). This part of ZFMA2 is not visualized in the geological site model.
- DZ 3: 232 to 242 mbl. constitutes a lower branch of the gently inclined zone ZFMA2 (orientation: about 80/24; Stephens et al. 2007).

A study of the character and kinematics of deformation zones have been performed in borehole KFM02B (Nordgulen and Saintot 2006). It presents the following characteristics for DZ1 to DZ3:

- DZ1, the deformation zone was not treated by Nordgulen and Saintot (2006).
- DZ2 contains at 212 mbl. a thin segment of cataclasite (labelled breccia in the core log; oriented 64/84). Noted are also two steep faults trending NW-SE and ENE-WSW characterised by dip-slip, a gently eastward dipping N-S fault and a general increase in fracture density.

- DZ3 contains a major core zone (237 to 244 mbl.) ”with relatively abundant sealed fractures and small faults present with strike-slip striae” (labelled breccias in the core log, cf. Fig. 3-102; orientations are mainly NE/sub-vertical), i.e. structures with a low angle to the borehole axis. There is also a set of open low-angle fractures.

Location of brittle deformation and zones of weakness

Geological data indicating structural features that may point to zones of weakness in the rock and relation between such structures and their imprint on the rock for borehole section 160 to 280 m along borehole KFM02B are (Fig. 3-101):

- Clustering of all fractures, open altered fractures and sets of fractures.
- Breccias.
- Crushed rock.
- Ductile shear zones.
- Networks of sealed fractures.
- Sections with altered host rock.
- Location of water-conductive sections in the borehole (PFL anomalies).

The general fracturing in section 160 to 280 mbl. is relatively high, i.e. when considering all fractures (9.0 fr/mbl.). For open fracture the corresponding number is less than a third of that for all fractures (2.6 fr/mbl.) and the frequency of open altered fractures is a fifth of the frequency for all fractures (1.8 fr/mbl.).

The clustering of all fractures and open altered fractures has been classified according to the mutual separation of fractures along the borehole (Table 3-12 and Figs. 3-101a and 3-101b; applied methodology is described in Chapter 2). The fracture population in the investigated section of borehole KFM04A contains three sets of fractures. Two are major sets with low-angle fractures (in this case dips< 55°) and fractures oriented NW/steep. The third set is a minor set with fractures in EW/moderateN (Fig. 3-101f to 3-101f). Clusters for the three fracture sets have been separately calculated (cf. Table 3-12 and Figs. 3-101d to 3-101h).

Lower-order clusters of all fractures (clusters >5 fr/mbl.; 4A:2, Table 3-12 and Fig. 3-101b) are frequently distributed along the investigated section while higher-order clusters (clusters>10 fr/mbl.; 4A:1, Table 3-12 and Fig. 3-101a) indicate more intense fracturing in two sections: 169 to 177 mbl. and 202 to 238 mbl. The clusters of open altered fractures (clusters >10 fr/mbl. and>5fr/mbl.; 4A:3 and 4A:4 Table 3-12 and Figs. 101c and 3-101d) indicate that the weaker parts of the core are located in the upper part of the two sections outlined by all fractures. Thus, the weaker sections are between 170 to 175 mbl. and 202 to about 204 mbl. and thin sections located at 186, 213 and 237 mbl.

Sorting of the fracture data can be processed further as the fractures in the rock belong to three sets, as pointed out above. The distribution of clusters belonging to each of these three sets indicates that:

- Clusters of low-angle fractures are mainly located at the rims of sections outlined by local increases in the general fracturing in the rock (considering all fractures). For example, both the clusters at 171 mbl. and in the interval between 202 to 208 mbl. are located in the upper part of the section with increased general fracturing, while the cluster at 235 mbl. is located in the lower part of the interval.
- NW/steep fractures form clusters located below clusters of low-angle fractures and below the lower swarm of clusters formed by the general fracturing (at 202 to 238 mbl.); located at 175, 213 and 242 mbl.
- One cluster is weakly indicated by fractures oriented EW/moderateN (at 191 mbl. indicated by three fractures).

Steeply dipping to sub-vertical fractures trending northeast to east-northeast are common in the area but such fractures are relatively rare in the investigated section of borehole KFM04A. The reason for this may be the angular relation between the borehole and such fractures (the alpha angle is about 10°), i.e. a sampling bias.

Sections mapped as breccias (Fig. 3-101k) are not associated with any clusters of open altered fractures and only one minor breccia correlates with a PFL anomaly, i.e. contain open water-conductive fractures. However, the section (at 232.5 mbl., cf. Fig. 3-101l) is overprinted by a section mapped as crushed rock (reactivation?).

Two sections with ductile shears zones (Fig. 3-101m) coincide in position with clusters formed by northwest trending sub-vertical fractures (at 174 and 213 mbl.). However, only the upper of the two sections is indicated as a PFL anomaly (cf. Fig.3-101p).

Sections with sealed networks of fractures (Fig. 3-101n) are intersected by three clusters with open altered fractures: two with NW/sub-vertical fractures (at 175 and 242 mbl.) and one with low-angle fractures (at 236 mbl.).

Large parts of the borehole are located in altered rock with positions consistent with the clusters formed by the general fracturing (clusters 4A:2; Fig. 3-101b). However, in the lowest part of the investigated borehole section (below 260 mbl.) the clusters formed by the general fracturing are not associated with any altered bedrock.

Only few (6 out of 16) PFL anomalies (Fig. 3.101p) correlate with fracture clusters: four clusters are formed by low-angle fractures (107.5, 203, 207 and 208 mbl.), one by a cluster outlined by sub-vertical northwest trending fractures (175 mbl.) and one by a cluster associated with open altered fractures with various orientations (186 mbl.).

Looking only at the general fracturing in the rock (clusters 4A:1 and 4A:2; Fig. 3-101a to 3-101b) it is indicated that:

- Deformation zone DZ1 has increased fracturing in its lower part (about 170 to 176 mbl.). However, the fracturing is still intense below DZ1 and there is a section inside DZ1 (160 to 170 mbl.) that has only a few clusters. The borehole radar measurements indicate a moderately northeastwards dipping reflector (323/32) at 171 mbl.
- Deformation zone DZ2 has a sharp distinct upper boundary and the fracturing is intense inside the zone. However, the general fracturing is still high below the zone, i.e. in the interval between DZ2 and DZ3. The borehole radar displays a steeply and a gently dipping reflector (128/73 and 316/10) at 205 and 211 mbl., respectively.
- The location of zone DZ3 is not clearly outlined by the general fracturing. However, the upper part (4A:1; 232 to 235.5 mbl.) is more intensely fractured. A borehole radar reflector at 234 mbl. has two alternative orientations presented; gently inclined (44/9) or moderately dipping (136/57).

PFL anomalies are recorded in SKB deformation zones DZ1, DZ2 and DZ3: 10 in DZ1, 4 in DZ2 and 3 in DZ3. However, there are several PFL anomalies in the borehole section between DZ1 and DZ2 (13 PFL anomalies; 176 to 201 mbl.). Furthermore, there is no PFL anomaly indicated between the upper and lower branch of the modelled gently inclined SKB zone ZFMA2, i.e. between DZ2 and DZ3.

All three SKB deformation zones (DZ1 to DZ3) have in common that their lower boundaries coincide with clusters formed by open altered NW/subvertical fractures. Deformation zone DZ2 (202 to 212 mbl.; upper branch of modelled zone ZFMA2) contains a sequence of clusters outlined by open altered low-angle fractures (4A:6; 202 to 208 mbl.). Single thin clusters of the same kind (4A:6) are located in DZ1 (at 170 mbl.; 0.4 m wide) and DZ2 (at 235 mbl.; 0.6 m wide).

Table 3-12. Character of clusters of fractures in borehole KFM04A section 160 to 280 m borehole length (cf. Fig 3-101). Two groups of fractures are treated: All fractures and open altered fractures (incl. all and three sets of open altered fractures). Identification of clusters is based on two criteria: 1. The minimum mutual separation between fractures, 0.10 and 0.20 m (corresponding to minimum fracture frequency of 10 and 5 fractures per metre borehole length, respectively) and 2. The minimum number of fractures to outline a cluster (3 or 4 fractures).

Cluster				Borehole KFM04A					
ID[2]	Group of fractures	Criterion to identify clusters		Borehole section 160 to 280 m borehole length					
		Minimum number of fractures to outline a cluster[1]	Minimum fracture frequency (fr/mbl.)[3]	Number of clusters	Length of clusters (mbl.)	Length of clusters in percent of section length (%)	Mean fracture frequency in section (fr/mbl.)	Mean fracture frequency in clusters (fr/mbl.)	Fractures in clusters in percent of fractures in section (%)
4A:1	*All.*	4	10	82	18.9	15.7	9.0	27.9	56.4
4A:2		4	5	70	51.3	42.8	9.0	16.0	82.7
4A:3	*Open and*	4	10	5	1.1	0.9	1.8	21.2	13.1
4A:4	*altered*:All,	4	5	13	4.4	4.5	1.8	13.3	38.8
4A:5	Dip	4	10[4]	4	1.0	0.8	1.0	16.5	17.2
4A:6	< 55°	4	5[4]	8	3.3	2.7	1.0	11.1	36.7
4A:7	NW/steep	4	10[4]	3	0.7	0.6	0.6	14.8	18.2
4A:8		4	5[4]	3	1.2	1.0	0.6	13.2	24.7
4A:9	EW/	3	10	0	-	-	0.07	-	-
4A:10	moderateN	3	5	1	0.1	0.1	0.07	15.9	37.5

[1] Minimum number of fractures to outline a cluster – 4 fractures = 3 core piece. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of clusters).

[2] ID of group of clusters.

[3] fr/mbl. = fractures per metre borehole length.

[4] Separation of fracture in clusters >10 fr/mbl. and >5 fr/mbl. are less than 0.14 and 0.28 mbl., respectively.

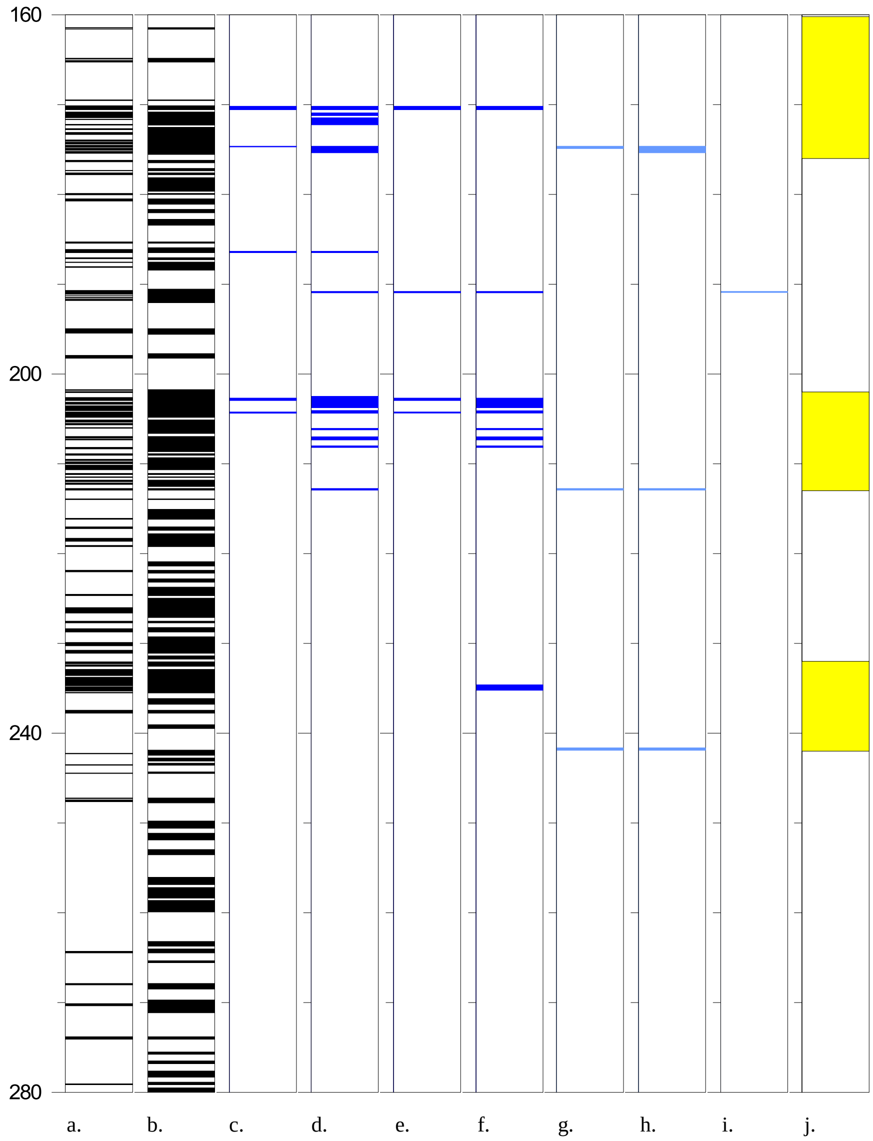


Figure 3-102: Borehole KFM04A section 160 to 280 mbl.; Clusters of fractures (Table 3-12) and location of SKB ESHI (incl. zone ZFMA2):

a. All fractures (cluster 4A:1), fracture separation less than 0.10 m (fracture frequency>10 fr/mbl.).

b. All fractures (cluster 4A:2), fracture separation less than 0.20 m (fracture frequency>5 fr/mbl.).

c. Open altered fractures (cluster 4A:3), separation less than 0.10 m (fracture frequency>10 fr/mbl.).

d. Open altered fractures (cluster 4A:4), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

e. Open altered fractures inclined less than 55° (cluster 4A:5), separation less than 0.10 m (fracture frequency>10 fr/mbl.).

f. Open altered fractures inclined less than 55°(cluster 4A:6), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

g. Open altered NW/steep fractures (cluster 4A:7), separation less than 0.10 m (fracture frequency>10 fr/mbl.).

h. Open altered NW/steep fractures (cluster 4A:8), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

i. Open altered EW/moderateN fractures (cluster 4A:10), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

j. SKB's interpreted location of the gently inclined zone ZFMA2 (upper section /DZ2: 202 to 213 mbl./ and lower section /DZ 3:232 to 242 m/) and an upper zone ZFMNW1200 (DZ1: 110 to 176 mbl.). To be continued.

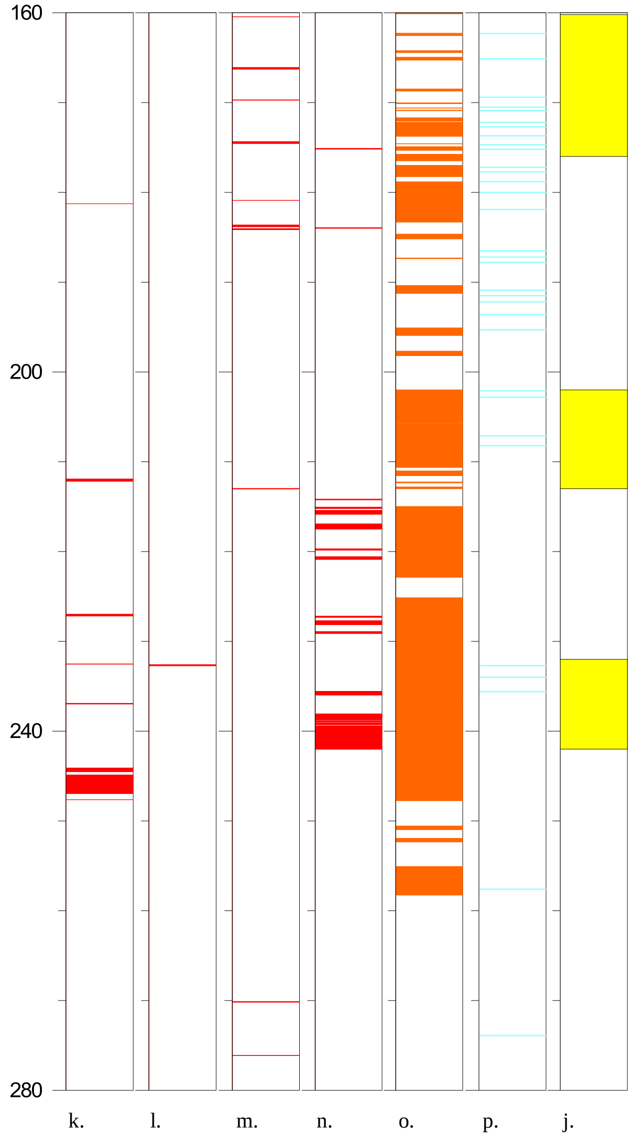


Figure 3-102 (continued): Borehole KFM04A section 160 to 280 mbl.; brittle/ductile structures, Posiva Flow log and location of SKB ESHI (incl. zone ZFMA2):

k. Breccia.

l. Sections with crushed rock.

m. Sections with ductile shear zones.

n. Sections with network of sealed fractures.

o. Sections with altered host rock, oxidation.

p. Indicated water-conductive fractures (PFL, point measurements, here given a width of 0.2 m).

j. SKB's interpreted location of the gently inclined zone ZFMA2 (upper section /DZ2: 202 to 213 mbl./ and lower section /DZ 3:232 to 242 m/) and an upper zone ZFMNW1200 (DZ1: 110 to 176 mbl.).

Fractures and sections with increase fracturing

Clustering in the rock along boreholes may indicate the location of brittle deformation zones (semi-planar structures) or outline domains where several sets of fractures interfere. For this reason, one should try to identify clusters outlined by all fractures and sets of fractures.

Regarding all fractures in the investigated section there are no major differences between fractures located outside clusters and fractures inside clusters except for the fracture density (Fig. 3-103). One minor difference between fractures inside clusters and outside clusters (4A:1 and 4A:2 clusters; cf. Table 3-12) is the relatively higher proportion of NE/steep fractures outside clusters outlined by all fractures.

The existence of relative extensive structures parallel to the fractures forming the two main sets is indicated by the borehole radar (Fig. 3-99).

Character of SKB DZ

It is indicated that clusters of NW/steep fractures are located just below clusters of low-angle fractures, i.e. sections with a mix of gently and steeply inclined fractures are exceptional. This is well displayed for clusters outlined by NW/steep fractures located immediately below the gently inclined SKB deformation zone ZFMA2. This structure relationship is of importance when estimating the extension/continuation of gently inclined brittle deformation zones found in the Forsmark site.

Comments

Looking at the relation between NW/steep fractures and sub-horizontal to gently inclined fractures in more detail (core log data), it is found that the low-angle fractures are seldom mixed with the NW/steep fractures. Instead, the low-angle fractures are more common above sequences with NW/steep fractures then below (Fig. 3-104, cf. Figs. 3-102 and 3-105). The NW/steep fractures are parallel to the structural grain in the bedrock.

One interpretation is that the gently inclined fractures stop against NW/steep fractures as they do not mix. A mix can be expected if fractures of one set offset fractures of another set or overprint the other set. Further studies are needed to clarify the relation between the two sets as it has implications on the interpretation of the extension of gently inclined zones within the Forsmark site. Do the gently inclined zones cross, intersect or stop at the major NW-trending zones bordering the Forsmark site?

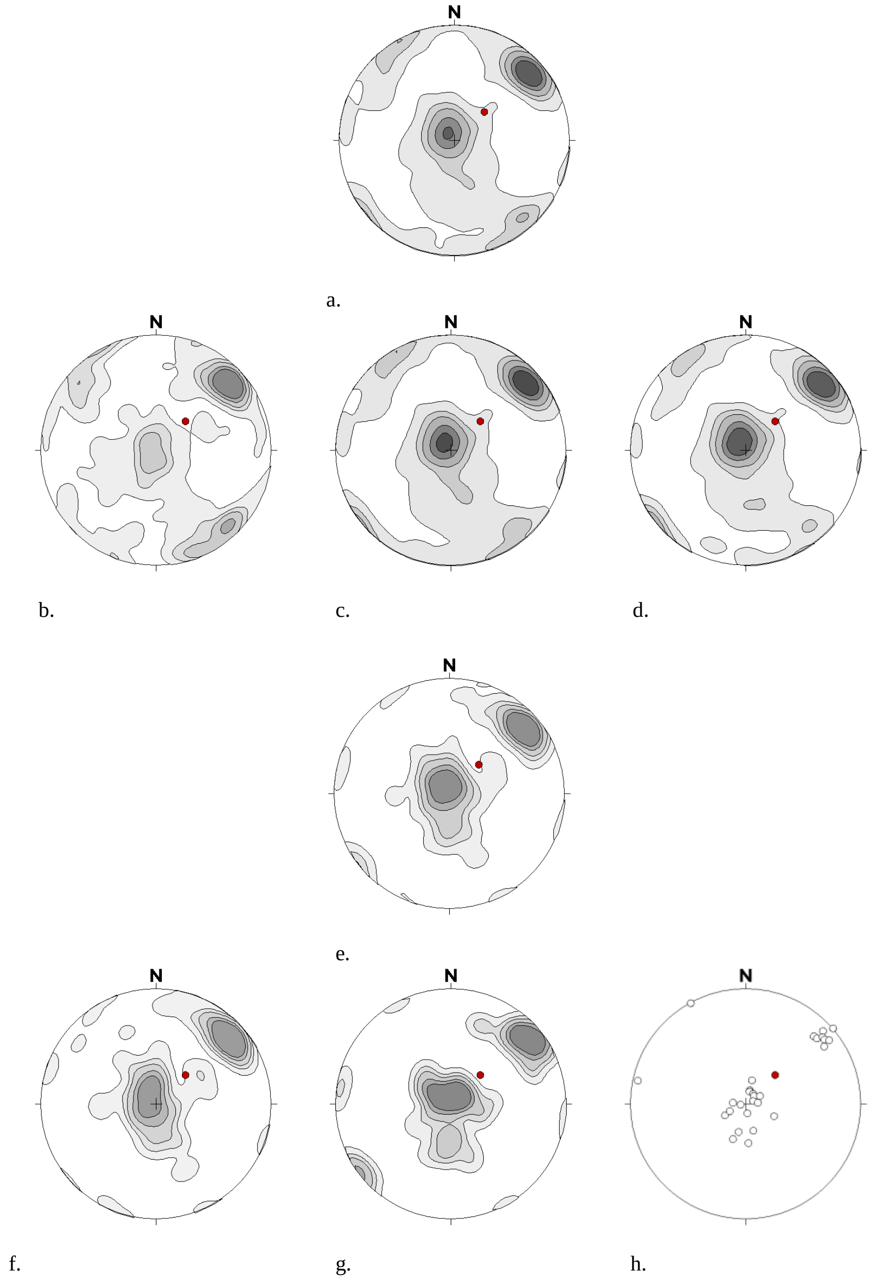


Figure 3-103: Fractures in borehole KFM04A, section 160 to 280 (cf. Table 3-12 and Fig 3-102):

a. All fractures, N=1078 (1078, one fracture missing orientation).

b. All fractures outside clusters (cluster type 4A:2), N=188.

c. All fractures inside clusters (cluster type 4A:2), N=891.

d. All fractures inside clusters (cluster type 4A:1), N=607.

e. Open altered fractures, N=214.

f. Open altered fractures outside clusters (cluster type 4A:2), N=131.

g. Open altered fractures in clusters (cluster type 4A:2), N=83.

h. Open altered fractures in clusters (cluster type 4A:1), N=28.

Red dot is the orientation of the borehole.

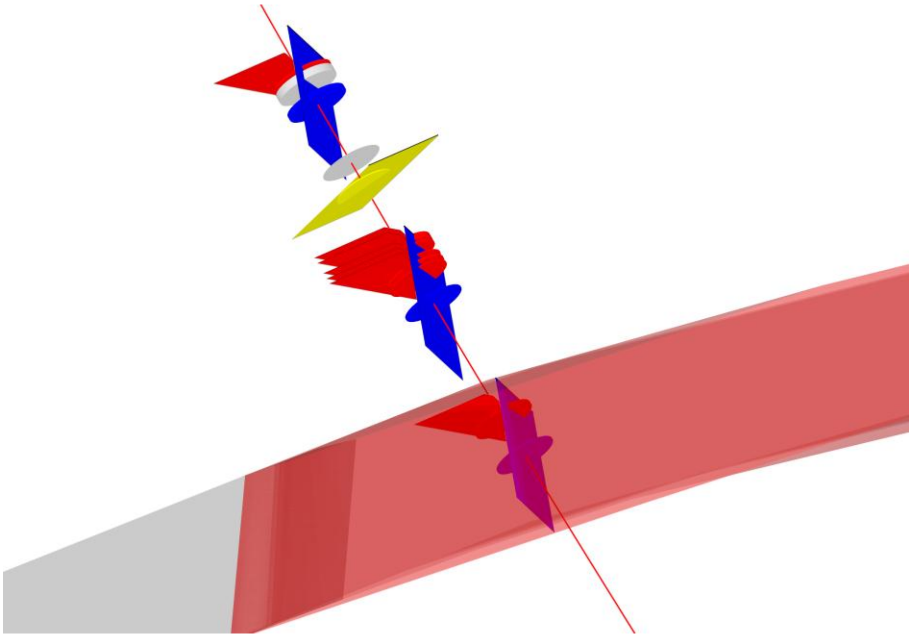
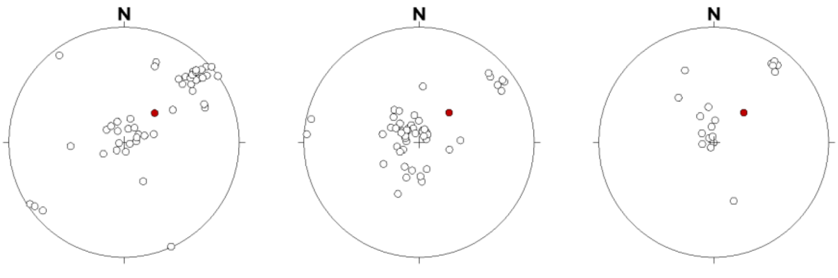


Figure 3-104: Relation between gently inclined fractures and NW/steep fractures in borehole KFM04A (the red line), above and in upper part of the gently inclined zone ZFMA2 (the wide red band). Positions of fractures intersecting the borehole are given by discs and the actual fractures are given by planes: gently inclined fractures (red), NW/steep fractures (blue) and moderately inclined fracture (green).



a. b. c.

Figure 3-105: Open altered fractures in SKB deformation zones (DZ1 to DZ3) in borehole KFM04A:

a. Lower part of DZ1 (ZFMNW1200; NW/steep, full extent is 110 to 176 m), 160 to176 mbl., N=48 (3.0 open altered fractures per metre borehole length).

b. DZ2 (upper branch of ZFMA2, gently inclined southeast), 202 to 212 mbl., N=51 (4.3 open altered fractures per metre borehole length).

c. DZ3 (lower branch of ZFMA2, gentle inclined southeast), 232 to 242 mbl., N=18 (1.8 open altered fractures per metre borehole length).

KFM05A - section 100 to 165 m borehole length

Borehole KFM05A is drilled in the southern central part of the SKB local model area and the borehole plunges steeply eastwards (80/60; Table 3-1 and Fig. 3-3).

The main rock types, in section 100 to 165 mbl., are fine to medium-grained metamorphic rocks with granitic to graniodioritic composition. There are also several bands (up to a metre wide; mean width less than 0.1 m) of metamorphic rocks, meta-basites to meta-granites. In the upper ten metres of the bedrock there are several centimetre-wide and gently inclined bands of rocks classified as having a sedimentary origin (cf. section Rock types/lithological contacts).

All fractures

Borehole section 100 to 165 mbl. is the uppermost core drilled part of the borehole KFM05A. Dominant are horizontal to gently inclined fractures (maximum 114/6) and subordinate fractures oriented NE/steepSW (135/72) and NE/steepNW (240/85), Figure 3-106.

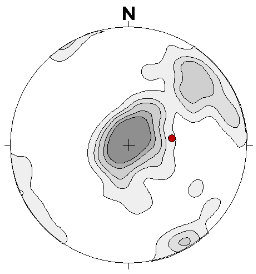


Figure 3-106: All fractures in borehole KFM05A, section 100-165 mbl., N= 242 (249; 7 without orientations). The red dot is the orientation of the borehole.

Open altered fractures

The open altered fractures display a similar pattern as the total population of fracture in the section 100 to 165 mbl. in borehole KFM05A (Fig. 3-107). However, open altered fractures oriented NE/steepNW to vertical are missing.

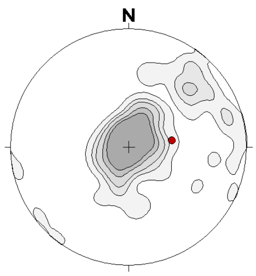


Figure 3-107: Open altered fractures in borehole KFM05A, section 100-165 mbl., N= 149 (154; 5 without orientations). The red dot is the orientation of the borehole.

Core loss

There is no core loss in the section 100 to 165 mbl. of the cored borehole KFM05A.

Crushed rock

Two minor intervals with crushed rock (0.07 to 0.25 mbl.) are mapped in the upper part (106-110 mbl.) of the section 100 to 165 m of the borehole KFM05A and the sections of crushed rock are sub-horizontal (Fig. 3-108).

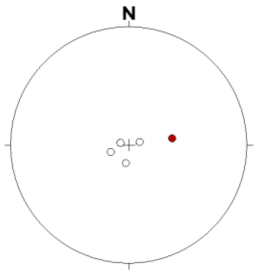


Fig 3-108: Sections with crushed rock in borehole KFM05A, N=4 (upper and lower contacts of two section). The red dot is the orientation of the borehole.

Sealed networks of fractures

Two networks of sealed fractures in section 100 to 165 mbl. are mapped (Fig. 3-109). The networks are relatively thin (widths: 0.10 to 0.15 mbl.) and located at 110 and 140 mbl., respectively. Most of the fractures forming the networks are gently dipping.

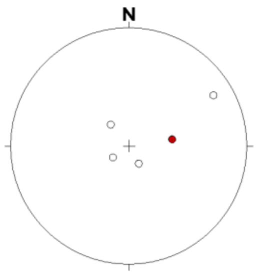


Figure 3-109: Sealed network of fractures in borehole KFM05A, section 100 to 165 mbl., N=4 (two sections). The red dot is the orientation of the borehole.

Altered host rock

Four sections with altered rock are recorded (Fig. 3-110; total 14.7 mbl); oxidation in the upper three sections and chloritization in the lowest section. The uppermost section is relatively wide (about 14 mbl. and located in the uppermost part of the core, cf. Fig. 3-118) while the other three are thinner (oxidation 0.3 to 0.6 mbl., chloritization only 0.01mbl.).

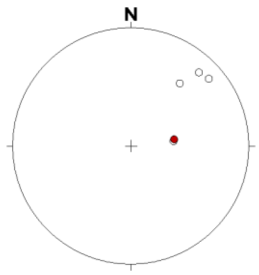


Figure 3-110: Altered rock section in borehole KFM05A, section 100 to 165 mbl., N=4. The red dot is the orientation of the borehole.

Rock types/lithological contacts

Within the metamorphic rocks 18 mapped bands of fine-grained, clay-dominated massive material (Fig. 3-111) are mapped to be cataclastic sedimentary rock having widths of 2 to 26 mm, and occurring to a depth of -136 m a.s.l. "A minor study on sediment-like fracture fillings was also carried out showing that the fracture filling material was partly gouge, partly quartz and adularia from Generation 3, i.e. the fillings were not sediments" (Sandström and Tullborg 2005). If this is the case there should have occurred displacements along at least some of the gently inclined fractures.

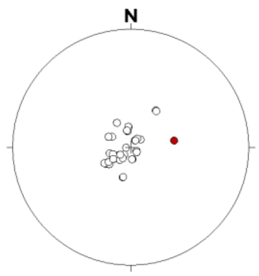


Figure 3-111. Massive fine grained rock types in borehole KFM05A, section 100 to 165 mbl., N=36 (18 bands; upper and lower contacts). The rock was mapped as "cataclastic massive rock" and reinterpreted as a tectonic rock (see text). The red dot is the orientation of the borehole.

The main orientation of rock contacts (main rock types and bands) is subparallel to the foliation and shear zones (Fig. 3-112, cf. Figs.3-113 to 3-115).

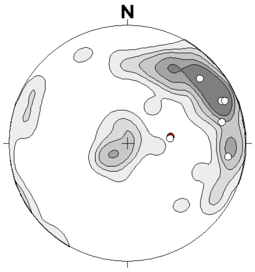


Figure 3-112: Lithological contacts in borehole KFM05A, section 100 to 165 mbl.: contoured are orientations of intercalated rock bands/veins, N= 244 (orientation of upper and lower contacts of 122 rock bands) and white dots (N=6) are contacts between main rock types. The red dot is the orientation of the borehole.

Brittle-ductile shear zones

Three brittle-ductile shear zones are noted at about 140 to 150 mbl. in borehole KFM05A (0.1 to 0.3 mbl.) and they are oriented NW/steepSW (Fig. 3-113).

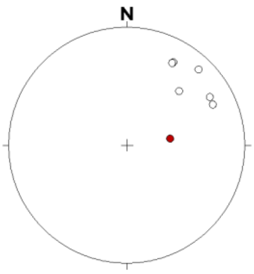


Figure 3-113: Brittle-ductile shears in borehole KFM05A, section 100 to 165 mbl., N=6 (3 sections with upper and lower contacts). The red dot is the orientation of the borehole.

Ductile shear zones

Six ductile shear zones are noted between 126 to 149 mbl. in borehole KFM05A (0.01 to 0.4 m wide along the borehole) and they are oriented NW/steepSW (fig. 3-114). In the borehole section 149 to 165 mbl. there is no ductile shear zone noted.

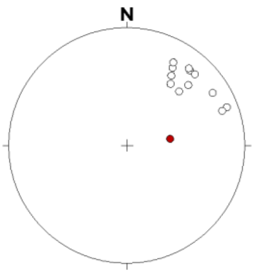


Figure 3-114: Ductile shears zones in borehole KFM05A, section 100 to 165 mbl., N=12 (6 sections with upper and lower contacts). The red dot is the orientation of the borehole.

Foliation

The foliation, gneissosity, has a predominant orientation in NW to NNW/steepSW (Fig. 3-115).

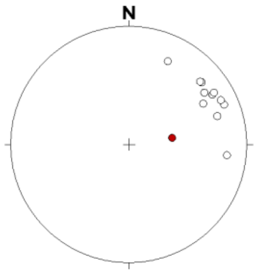


Figure 3-115: Foliation in borehole KFM05A, section 100 to 150 mbl., N=11. The red dot is the orientation of the borehole.

Water-conductive fractures

In the upper part of the borehole KFM05A 110 (PFL starts at 110 mbl.) to 126 mbl., the separation between the PFL anomalies (14 noted hydraulic fractures) is less than 3.5 mbl. (mean and median separations are 1.1.mbl.). Water-conductive fractures are sub-horizontal to gently inclined (Fig. 3-116). The correlation between the PFL anomalies and radar reflectors is poor (one out of 20).

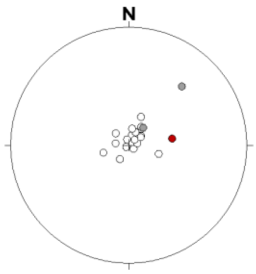


Figure 3-116: Posiva Flow Log (PFL) measured in borehole KFM05A, section 110 to 165 mbl. Orientations are given by correlation PFL data with open altered fractures (performed in this study), N=20. Uncertain correlations are marked as grey dots (N=2). The red dot is the orientation of the borehole.

Borehole radar

The reflectors detected by the borehole radar are oriented either parallel to the foliation or conforming to the gently inclined open and altered fractures (Fig. 3-117). However, the correlation to specific open fractures is poor (one out of six).

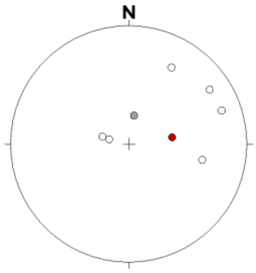


Figure 3-117: Borehole radar, directional antenna, in borehole KFM05A, section 100 to 165 mbl., N=6 (one has an alternative strike/dip noted to be 100/20; a grey dot). The red dot is the orientation of the borehole.

Fracture minerals

In borehole KFM05A, there are 249 fractures in section 100 to 160 mbl. with 67.9 percent of all fractures open and 2.4 percent partly open. The most common fracture minerals (Table 3-13) are chlorite, clay minerals and calcite and their relative proportion of open fractures are: 72.5, 89.9 and 67.4 percent, respectively. The proportion of altered open fractures in relation to open fractures is for chlorite 89.4 percent, for clay minerals 97.8 percent and for calcite 90.9 percent. Partly open fractures are notably few (6) and half of them are altered (two with clay minerals and one without fill).

Other fractures that have a notably high relative percentage of open fractures are fractures with “no fill” (76.7 %), with asphaltite (97.4 %), with pyrite (88.2 %) and fractures coated with iron hydroxides (76.7 %). The relative proportion of open fractures noted as altered are for fractures with “no fill” 93.6 percent (29 out of 31), for asphaltite 94.7 percent (36 out of 38), for pyrite 93.3 percent (14 out of 15) and iron hydroxides 83.3 percent (5 out of 6).

Fractures with oxidized walls are generally tight (9.5 % are open). Fractures with laumontite, prehnite and red feldspar appear to be tight, although the samples are too small to make a definite judgement.

Table 3-13: Relation between all, open and partly open fractures and their fracture fills and wall rock alteration in the shallow parts of cored borehole KFM05A, section 100 to 165 m borehole length (number of sealed fractures = all fractures – (open + partly open fractures)).

	Fractures – number of observations			In percent of total number of fractures (249)		
Fracture fill	**All fractures**	**Open Fractures**	**Partly open fractures**	**All fractures**	**Open fractures**	**Partly open fractures**
Fractures that have a potential to be soft or connect water						
Chlorite	109	79	1	43.8	31.7	0.4
Clay minerals	99	89	3	39.8	35.7	1.2
Calcite	98	66	1	39.4	26.5	0.4
No infill	43	31	2	17.3	12.4	0.8
Asphaltite	39	38	0	15.7	15.3	0.0
Pyrite	17	15	0	6.8	6.0	0
Hematite	9	4	0	3.6	1.6	0
Iron hydroxide	8	6	0	3.2	2.4	0
Fractures that have a potential to be stiff and tight						
Oxidized walls	21	2	0	8.4	0.8	0
Laumontite	7	0	0	2.8	0	0
Quartz	6	2	0	2.4	0.8	0
Prehnite	3	0	0	1.2	0.0	0
Accessorial mineral						
Red feldspar	2	0	0	0.8	0	0
Potash feldspar	1	1	0	0	0	0.4
Sulphides	1	1	0	0.4	0.4	0

Brittle deformation zones in the SKB model

The investigated shallow section of borehole KFM05A contains one SKB deformation zone (DZ1: 102 to 114 mbl., cf. Fig. 3-118), which corresponds to the gently inclined brittle deformation zone ZFMA2 in the geological model of the area (orientation: 80/24; Stephens et al. 2007). It should be noted that the cored part of the borehole starts at about 102 mbl., so the location of the upper boundary of the zone may not be reflected in the core log.

A study of the character and kinematics of deformation zones have been performed in borehole KFM05A (Nordgulen and Saintot 2006). Deformation zone DZ1 is very briefly described. Noted is:

- A low frequency of oriented sealed fractures and more abundant gently dipping open fractures.
- Two narrow crush zones (up to two decimetre wide) at the base of the deformation zone – classified as fault core.

- No kinematic indicators found.

Location of brittle deformation and zones of weakness

Structural features that may indicate weaker section in the bedrock and location of brittle deformation zones are compiled in Figure 3-118. The text is focused on discrete fractures (fractures mapped as single structures); how they are clustered and how they are related to other geological observations. These observations concern:

- Sections with crushed rock.
- Sections with brittle-ductile shear zones.
- Sections with ductile shear zones.
- Sections with network of sealed fractures.
- Sections with altered host rock.
- Location of water-conductive sections in the borehole (PFL anomalies).

The general fracturing in section 100 to 160 mbl. in borehole KFM05A is 4.0 fr/mbl. Corresponding numbers for open and open altered fractures are 2.7 fr/mbl. and 2.5 fr/mbl., respectively. This implies that 93 percent of all open fractures are affected by alteration. The general fracturing in the first 60 m of borehole KFM05A appears not to be enhanced in comparison to other parts of the Forsmark area and might even be lower. Clusters of fractures occur primarily in the borehole interval 102 to 115 mbl. and at 116.5, 120.4, 124 and 164 mbl. (Figs. 3-118a to 3-118f). All of these four single clusters comprise open altered low-angle fractures. The clusters are about 0.1 mbl. wide and correlate with PFL anomalies. In section 102 to 115 mbl. open altered low-angle fractures are most common at 102.5, 108 and 112.5 mbl., i.e. the clusters are fairly regularly distributed in the upper part of the borehole, from 102 to 124 mbl. (Figs. 3-118c to 3-118f).

In the upper part of the borehole, at about 107 and 109 mbl. there are two thin zones (less than 0.25 m wide) with crushed rock. The rock between these zones has an increased density of open altered low-angle fractures (Figs. 3-118a-h). Three brittle-ductile shear zones are noted (Fig. 3-118h); two at about 139.5 mbl. (widths are 0.3 and 0.07 mbl) and one at 149 mbl. (0.08 mbl). Ductile shear zones (Fig. 3-118k) are located close to two of the brittle-ductile shear zones (at 139 and 149 mbl.). The two types of shear do not fully agree in position; ductile shears are located either just above or below the brittle shears. Two additional ductile shears occur at 127 and 136 mbl. The width of ductile shears is less the 0.4 mbl.

Two sections with networks of sealed fractures are recorded. The upper section (110 mbl.; 0.15 m wide) is located just below a section with crushed rock and the other occurs together with brittle-ductile and ductile shear zones (139 mbl.; 0.1 m wide). Sections with altered host rock occur in the upper part of the borehole and coincide with sections with a general increase in fracturing (Fig. 3-118m).

Connected structures outlining the flow paths for groundwater are primarily located in the upper part of the investigated borehole section (Fig. 3-118n). Such structures are dominantly sub-horizontal to gently dipping. Sixty-five percent (13 out of 20 PFL anomalies) are correlated with intervals with increased fracturing (clusters of fractures, crushed rock and brittle-ductile shear zones). Remaining PFL-anomalies are correlated with discrete fractures.

The SKB deformation zone DZI (the intersection of the gently inclined zone ZFMA2 in borehole KFM05A) is located in the upper part of the borehole (between 102 and 114 mbl.) and display inhomogeneous fracturing; enhanced in its lower part. Low-angle fractures dominate and clusters of open altered low-angle fractures form the upper boundary of DZ1 and dominate the central and lower parts of DZ1. There are also two sections of crushed rock in the central part of DZ1 at 107 and 109 mbl., respectively.

However, the general fracturing of the rock increases below DZ1 and clusters of open altered low-angle fractures appear at regular intervals to about 125 m borehole depth (separations of clusters are about 3 to 4 mbl.). Indicated water-conducting intervals in DZ1 are also focused to its central and lower parts. However, indicated water-conducting structures are also common below DZ1 (Fig. 3-118), in the section with a regular appearance of clusters formed by open altered low-angle fractures at about 115 to 125 mbl. Zone ZFMA2 appears to be weaker in its central and lower parts and there are some indicated thin weak structures below zone ZFMA2, for example at 124 mbl. (about 0.4 mbl. wide) and 164 mbl. (about 0.4 mbl.). An additional minor weakness zone is indicated by PFL measurements at a minor brittle-ductile shear zone at 149 mbl. (about 0.08 mbl. wide).

Table 3-14. Character of clusters of fractures in borehole KFM05A section 100 to 165 m borehole length (cf. Fig 3-118). Two groups of fractures are treated: All fractures and open altered fractures. Identification of clusters is based on two criteria: 1. The minimum mutual separation between fractures, 0.10 and 0.20 m (corresponding to minimum fracture frequency of 10 and 5 fractures per metre borehole length, respectively) and 2. The minimum number of fractures to outline a cluster (4 fractures).

Cluster				**Borehole KFM05A**					
ID[2]	**Group of fractures**	**Criterion to identify clusters**		**Borehole section 100 to 165 m borehole length**					
		Minimum number of fractures to outline a cluster[1]	**Minimum fracture frequency (fr/mbl.)[3]**	**Number of clusters**	**Length of clusters (mbl.)**	**Length of clusters in percent of section length (%)**	**Mean fracture frequency in section (fr/mbl.)**	**Mean fracture frequency in clusters (fr/mbl.)**	**Fractures in clusters in percent of fractures in section (%)**
5A:1	*All.*	4	10	11	2.2	3.4	4.0	30.8	30.9
5A:2		4	5	15	7.3	11.7	4.0	14.6	58.8
5A:3	*Open and*	4	10	5	1.0	1.6	2.5	33.6	24.7
5A:4	*altered*:All,	4	5	12	3.9	6.2	2.5	16.5	49.4
5A:5	Dip< 45°	4	10[4]	5	0.8	1.3	1.9	33.5	27.3
5A:6	Dip< 45°	4	5[4]	10	3.5	5.5	1.9	14.4	49.6
5A:7	Dip> 45°	4	5	0	-	-	0.4	-	-

[1] Minimum number of fractures to outline a cluster – 4 fractures = 3 core piece. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of clusters).

[2] ID of group of clusters.

[3] fr/mbl. = fractures per metre borehole length.

[4] Separation of fractures in clusters (bias corrected) >10 fr/m and >5 fr/m are less than 0.13 and 0.26 mbl., respectively.

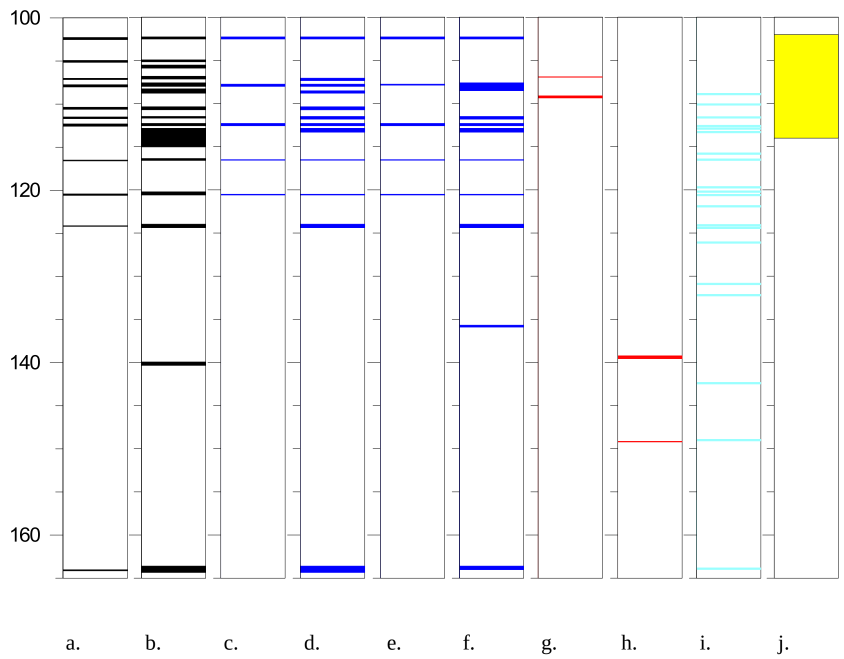


Figure 3-118: Borehole KFM05A section 100 to 165 mbl.; Clusters of fractures (Table 3-14), brittle structures, Posiva Flow log and location of SKB ESHI (zone ZFMA2):

a. All fractures (cluster 5A:1), fracture separation less than 0.10 m (fracture frequency>10 fr/mbl.).

b. All fractures (cluster 5A:2), fracture separation less than 0.20 m (fracture frequency>5 fr/mbl.).

c. Open altered fractures (cluster 5A:3), separation less than 0.10 m (fracture frequency>10 fr/mbl.).

d. Open altered fractures (cluster 5A:4), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

e. Open altered fractures inclined less than 45° (cluster 5A:5), separation less than 0.13 m (fracture frequency>10 fr/mbl.).

f. Open altered fractures inclined less than 45° (cluster 5A:6), separation less than 0.26 m (fracture frequency>5 fr/mbl.).

g. Sections with crushed rock.

h. Sections with brittle-ductile shear zones.

i. Indicated water-conductive fractures (PFL, point measurements, here given a width of 0.2 m).

j. SKB's interpreted location of the gently inclined zone ZFMA2 (102 to 114 mbl.). To be continued.

(To be continued.)

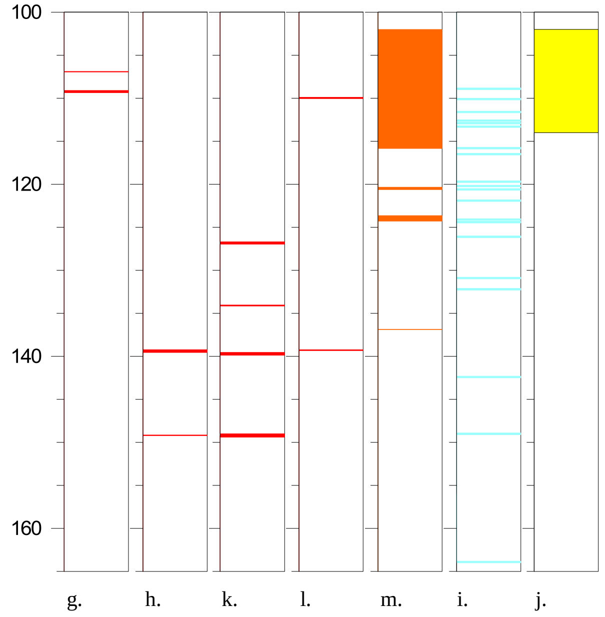


Figure 3-118 (continued): Borehole KFM05A section 100 to 165 mbl.; brittle structures, Posiva Flow log and location of SKB ESHI (zone ZFMA2):

g. Sections with crushed rock.

h. Sections with brittle-ductile shear zones.

k. Sections with ductile shear zones.

l. Sections with network of sealed fractures.

m. Sections with altered host rock, oxidation.

i. Indicated water-conductive fractures (PFL, point measurements, here given a width of 0.2 m).

j. SKB's interpreted location of the gently inclined zone ZFMA2 (102 to 114 mbl.).

Fractures and sections with increased fracturing

All fractures outside clusters (5A:2, Fig. 3-119b) display a pseudo-orthorhombic pattern, while open altered fractures outside clusters (5A:4, Fig. 3-119d) are mainly without NW/subvertical fractures. The pattern of all fractures and open altered fractures inside clusters (5A:2 and 5A:4, Figs. 3-119a,c) are controlled by gently dipping to horizontal fractures while NW/steepW fractures are absent and NE/sub-vertical fractures are very few.

Furthermore, the fractures inside the gently inclined brittle deformation zone ZFMA2 display similar sets of open altered fractures found elsewhere in the borehole (cf. Figs. 3-120 and 3-119d). The main difference between the fracture population in and outside zone ZFMA2 is the fracture density; 6.5 in the zone and 0.2 open altered fractures per metre borehole length below the zone.

The NW/steep open altered fractures are spread along the borehole and often form minor groups (2 to 3 fractures together).

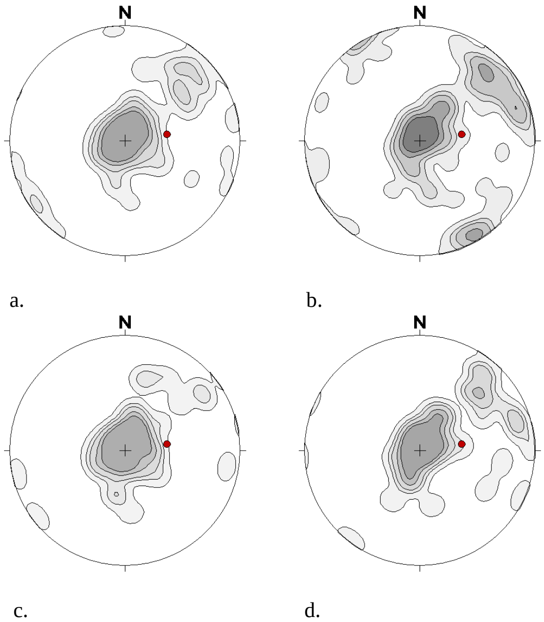


Figure 3-119: Fractures in borehole KFM05A, section 100 to 160 mbl.:

a. Fractures inside clusters (5A:2; cf. Table 3-14); N=122 (123, one without orientation).

b. Fractures outside clusters (5A:2), N=119 (125, 6 fractures missing orientation).

c. Open altered fractures in clusters (5A:4), N= 75 (76, one fracture missing orientation.

d. Open altered fractures outside clusters (5A:4), N= 71 (75, one fracture missing orientation).

The red dot is the orientation of the borehole.

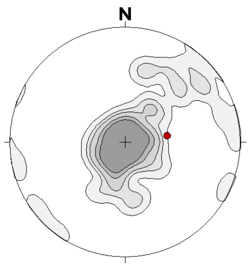


Figure 3-120: Open altered fractures in SKB deformation zone DZ1, modelled gently inclined brittle deformation zone ZFMA2 in borehole KFM05A (102 to 114 mbl.), N=78. The red dot is the orientation of the borehole.

Character of SKB DZ

The intersection of the gently inclined brittle deformation zone ZFMA2 (SKB DZ1; 102 to 114 mbl) is located in the uppermost part of borehole described in the core log. All rock in DZ1 is oxidized and the oxidation extends some metres below DZ1 (at 116 mbl.). DZ1 contains two minor sections of crushed rock (the lower associated with a minor section with a network of sealed fractures) located in its central part. The density of open alter fractures is enhanced in the central to lower part of DZ1. The lower boundary of DZ1 is located in a section of general increased fracture density (considering all fractures). Gently dipping open altered fractures are common in the uppermost, central and lower part of DZ1.

PFL anomalies are common in the section of DZI that is logged. However, PFL anomalies are also common below DZ1.

Comments

The fracturing in the upper part of borehole KFM05A differs from other investigated shallow borehole sections in that respect that it has, in relative terms, a low fracture frequency. All PFL anomalies in the uppermost 5 mbl. of the PFL logged section (110 to 115 mbl.; mainly located in SKB DZ1) are associated with swarms of fracture clusters formed by gently inclined to sub-horizontal, open altered fractures. From 115 to 125 mbl., swarms of PFL anomalies occur still, and here they are related to discrete fracture clusters and discrete fractures of the same fracture set constituting clusters in the uppermost section of the borehole. From 125 to 165 mbl. there are additional six PFL anomalies and out of these 4 are well correlated with open altered gently inclined fractures (one intersects a steeply dipping brittle reactivated ductile shear zone), while two PFL anomalies have no obvious correlation to open fractures.

An alternative interpretation of the structural and hydrological data in bore-hole KFM05A is to extend the width of zone ZFMA2 about 15 m (to 126 mbl.) and by that the borehole section may represent a structural segment containing splays located below the main zone.

Fractures parting the core (called broken fractures in SICADA; contain mainly open fractures and also broken partly open and sealed fractures) are most frequent in the upper part of the borehole (above 126 mbl.). However, the number of fractures related to sheet jointing is not known. Furthermore, all open sub-horizontal fracture without fracture fill (6) are slightly altered and occur above 160 mbl. (- 133 m a.s.l.).

KFM10A - section 350 to 500 m borehole length

The cored borehole KFM10A is located in the southern part of the detailed study area at Forsmark (Fig. 3-3) and the borehole is drilled northwards with a moderate plunge (orientation: 001/50; Table 3-1). The investigated section in borehole KFM10A, section 350 to 500 mbl., is the deepest part of the bedrock investigated in this study; - 248 to -338 m a.s.l. However, investigated sections in boreholes KFM02A and KFM02B located outside the local Forsmark model area are even deeper (about -340 to -480 m a.s.l, Table 3-1).

Rock types and general structure elements

Rock types

The bedrock in borehole KFM10A consists mainly of metamorphic/foliated granitic to granodioritic rocks with some intercalated wider bands (up to 3 m wide along the borehole) of somewhat more coarse-grained pegmatitic rocks, commonly foliated, and a band of amphibolite. A high density of centimetre to decimetre wide parallel bands gives the bedrock a pronounced structural grain, a well-developed foliation.

All fractures

For all fractures in the section 350 to 500 mbl. along borehole KFM10A fracture dipping gently southwards are dominant and frequent are also fractures oriented WNW/sub-horizontal to steep SSW (Fig. 3-121). There are subdominant sets of fractures oriented EW/steepN, WNW/steepNNE and NE/steepSE.

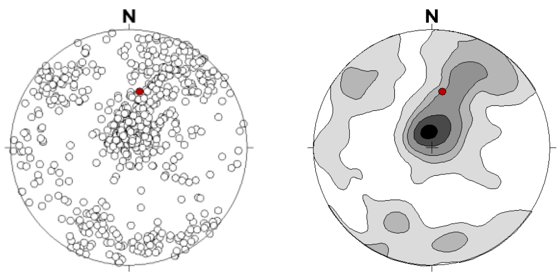


Figure 3-121: All fractures in section borehole KFM10A, section 350 to 500 mbl., N=652 (682 with 30 fractures without orientation). The red dot is the orientation of the borehole.

Open altered fractures

The dominant orientation for open altered fractures is similar to all fractures in the studied section of the borehole KFM10A (Fig. 3-122). The subdominant sets of all fractures (Fig. 3-121) are represented by only very few open altered fractures.

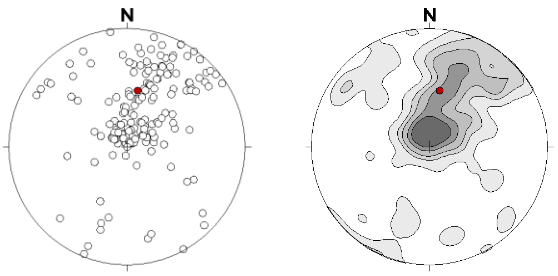


Figure 3-122: Open altered fractures in borehole KFM10A, section 350 to 500 mbl., N=168 (176 total including 8 without orientation). The red dot is the orientation of the borehole.

Core loss

One section with core loss is noted at 448.24 to 448.33 m (0.09 m) borehole length. The core loss is noted as mechanical, i.e. caused by the drilling.

Crushed rock

Crushed rock is not noted in the investigated section of borehole KFM10A.

Sealed networks of fractures

The twenty-seven sections with sealed fractures in section 350 to 500 mbl. of borehole KFM10A constitute a total of 5.1 m of the drill core (3.4 % of the length of the investigated section). The widest section with sealed network of fractures is 1.06 m and the mean width is about 0.2 m. The orientations of

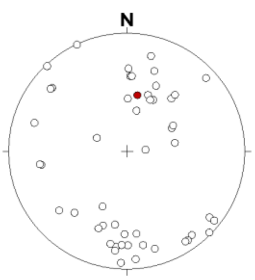


Figure 3-123: Sealed network of fractures in borehole KFM10A, section 350 to 500 mbl., upper and lower contacts, N=54 (27 sections, upper and lower contacts). The red dot is the orientation of the borehole.

the sealed networks of fractures are somewhat scattered (Fig. 3-123). The dominant orientations are EW/steepN, WNW/moderateS and NE/sub-vertical, i.e. they deviate from the main orientations of open altered fractures.

Rock alteration

The sections with altered rock appear generally as thin domains (80 sections, some types of alterations overprint each other; mean width less than 0.2 m, maximum borehole section length is 5.0 m) and have two dominant orientations; NNW/vertical and NW/steepSW (Fig. 3-124). Dominant type of alterations is oxidation (9 sections; total 10.6 mbl). Between 483.6 to 487.8 mbl., within a 5 mbl. wide section of oxidized rock, the quartz grains are dissolved (vuggy granite; 4.2 mbl., the only section). At about 484 mbl. there are also two minor sections (total about 0.1 mbl.) affected by argillization. Most common in number is albitization (54 sections; 1.9 mbl.).

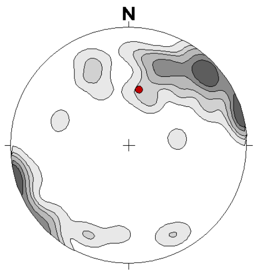


Figure 3-124: Altered the rock in borehole KFM10A, section 350 to 500 mbl., N=80. The red dot is the orientation of the borehole.

Lithological contacts

The dominant orientations of lithological contacts is NW/steepSW and subdominant is NE/moderate SE (Fig. 3-125). Orientations of the contacts between main rock types conform to the orientation of thinner rock bands and veins.

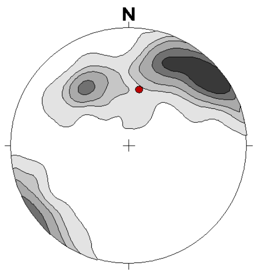


Figure 3-125: Lithological contacts in borehole KFM10A, section 350 to 500mbl., N=1307 (23 are contacts between main rock types and 1284 are upper and lower contacts of thinner bands such as veins). The red dot is the orientation of the borehole.

Ductile shear zones

Three ductile shear zones occur. Two are oriented NW/sub-vertical while the third is more moderately dipping and appears to be irregular (Fig. 3-126).

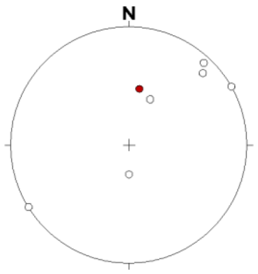


Figure 3-126: Ductile shear zones in borehole KFM10A, section 350 to 500 mbl., N=6 (3 zones, upper and lower contacts). The red dot is the orientation of the borehole.

Brittle-ductile zones

One brittle-ductile shear zone is mapped and its orientation is EW/moderateS (Fig. 3-127).

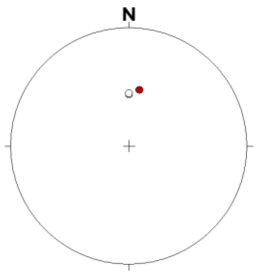


Figure 3-127: Brittle-ductile shear zone in borehole KFM10A, section 350 to 500 mbl., N=1. The red dot is the orientation of the borehole.

Cataclastic rocks

Two parallel bands of cataclastic rocks are noted (Fig. 3-128), with a separation of 10 mbl. (found at 419 and 429 mbl.).

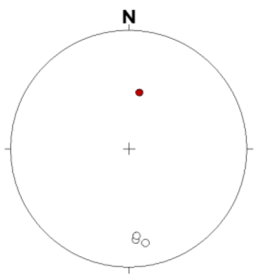


Figure 3-128: Cataclastic rocks in borehole KFM10A, section 350 to 500 mbl., N=4 (2 zones; upper and lower contacts plotted). The red dot is the orientation of the borehole.

Breccia

The noted breccia is sub-parallel to the foliation (cf. Figs. 3-129 and 3-130).

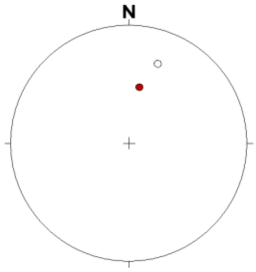


Figure 3-129: Breccia in borehole KFM10A, section 350 to 500 mbl., N=2 (1 zone). The red dot is the orientation of the borehole.

Foliation

The foliation is uniform and oriented NW/steepSW (Fig. 3-130) and it is parallel to the banding in the rock (cf. Fig. 3-125).

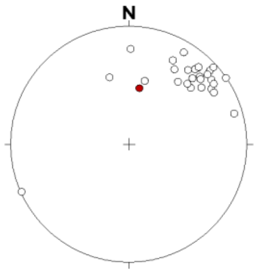


Figure 3-130: Foliations in borehole KFM10A, section 350 to 500 mbl., N=27. The red dot is the orientation of the borehole.

Water-conductive fractures

Eleven water-conductive fractures are indicated by the Posiva Flow Log (PFL) and all could be correlated to open altered fractures (Fig. 3-131). The most common orientation of the conductive fractures is horizontal and remaining hydraulic fractures have NNW:ly trends and variable dips. The correlation between hydraulic fractures and borehole radar reflectors is weak (possibly 3 out of 11). The deepest located PFL anomaly in KFM10A, at 484 mbl., is located within the vuggy granite and dips southward (105/56).

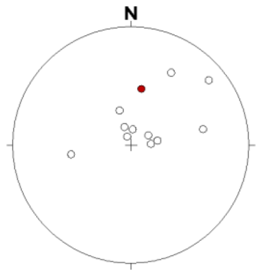


Figure 3-131: Orientation of PFL anomalies in borehole KFM10A, sections 350 to 500 mbl., N=11. Correlation between PFL anomalies and fractures are made in the present study. The red dot is the orientation of the borehole.

Borehole radar

Four orientations are indicated. However, the radar reflectors may represent only two sets of reflectors; sub-horizontal and NW/steepSW (Fig. 3-132). These two orientations agree with geological data (e.g. open altered fractures and foliation/ductile shears).

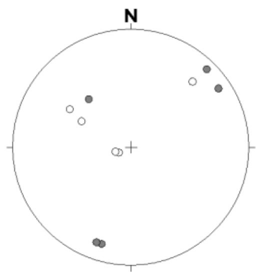


Figure 3-132: Borehole radar reflectors in borehole KFM10A, section 350 to 500 mbl., N=5 (two alternative orientations: alt.1 open circles and alt. 2 grey dots).

Fracture minerals

Section 350 to 500 m of borehole KFM10A contain 682 fractures and of these are 41.1 percent open and 25.7 percent are partly open, i.e. a third of all fractures are sealed. The most common fracture minerals are calcite and chlorite (Table 3-15) and their relative proportion of open fractures are 40 and 54 percent, respectively. Common are also fractures without fill and 58 percent of these are mapped as open. These three types of fracture minerals are associated with the main part of fractures having low cohesion, i.e. altered fractures. The relative amount of altered fractures is for fractures with calcite 30.5 percent (47 out of 154), for fractures with chlorite 93.1 percent (95 out of 102) and for fractures with “no fill” 25.6 percent (14 out of 57).

The relative amounts of open fractures containing quartz and prehnite are relatively high (48.9 and 79.5 %) in this borehole and their proportions of altered fractures are 72.7 percent (16 out of 22) and 67.7 percent (21 out 0f 31), respectively. Fractures containing minerals such as pyrite or clay minerals have generally a high percentage of open fractures, although their percentages of all fractures are low. Pyrite and clay minerals are found in a few percent of all fractures (>3 %) in borehole KFM10A and their relative percentage of open fractures are high (about 80 %) while the relative proportion of open altered fractures vary from 37.5 percent for pyrite (6 out of 16) to 100 percent for clay minerals.

Typical characteristics for tight fractures are that they either have oxidized walls (constitutes 25 % of all fractures) and/or contain adularia, laumontite and an “unknown” mineral.

Table 3-15: Relation between all, open and partly open fractures and their fracture fills and wall rock alteration in the cored borehole KFM10A, section 350 to 500 m borehole length (number of sealed fractures = all fractures – (open + partly open fractures)).

	Fractures – number of observations			In percent of total number of fractures (682)		
Fracture fill	**All fractures**	**Open fractures**	**Partly open fractures**	**All Fractures**	**Open fractures**	**Partly open fractures**
Fractures that have a potential to be soft or connect water						
Calcite	382	154	18	56.0	22.6	2.6
Chlorite	190	102	12	27.9	15.0	1.8
No infill	93	57	4	13.6	8.4	0.6
Quartz	45	22	4	6.6	3.2	0.6
Prehnite	39	31	0	5.7	4.5	0
Pyrite	19	16	1	2.8	2.3	0.1
Clay minerals	16	11	3	2.3	1.6	0.4
Fractures that have a potential to be stiff and tight						
Oxidized walls	167	24	7	24.5	3.5	1.0
Adularia	71	12	5	10.4	1.8	0.7
Laumontite	21	6	0	3.1	0.9	0
Unknown minerals	21	2	6	3.1	0.3	0.9
Accessorial mineral						
Epidote	6	2	0	0.9	0.3	0
Hematite	3	1	2	0.4	0.1	0.3
Polished walls	2	2	0	0	0	0
Sulphides (not pyrite)	1	1	0	0.1	0.1	0
Sericite	1	1	0	0.1	0.1	0

Brittle deformation zones in the SKB model

The investigated section of borehole KFM10A is centred on the gently inclined brittle deformation zone ZFM02A, which have two branches. The upper branch (DZ2) intersects the borehole between 430 to 449 mbl. and the lower (DZ3) at 478 to 490 mbl. Fault core zones are not developed in either of the two branches. Occurrence of vuggy granites is noted in the lower branch (Stephens et al. 2008; cf. section Rock alteration above).

In a study of fracture kinematics (Saintot and Nordgulen 2007) it is noted that sealed fractures are typical in the most fractured part of DZ2 (at about 440 mbl.). In DZ3, there is a gently inclined fault (a striated fracture) and the fracturing is increased at 485 mbl.

Location of brittle deformation and zones of weakness

Structural features that may indicate weaker sections in the bedrock and locations of brittle deformation zones are compiled in Figure 3-133. The text is focused on discrete fractures (fractures mapped as single structures); how they are clustered and how they are related to other geological observations. These observations concern:

- Clustering of all fractures, open altered fractures, open altered low-angle fractures and open altered EW/moderateS fractures.
- Section with core loss.
- Sections with brittle-ductile shear zones.
- Sections with ductile shear zones.
- Sections with network of sealed fractures.
- Sections with cataclastic rocks.
- Sections with altered host rock.
- Locations of water-conductive sections in the borehole (PFL anomalies).

The general fracturing in section 350 to 500 mbl. in borehole KFM10A is 4.5 fr/mbl. Corresponding numbers for open and open altered fractures are 1.9 fr/mbl. and 1.2 fr/mbl., respectively. This implies that 63 percent of all open fractures are affected by alteration. However, the general fracturing in the rock is inhomogeneous and the investigated section can be divided into three parts (Figs. 3-133a to 3-133g and Table 3-16):

- An upper part, 350 to 392 mbl., with a distribution of thin clusters (10A:2, up to 0.5 m wide). Open altered fractures do not form clusters, according to the definition of clusters applied in this report.
- A central part, 423 to 449 mbl., with enhanced density of fracture clusters (10A:1 and 10A:2). Clusters of open altered fractures occur at three levels, of which the upper one at 431 mbl. is about 0.5 m wide and comprise gently inclined fractures (10A:5). Other clusters of open altered fractures (10A:4) are located at 433 and 438 mbl.
- A lower part, 479 to 489 mbl., which is the most fractured part of the investigated section of borehole KFM10A (10A:1 and 10A:2). Clusters of open altered fractures (10A:4) occur at the uppermost part of this interval and primarily in its middle part (483 to 487 mbl.). There are no clusters formed by gently inclined to sub-horizontal open altered fractures, which indicate that the clusters formed by open altered fractures (10A:4) mainly have inclinations greater than 20°, e.g. clusters formed by fractures oriented EW/moderateS (10A:7, less than 0.4 m wide at 483 and 485 mbl.).

Core loss is noted in the lower segment of the central part (448 mbl., Fig. 3-133j) and a brittle-ductile shear zone is located in the central lower part of the investigated section of the borehole (484 mbl., Fig. 3-133k). Ductile shear zones are located in the upper and lower parts of the investigated section (Fig. 3-133l) and they are neither associated with brittle-ductile shears, cataclastic rocks nor crushed rock (the latter not found in the borehole). However, two bands of cataclastic rocks are noted in the central part of the investigated section, at 417 and 429 mbl. (Fig. 3-133n). These bands are associated with networks of sealed fractures and such networks are most common in the middle and lower parts of the investigated section (Fig. 3-133m). The bedrock is commonly altered throughout the investigated section and the widest altered section occurs between 479 to 488 mbl. (Fig. 3-133o).

Indicated water-conductive structures (11 PFL anomalies, Fig. 3-133h) are all located in the three parts of the borehole with enhanced fracturing (see text above). However, only three PFL anomalies correlate with clusters of open altered fractures and one of the three with a cluster formed by low-angle fractures (dip<20°, at 432 mbl.). Six more PFL anomalies are located in clusters outlined by the general fracturing in the rock (all fractures). PFL anomalies are also correlated with one ductile (at 360 mbl.) and one brittle-ductile shear zone (at 484 mbl.). Only the latter is associated with general increase of fracturing in the rock,

The SKB deformation zones (DZ2 and DZ3, Fig. 3-133i) agree with the clusters outlined by the general fracturing (clusters 10A:1 and 10A:2, Figs. 133a and b). The upper zone DZ2 is inhomogeneous and contain three segments with lower fracture densities and these sections are regularly distributed inside zone DZ2. A cluster of open altered low-angle fractures (10A:5/10A:6, Figs. 133e and f), correlated with a PFL anomaly, is located in the upper part of DZ2 (at 432 mbl.). Three other PFL anomalies (between 436 to 438 mbl.) are located in the central part of DZ2 and the lower of these PFL anomalies is located with cluster of open altered fractures (10A:4, Fig. 3-133d). A cluster of fractures (10A:2) are found just above DZ2. The weak parts of DZ2 are mainly found at two levels; i.e. about 436 and 438 mbl.

The lower SKB deformation zone DZ3 coincides with an intensely fractured section (10A:1 and 10A:2). The general fracturing in zone DZ3 is as in DZ2 inhomogeneous and it is more intense and more focused to a narrower section in the rock. Clusters of open altered fracture (10A:4) are primarily found in the central parts of DZ3, between 483 to 487 mbl., and in its upper part (2 clusters at about 479 mbl.). The central part of DZ3 also contains clusters formed by moderately inclined open altered fractures (10A:7) and the bedrock is altered. Three PFL anomalies are recorded inside zone DZ3; two at about 480.5 m and one at 484.5 mbl. The weaker part of DZ3 appears to be its central part, which contains moderately inclined open fractures, a brittle-ductile shear zone and a network of sealed fractures located in altered rock.

Further studies are needed for analysis of the structural relation between DZ2 and DZ3. Zone DZ3 contains no clusters outlined by low-angle fractures (10A:5/10A:6) and DZ2 has no pronounced density of moderately inclined fractures (10A:7). The distribution of fractures differs between the two DZ's.

Table 3-16. Character of clusters of fractures in borehole KFM10A section 350 to 500 m borehole length (cf. Fig 3-102). Two groups of fractures are treated: All fractures and open altered fractures (all open altered and two sets of fractures). Identification of clusters is based on two criteria: 1. The minimum mutual separation between fractures, 0.10 and 0.20 m (corresponding to minimum fracture frequency of 10 and 5 fractures per metre borehole length, respectively) and 2. The minimum number of fractures to outline a cluster (4 fractures).

Cluster				**Borehole KFM10A**					
ID[2]	**Group of fractures**	**Criterion to identify clusters**		**Borehole section 350 to 500 m borehole length**					
		Minimum number of fractures to outline a cluster[1]	**Minimum fracture frequency (fr/mbl.)[3]**	**Number of clusters**	**Length of clusters (mbl.)**	**Length of clusters in percent of section length (%)**	**Mean fracture frequency in section (fr/mbl.)**	**Mean fracture frequency in clusters (fr/mbl.)**	**Fractures in clusters in percent of fractures in section (%)**
10A:1	*All.*	4	10	46	10.5	7.0	4.5	28.7	50.7
10A:2		4	5	40	23.6	15.7	4.5	18.1	68.3
10A:3	*Open and*	4	10	6	1.0	0.7	1.2	24.6	17.1
10A:4	*altered*:All,	4	5	9	3.6	2.4	1.2	15.2	36.0
10A:5	Dip < 20°	4	10[4]	1	0.3	0.2	0.4	38.6	15.1
10A:6	Dip < 20°	4	5[4]	1	0.5	0.3	0.4	19.3	18.7
10A:7	EW/modS	4	5	2	0.5	0.4	0.2	18.8	30.6

[1] Minimum number of fractures to outline a cluster – 4 fractures = 3 core piece. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of clusters).

[2] ID of group of clusters.

[3] fr/mbl. = fractures per metre borehole length.

[4] Separation of fracture in clusters >10 fr/mbl. and >5 fr/mbl. are less than 0.13 and 0.25 mbl., respectively.

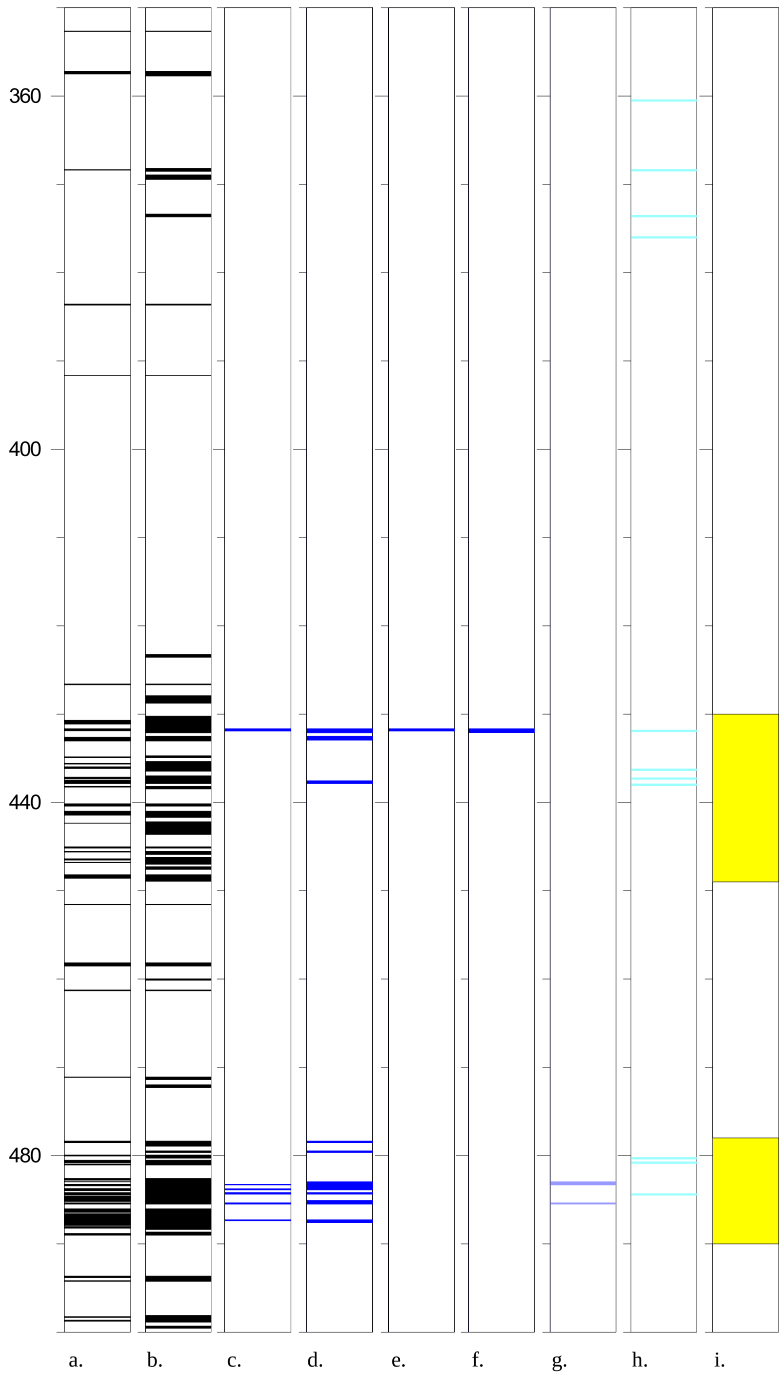


Figure 3-133. Borehole KFM010A section 350 to 500 mbl.; Clusters of fractures (Table 3-16), brittle structures, ductile structures, alteration, Posiva Flow log and location of SKB ESHI (zone ZFMA2):

a. All fractures (cluster 10A:1), fracture separation less than 0.10 m (fracture frequency>10 fr/mbl.).

b. All fractures (cluster 10A:2), fracture separation less than 0.20 m (fracture frequency>5 fr/mbl.).

c. Open altered fractures (cluster 10A:3), separation less than 0.10 m (fracture frequency>10 fr/mbl.).

d. Open altered fractures (cluster 10A:4), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

e. Open altered fractures inclined less than 20° (cluster 10A:5), separation less than 0.13 m (fracture frequency>10 fr/mbl.).

f. Open altered fractures inclined less than 20° (cluster 10A:6) , separation less than 0.25 m (fracture frequency>5 fr/mbl.).

g. Open altered fractures oriented EW/moderateS (cluster 10A:7), separation less than 0.20 m (fracture frequency>5 fr/mbl.).

h. Indicated water-conductive fractures (PFL, point measurements, here given a width of 0.2 m).

i. SKB's interpreted location of the gently inclined zone ZFMA2 (upper /DZ2 430-449 m/ and lower /DZ3 478-490 mbl./ branches). (To be continued)

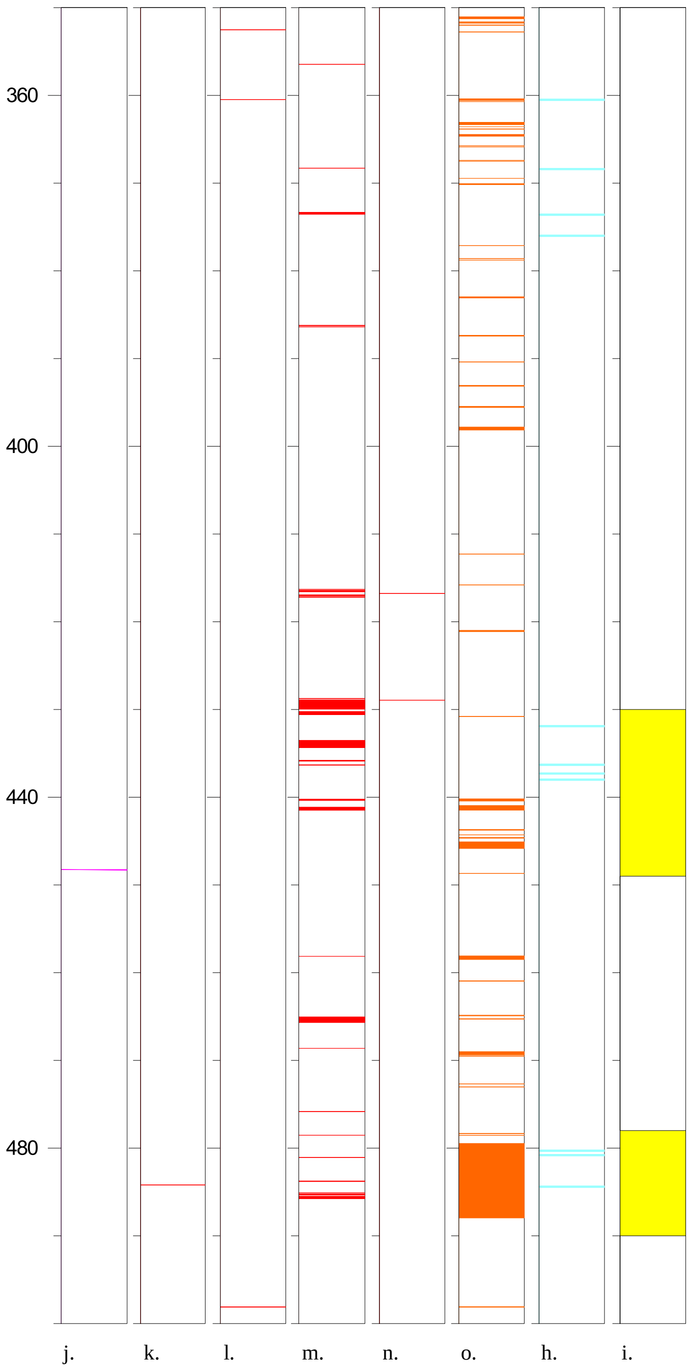


Figure 3-133 (continued): Borehole KFM010A section 350 to 500 mbl.; Clusters of fractures (Table 3-16), brittle structures, ductile structures, alteration, Posiva Flow log and location of SKB ESHI (zone ZFMA2):

j. Section with core loss.

k. Section with brittle-ductile shear zone.

l. Sections with ductile shear zones.

m. Sections with network of sealed fractures.

n. Sections with cataclastic rocks.

o. Sections with altered host rock, oxidation. Vuggy granite in section 483.6 to 487.8 mbl.

h. Indicated water-conductive fractures (PFL, point measurements, here given a width of 0.2 m).

i. SKB's interpreted location of the gently inclined zone ZFMA2 (upper /DZ2 430-449 m/ and lower /DZ3 478-490 mbl./ branches).

Fractures and sections with increased fracturing

In section of KFM10A, 350 to 500 mbl., most of the fractures are incorporated in clusters outlined by at least four fractures having mutual separations less the 0.2 m (10A:2). The orientations of fractures inside such clusters differ to some extent in orientation from fractures located outside the clusters (cf. Fig. 3-134a and 3-134b). The relative proportion of fractures oriented NW/steepSW and NW/sub-verticalSE are higher outside clusters than inside and the clusters are mainly formed by low-angle fractures (dip<20°).

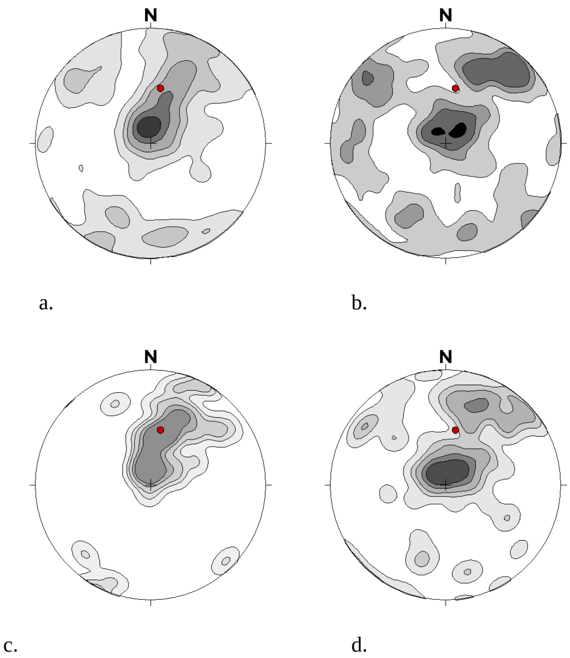


Figure 3-134: Fractures in borehole KFM10A, section 350 to 500 mbl.;

a. Fractures inside clusters (10A:2, cf. Table 3-16), N=438 (465, 27 without orientation).

b. Fracture outside clusters (10A:2), N=214 (217, 2 without orientations).

c. Open altered fractures inside clusters (10A:4), N= 57 (65, 9 without orientation).

d. Open altered fractures outside clusters (10A:4), N=112.

Clusters outlined by open altered factures display the same fracture orientations as clusters outlined by all fractures (cf. Figs. 3-134c and 3-134a) but the orientations of the open altered fractures are more evenly spread with respect to inclination (horizontal to steeply south-westwards). Amongst open altered fracture located outside clusters (10A:4, Fig. 3-134d), the horizontal to gently inclined fractures are in relative terms more accentuated and a subordinate set of fractures is oriented WNW/steepSW. Generally, fractures outside clusters display a greater spread in orientation than fractures inside clusters (cf. Figs. 3-134b,d and 3-134a,c).

Character of SKB DZ

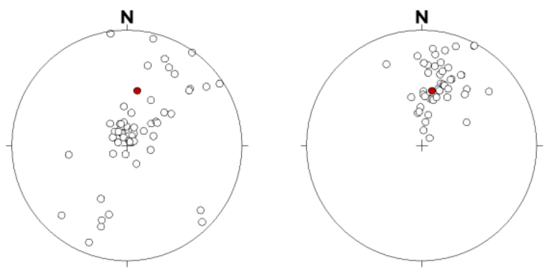
The potential deformation zones (SKB DZ2 and DZ3, Fig. 3-133) outlined in borehole KFM10A cover the two main sections with increased fracturing in the studied part of the borehole. The upper boundary of DZ2 is uncertain as it is located within a section of increased fracturing and located below a network of sealed fractures and a thin band of cataclastic rock. The internal structure in DZ2 displays a regular pattern of alternating well fractured and less fractures sections. The upper part of DZ2 contains a thin cluster of gently inclined open fractures coinciding with a PFL anomaly. In the central part of DZ2 there are three more PFL anomalies and these are associated with sub-horizontal to moderately dipping open altered fractures. DZ2 contains some thin bands with oxidized rock and they are not exceptional in relation to other parts of the borehole.

The lover potential zone, SKB DZ3, is a more distinct brittle structure than DZ2 and it coincides with a section of oxidized rock, which in its turn contains a several meter wide section with vuggy granite. The relation between the vuggy granite and DZ3 (lower branch of zone ZFMA2) is not clear. However, in the central parts of DZ3 there is a thin brittle-ductile shear zone, dipping moderately southward, which is bordered by networks of sealed fractures. As in DZ2 zone DZ3 contains PFL anomalies in its upper part (along two gently inclined fractures) and in its central part (along a moderately dipping fracture).

Fractures inside the two SKB brittle deformation zones DZ2 and DZ3 (upper and lower branch/arm of the region and local modelled zone ZFMA2) differ in some respects:

- The frequency of all fracture is lower in DZ2 compared to DZ3 (10.8 fr/mbl. compared to 14.4 fr/mbl.).
- The frequency of open altered fractures in DZ2 is slightly lower than in DZ3 (3.0 compared to 4.8 fr/mbl.). However, the relative proportion of open altered fractures is somewhat higher in DZ2 than in DZ3.

The dominating orientation of fractures in DZ2 is sub-horizontal and the more inclined fractures have WNW-trends, while in DZ3 fractures have moderate to steep southward dips (Fig. 3-135).



a. b.

Figure 3-135: Open altered fractures in SKB DZs in borehole KFM10A, section 350 to 500 mbl.:

a. DZ2, N=57.

b. DZ3, N=49 (58 fractures, 9 without orientation).

Comments

Based only on the geological core log, it is not possible to determine if the two indicated structures (DZ2 and DZ3) are structurally relate to each other, i.e.to establish whether or not the lower section is a steeply inclined branch emanating from the upper more gently inclined zone (representing zone ZFMA2).

An alternative interpretation could be that the lower section (DZ3) represents a moderately inclined zone, which could stop at zone ZFMA2 or cross it.

Character of zone ZFMA2

The methodology outlined in Chapter 2 for identifying sections of increased fracturing has been applied to seven boreholes penetrating the gently inclined brittle deformation zone ZFMA2. A brief summary is given below focusing on fracture data. Before describing the zone, the general fracturing in the seven investigated sections is given.

The seven investigated borehole sections have a total length of about 850 m and the range in width for separate borehole sections is from 65 to 150 mbl. Three sections are located in shallow bedrock (0 to - 140 m a.s.l.), one at intermediate depth (-132 to -237 m a.s.l.) and three at deeper levels (from - 248 to - 480 m. a.s.l.; although the deeper borehole sections below - 338 m a.s.l. are located outside the local Forsmark model area).

Fracturing in Forsmark reflected by seven borehole sections

The fracture frequency varies in the seven investigated sections and is neither a simple function of depth nor a function of the natural variability of the width of the gently inclined zone ZFMA2.

In the three shallow borehole sections (KFM01B, 01C and 05A), fractures occur as discrete structures and also in sections with crushed rock (total borehole length of 2 to 3 m in KFM01B and 01C, and 0.3 m in KFM05; note that zones of crushed rock are not included in fracture frequencies given below). Boreholes KFM01B and KFM01C generally have a high fracture frequency regarding all fractures (9 to 11 fr/mbl., respectively) and the frequency of open altered fractures varies (3 and 1 fracture per metre borehole length for the two boreholes, respectively). Borehole KFM01B, having a higher proportion of crushed rock, has a lower frequency of discrete fractures and a higher frequency of open altered fractures compared to the adjacent borehole KFM01C. The fracture frequency in the investigated borehole section in borehole KFM05A is only 4 fr/mbl. for all discrete fractures and about 2 fr/mbl. for open altered fractures. The dominating orientation of fractures in the three borehole sections is sub-horizontal for all fractures and open altered fractures. Intersections with steeply dipping zones in boreholes

KFM01C and KFM05C are reflected by fractures oriented ENE/sub-vertical and NW/steepSW, respectively.

The borehole KFM04A is drilled close to a regional-scale NW-trending deformation zone and penetrates a NW-trending brittle deformation zone. The investigated borehole section contains one segment with crushed rock (0.2 m wide) and the frequency of all fractures is 9 fr/mbl. The corresponding number for open altered fractures is about 2 fr/mbl. The dominant fracture orientations are sub-horizontal and NW/steepSW for both all fractures and open altered fractures. The section displays a distinct relation between sub-horizontal fractures and the steeply dipping fractures; fractures of the two sets do not mix and domains of sub-horizontal fractures are located above NW/steepSW fractures.

In the deeper sections in boreholes KFM02A, 02B and 10A, the fracture frequencies of all fractures are about 3 to 5 fr/mbl. and 0.2 to 1.2 fr/mbl. for open altered fractures. Only the borehole section in KFM02B contains some minor segment with crushed rock (total width of about 0.2 mbl.). The dominating orientation of all fractures and open altered fracture is sub-horizontal for all three borehole sections. However, there are also subdominant fracture sets in the boreholes. For example, in KFM02A and 02B there are fractures oriented EW/steepN, a set of fractures not appearing as open altered fractures in borehole KFM02A. Another example is fractures that dip moderately south-southwest in borehole KFM10A and these are also found as open altered fractures occurring primarily in the central and lower parts of the investigated section.

The boundaries of zone ZFMA2

Based on the evaluation of fracture data it is in some cases fairly obvious where to set the boundaries of zones while in other cases, even for the same zone, it is more intricate. The former case holds in borehole sections with distinct sets of fractures and where the zone has a high contrast in fracture density compared to the host rock. However, when the general fracturing is enhanced and clusters of fractures may have more or less random distribution within large borehole sections, the second case holds. Especially when a general understanding of the structural framework in the rock is yet not obtained, a high resolution in the investigation is needed. Generalizations may be more adequately formulated when data are understood. Furthermore, there is a general need for a guide describing how to locate structures such as brittle deformation zones and weakness zones (cf. Chapters 2 and 4). Zone ZFMA2 – its variability in character.

Zone ZFMA2 – its variability in character

Zone ZFMA2 have been identified during the SKB site characterization of the Forsmark area. What is presented herein is how the general fracturing in the rock reflects the position of zone ZFMA2 and locations of weaker parts within zone ZFMA2. Staring the description of zone ZFMA2 with information from boreholes intersect the zone at shallow levels and end it with information from the deepest borehole intersection of the zone inside the local model volume.

Zone ZFMA2 in shallow borehole sections

The two shallow borehole sections (in KFM01B and 01C) have relatively high fracture frequencies regarding both all fractures and open altered fractures. In borehole KFM01B, the location of increased fracturing (cluster 1B:2) outlines a section that is somewhat shorter than the width given for ZFMA2 and the zone ZFMA2 displays intense and inhomogeneous deformation in its central parts. The weakest parts of the zone are found in its central parts (indicated by 3 swarms of 1B:3/1B:4 clusters cf. Fig 3-48) and associated with segments of crushed rock. The upper part of ZFMA2 in borehole KFM01B is also weak and contains crushed rock.

In borehole KFM01C it is more difficult to discern the location of zone ZFMA2 within the distribution of all fractures (cf. Fig. 3-61). Zone ZFMA2 is interpreted in the SKB model to occupy two sections (DZ1 at 23 to 48 and DZ2 at 62 to 99 mbl.) in borehole KFM01C. The most intense fracturing in borehole KFM01C occurs in the central to lower parts of DZ1, where the gently inclined zone ZFMA2 is intersected by steeply dipping ENE to NE trending fractures belonging to another SKB zone, ZFMENE1192. The weakest part of DZ1is its central part (about 34 to 43 mbl.) comprising an upper section with both gently inclined and sub-vertical open altered fractures and a lower part with mainly open altered gently inclined fractures and a 0.5 mbl. wide section with crushed rock. The lower branch of ZFMA2 (DZ2) in borehole KFM01C is located in a section of the borehole with enhanced and fairly regular fracturing and the fracturing also extends outside DZ2. Minor weakness zones with a regular spacing (1C:4 and 1C:6 clusters having separations of a few metres up to 10 mbl., from 72 to 109 mbl. in borehole KFM01C) cover the central and lower part of DZ2 and extends below DZ2. A minor ENE/sub-vertical zone (represented by 2 1C:8 clusters, cf. Table 3-6) intersects DZ2 at about 80 mbl. and gently inclined fractures dominate the open altered fractures.

The location of ZFMA2 in the uppermost part of borehole KFM05A (Fig. 3-118) implies that the entire zone may not be covered by available core log data. The fracture data support the location of ZFMA2. However, below ZFMA2 there are three minor sections with regular separations (3 to 4 mbl.) comprising the same set of fractures as in zone ZFMA2, i.e. sub-horizontal to gently inclined fractures that are open and altered. The deformation inside ZFMA2 is inhomogeneous. The weakest parts of ZFMA2 are mainly focused to three thin sections (widths about 0.3 mbl. and evenly separated, about 5mbl.) located in the upper part of ZFMA2 and in the central and lower parts of ZFMA2, respectively.

Zone ZFMA2 in borehole section at intermediate depth

In KFM04A, zone ZFMA2 is again interpreted to have two branches (DZ2 and DZ3), both relatively thin and located between 202 to 213 and 232 to 242 mbl. (Fig. 3-102). The fracture data express clearly the upper boundary of DZ2 and indicate the lower, reflected by 4A:1 clusters. The location of the lower branch of ZFMA2 (DZ3) is uncertain and only supported by a minor cluster of gently inclined fractures at the centre of DZ3 (0.5 m wide at 234 mbl.) and a sub-horizontal section of crushed rock in its upper part (at 232 mbl., 0.2 mbl. wide). The weaker part of DZ2 is its upper half and the weakness is caused by open altered low-angle fractures. The upper SKB deformation (DZ1) in the investigated section of borehole KFM04A is related to a steeply south-westward dipping brittle deformation zone (ZFMNW1200). However, clusters outlined by NW/steepSW fractures are here only found in the lowest part of DZ1. Notable is that both branches of ZFMA2 (DZ2 and DZ3) appear to terminate against thin sub-vertical weakness zones with north-westerly trends. The fracturing between the two branches of zone ZFMA2 is enhanced and fractures are mainly sealed.

Zone ZFMA2 in deep borehole sections

In borehole KFM02A, a wide potential deformation zone is noted (DZ6; 415 to 520 mbl.). The borehole above DZ6 (Fig. 3-72) is poorly fractured and the upper part of DZ6 contains zone ZFMA2 (417 to 442 mbl.). However, fracture data indicate that zone ZFMA2 has an upper part and a lower part separated by a 9 m wide borehole section with few fractures. The separation is of the same order as the width of the upper part of zone ZFM2A and nearly twice the width of the lower part of the zone. Two minor weak zones occur in the upper part of zone ZFMA2. These zones are composed of open altered fractures that dip gently to moderately southeastwards, i.e. they do not conform to the “general orientation” of fractures inside zone ZFMA2. The low number of fractures in the investigated section makes the interpretation uncertain.

In borehole KFM02B zone ZFMA2 occupies a section (DZ3 411 to 431 mbl., cf. Fig. 3-87) of similar width as in the adjacent borehole KFM02A. The distribution of fracture clusters agrees with the location of the zone and clusters of fractures (all) are regularly spread within DZ3. The spit of zone ZFMA2 into two branches generally found in other boreholes is not indicated in borehole KFMA2B. Open altered fractures dipping mainly gently to moderately eastwards indicate three thin weak sections (widths of 0.1 m to 0.5 mbl. The wider sections (both 0.5 mbl.) are located in the central part of the zone, cf. ZFMA2 in KFM02A, and contain mainly open altered fractures dipping gently east-southeast. The distribution of water conductive fractures in ZFMA2 in boreholes KFM02A and 2B are very similar. However, the relation between indicated groundwater flow paths (PFL anomalies) and their relation to fractures in zone ZFMA2 should be worked out in detail (i.e. are they controlled by fracture planes or channels formed along or at the intersections of fractures - indicating differential displacements along the zone?).

In borehole KFM10A zone ZFMA2 occurs in two sections, an upper and lower branch (430 to 449 m and 478 to 490 mbl.). Both sections are fairly well indicated by clusters outlined by all fractures (Fig. 3-133). There are discrepancies in the distribution of clusters within the two branches. The upper branch of ZFMA2 has a regular spacing between clusters outlined by all fractures, while the lower branch is more compact (the clusters are wider and there are smaller separations between clusters). The upper branch of zone ZFMA2 has three weaker sections (widths from 0.3 to 0.5 mbl.). The upper weak section is a weakness zone outlined by gently inclined open altered fractures and the other weak sections appear to be intersections between open altered fractures with variable dips. The lower branch of zone ZFMA2 has a wider section of weak rock located in its central part and a minor weakness in its upper part. The fractures in the weak sections are dominantly trending east-west and dipping moderately south. It is not apparent that the lower branch of zone ZFMA2 is a gently inclined zone.

Zone ZFMA2 – short summary

In most boreholes the location of zone ZFMA2 is fairly well established. However, some specific locations of zone ZFMA2 could be re-examined. Only minor parts of zone ZFMA2 represent weakness zones and these are primarily located in the central or upper part parts of the brittle zone ZFMA2 or in both parts. It is possible to use an identification approach for detection and classification of weakness zones that is analogous to that for brittle deformation zones (cf. Chapter 4).

4. Discussion

Definition of deformation zones

Nomenclature is a tool for understanding and communication. It is a system of words, terminology, used to name things in a particular discipline and documentation of the concept of the name (term) should be available. The latter is generally found in glossaries. In some cases, the nomenclature may appear to be too general or imprecise and then a redefinition of the term is given associated to a specific study. Sometimes, instead of introducing a new term the existing term is redefined. The term may also appear in closely related sciences, but, e.g. referring to somewhat different aspects of the named object or character. Nomenclature is not only a list of names but it is also a system of principles, procedures and terms related to naming. When a term is not clearly defined semantic problem will arise.

The character of a brittle deformation zone will change over time due to, e.g. precipitation of fracture minerals, alteration and reactivation. Different parts of a brittle deformation zone may change differently. For example, the core zone may initially form a fluid flow conduit and by alteration of the fragmented rock and precipitation of fracture mineral become sealed and constitute a barrier to flow (Caine et al. 1996) while the outer part of the deformation zone (the damage zone, cf. SKB transition zone, Munier et al. 2003) controls the groundwater flow along the zone. Reactivation of a zone may only affect parts of the zone.

The total deformation of the rock along a deformation zone is related to the geological history of the zone and thereby the zone may have been affected by several different types of deformation processes (from ductile to brittle). This may result in a complex character of the deformation zone and despite of this one should try to give the zone a description usable in modelling the extension of the zone. However, the present ability of a deformation zone to conduct water is mainly controlled by the existence and character of open fractures within the zone while for its mechanical properties the configuration of soft fractures (low tensile and shear strength) is of importance.

This implies that the number of fractures that gives the present character of a brittle deformation zone as a weakness zone may only constitute a fraction of all fractures genetically related to the deformation history of the zone. However, in borehole surveys open fractures that interfere with an open zone (they may either predate or post-data/overprint/ the zone) can be difficult to distinguish from open fractures related to the zone.

The objective of the present study is to present a tool to locate clusters of discrete fractures that may contribute to outline the locations of brittle deformation zones. The type of fracture clusters used to indicate the existence of a brittle deformation zone depends on the applied definition of the term brittle deformation zone in the performed study, and the applied definition should meet the aim of the study. However, the present study does not present a definition of a brittle deformation zone although some tests based on existing SKB definition (Munier et al. 2003) are performed.

Sensitivity test

All line sampling of planes in a three dimensional space, for example fractures, introduces sampling bias (cf. Priest 1985). In this part of the study, fracturing along a borehole is characterized by considering the separation between fractures of various types, especially: a) all fractures, b) all open fractures, and c) open altered fractures.

Fracture distribution

The basic requirement for identifying location of , e.g., brittle deformation zones (anomalies) in a drill core (borehole), is to have a general knowledge about the fracture distribution in the rock (at least on borehole scale to fracture scale) and a concept to identify anomalous fracturing and terms to describe (classify) the anomalous fracturing.

In the present study, the distribution of fractures is described by following measures:

- Separation for a sequence of at least four relatively adjacent fractures; the fractures divide the core into three or more parts, and the mutual separations of fractures is less than 0.20 mbl. (corresponding to a fracture frequency greater than 5 fractures per metre borehole length).
- As in the previous item except from that the mutual separation of fractures is less than 0.10 mbl. (corresponding to a fracture frequency greater than 10 fractures per metre borehole length).

The outcome of the performed study, identification of clusters of fractures, shows that the average fracture frequencies for the two types of clusters, as described above, are well above 5 and 10 fractures per metre borehole length, respectively. Furthermore, the location of boundaries of minor fractured sections are in many cases identical for the two types of clusters i.e. on many scales the fracturing appears to be focused to distinct sections in the rock.

Two tests are performed to examine the sensitivity of the applied approach for identification of fracture clusters:

1. Test of additional four sets of clusters, which are at least outlined by 3 or 5 fractures, having mutual separations less than 0.20 and 0.10 mbl., respectively (cf. Fig. 4-3 and Table 4-4).
2. Increase the mutual separation of fractures so it is less than 0.50 m (for successions of 4 fractures; cf. Fig. 4-3 and Table 4-4).

A part of a sensitivity test should include the selection of fractures included in the description of the character of the deformed sections, e.g. as displayed in a drill core/borehole. These issues are discussed in the following section.

The following step, after the sensitivity test is performed, will then be to study the distribution of fracture clusters, i.e. to judge whether they constitute swarms of fracture clusters representing brittle deformation zones or whether the clusters are solitary zones or are set up by interfering sets of fractures (cf. the next following section “From cluster classification to identification of brittle deformation zones”). The outcome is related to the applied definition of brittle deformation zones, which in its turn should be related to the general knowledge about how such zones appear within the investigated area. This is to identify wider sections with fractured rock; identification of inhomogeneous brittle deformation and weakness zones on a larger scale (cf. Fig. 4-13).

Character of brittle structures in sections of increased deformation

The descriptions of fracture distribution in boreholes presented in the previous chapter consider mainly two categories of fractures, all mapped fractures and open altered fractures. Another way of classifying fractures in drill cores is to use the relatively unambiguous measure of whether they part the drill core or not (cf. SKB MD 143.006 version 2.2, 2005). A characterization based on such a classification will give a conservative estimate of the location of sound rock (solid rock despite existence of internal structures as long they are cohesive). However, such a classification does not consider all water-conductive fractures in the rock. For instance, fractures mapped as partly sealed fractures contain voids that may represent conduits (channels) for groundwater.

Broken fractures and open, partly open and sealed fractures

Fractures that split a drill core, “broken fractures”, are during the SKB core logging process classified as:

- Sealed – if the fractures have no aperture (core pieces fit perfectly together, apertures are zero, and breaks have the lustre of broken minerals). The fractures may be fresh or altered.
- Open – Three categories of open fractures are distinguished:
    - Fractures with measurable apertures in the borehole (BIPS instrument); apertures ≥1.0 mm. Fractures may be fresh or altered. Given the fracture attribute “certain” in SICADA.
    - Fractures where core pieces do not fit perfectly leaving open space(s) along the fracture. The aperture of the fracture cannot be measured (below the resolution of the BIPS system); apertures noted as 0.5 mm. Fractures may be fresh or altered. Given the fracture attribute “probable” in SICADA.
    - Fracture where the core pieces fit perfectly and the fracture plane has a dull appearance indicating that it is affected by water (does not have the shine of fresh minerals). The aperture of the fracture cannot be measured (below the resolution of the BIPS system); apertures noted as 0.5 mm. How-

ever, the fractures may be noted as fresh or altered. Given the fracture attribute “possible” in SICADA.

In other words, fractures (SICADA data on fractures) that break the core, having apertures smaller than the resolution of the BIPS instrument (less than 1.0 mm), having a judged fit from close to perfect and alteration of the fracture surfaces from altered (slightly altered – moderately altered and highly altered) via dull to fresh form three classes of fractures: sealed fractures, probably open fractures and possibly open fractures. This implies that calculation of separation between different types of fractures breaking the core (fractures interpreted as probable and possible open, and sealed) are to some degree depending on expert judgements. It could be very likely that such judgement could change with time and differ between different core logging teams. Such differences may be of potential importance for hydrological modelling (i.e. determination whether fractures are open or sealed) and have previously been documented for different mapping teams (Glamheden and Curtis, 2006).

All fractures

The average fracture frequency for all mapped fractures varies from 3.6 to 11.0 fractures per mbl. in the seven investigated borehole sections containing the gently dipping deformation zone ZFMA2 (Table 4-1). Lower fracture frequencies are found in deeper borehole sections (3.5 to 4.9 fr/mbl.bl.; boreholes KFM02A, 02B and 10A), while higher fracture frequencies dominate in shallower borehole sections (7.4 to 11.0 fr/mbl.; KFM01B, 01C and KFM04A). However, there are exceptions. For example, the shallow section in borehole KFM05A (Table 4-1) has a relatively low average fracture frequency (3.8 fr/mbl.).

Open fractures

The distribution of open fractures within the investigated borehole sections varies from 14.7 to 67.9 per cent of all fractures (14.7 to 40.9 % in the deeper sections; cf. Table 4-1). The relative percentage of open fresh fractures in the borehole sections varies from 19.8 to 95.4 per cent of all open fractures (86.3 to 95.4 % in the deeper sections). Amongst the open fresh fractures there is a majority of thin fractures (68.8 to 97.1 %, on average 86.3 % of all open fresh fractures, 85.5 to 97.1 % in the deeper section; cf. Table 4-1); i.e. fractures with apertures noted as 0.5 mm.

Open Fresh fractures

Amongst the open fresh fractures that have apertures greater than the resolution of the BIPS instrument (81 fractures; 3.8 % of all open fractures and 13.3 % of all open fresh fractures, cf. Table 4-1) the majority of the fractures (66.7 %: 54 out of 81) have apertures equal to 1 mm and some open fresh fractures (4) have apertures on the order of 10 mm. Furthermore, about 50 per cent of all fresh fractures with an aperture equal to or greater than 1 mm have no fracture fill and notable is that all partially open fractures (fractures with voids) that have been artificially broken are mapped as open.

Relation between fresh/altered and open/partly open/sealed fractures

The percentages of fresh fractures amongst the open, partly open and sealed fractures are: 24.9, 58.2 and 67.6 %. The total number of sealed fractures in the seven investigated sections along which the drill core is parted (broken) is 666. Of these, 576 fractures are interpreted as fresh, i.e. 86.5 % are fresh (cf. Table 4-2). This is somewhat unexpected as weathered sealed fractures ought to be weaker than unaltered fractures/unaltered fracture fills, i.e. the percentage of broken fresh fractures interpreted as being broken during drilling and handling of the drill core would likely be lower. However, the ratio between sealed altered fractures and all sealed fractures varies strongly for the investigated borehole sections (from 2 to 70 %) and so does the relation between the amount of sealed fractures in relation to all mapped discrete fractures (from 30 to 77 %; cf. Table 4-2). However, it may indicate that some sealed fractures that part the drill core are mistaken for open fractures.

Table 4-1: Relation between different populations of open fractures in investigated borehole sections, Forsmark area. ("broken fractures" is the SKB SICADA nomenclature for fractures parting the core in files p_fract_core-KFMXXY.xls).

Investigated borehole section			Fractures in borehole				
Bore-hole ID	Upper limit of borehole section (m borehole length)	Lower limit of borehole section (m bore-hole length	To-tal	Broken, all	Broken, open	Broken open, fresh	Thin bro-ken open, fresh[1]
KFM01B	15	120	778	441	368	79	63
KFM01C	0	150	1645	681	620	111	107
KFM02A	350	490	496	401	73	44	42
KFM02B[2]	360	480	599	267	243	147	125
KFM04A	160	280	1079	447	306	92	65
KFM05A	100	165	249	196	169	15	8
KFM10A	350	500	682	291	279	104	101

[1] With thin fractures means that core pieces do not fit together perfectly and that the thickness of the fracture is below the resolution of the BIPS instrument, i.e. have a given width of 0.5 mm for all boreholes except for KFM02A where the minimum width for open fractures is given to be 1.0 mm (the resolution of the BIPS instrument).

[2] Borehole KFM02B is mapped by a geologist not included in the ordinary mapping team.

Table 4-2: Populations of partly open fractures and sealed fractures in investigated borehole sections, Forsmark area (cf. Table 4-1).

Investigated borehole section			Fractures in borehole				
Bore-hole ID	Upper limit of borehole section (m borehole length)	Lower limit of borehole section (m bore-hole length	To-tal	Partly open[1], all	Partly open, fresh	Sealed, all	Sealed, fresh
KFM01B	15	120	778	63	31	347	329
KFM01C	0	150	1645	198	67	826	251
KFM02A	350	490	496	42	37	381	322
KFM02B	360	480	599	16	13	300	170
KFM04A	160	280	1079	114	99	659	647
KFM05A	100	165	249	6	3	74	71
KFM10A	350	500	682	42	30	361	202

[1] Partly open fractures are fractures with apertures which are not broken. However, broken partly open fractures are mapped as open fractures.

Separation of fractures

In the present study two groups of fractures are studied regarding their separation in borehole sections across the gently inclined zone ZFM02A in boreholes KFM01B, 01C, 02A, 02B, 04A, 05A and 10A (Table 4-3; SKB SICADA data files p_fract_core-KFMXXY, cf. Section 3):

1. All fractures.
2. Altered open fractures.

The relative number of altered fractures can be questioned as inspection of unbroken partly open and sealed fractures generally is not possible, i.e. the base for the judgement whether a fracture is weathered or not is not the same for fractures parting the drill core compared to cohesive fractures.

The performed investigation may be complemented by including a separate study of all open fractures and open fractures with measurable apertures (i.e. apertures 1 ≥ mm). Such a check is made here for the section 350 to 500 m in borehole KFM10A (i.e. within the depth interval -248 to -338 m a.s.l., the deepest investigated section across zone KFMA2 inside the target area for a potential repository), which contains only 8 open fractures with aperture equal or greater than 1 mm located at following borehole positions: 373.6, 376.0, 391.6, 431.1, 431.6, 431.8 and 484.3 mbl. (mainly fractures with gently dips; a fracture at 431 m has an aperture of 5 mm and is sub-parallel to zone ZFMA2). However, there are also three partly open fractures with apertures of 1 mm at 442.6, 485.1 and 485.1 mbl. (all dipping gently southwards). A similar study on this theme is presented below (section "Fractures and borehole geophysics").

Table 4-3: Population of open and partly open fractures in investigated borehole sections, Forsmark area. Fresh fractures are unaltered and break the core while fractures denoted partly open in SICADA have voids and do not break the core. Apertures are measured by the BIPS instrument (borehole TV) and fractures with a width below the resolution of the instrument are generally given apertures of 0.5 mm.

		Borehole (KFMXXY)						
		01B	**01C**	**02A**	**02B**	**04A**	**05A**	**10A**
Section (m borehole length)		**15-120**	**0-150**	**350-490**	**360-480**	**160-280**	**100-165**	**350-500**
Fractures in bore-holes								
All		778	1645	496	719	1078	249	682
Fresh								
	Open	79	111	44	165	92	16	104
	Partly open	31	67	37	13	99	6	36
Altered								
	Open	286	508	29	126	214	153	175
	Partly open	32	131	5	3	15	3	6
Aperture >x mm		x=0.5	x=0.5	x=1.0[1]	x=0.5	x=0.5	x=0.5	x=0.5
Fresh								
	Open	16	4	2	24	27	5	3
	Partly open	1	3	1	4	14		3
Altered								
	Open	138	48	7	14	27	65	5
	Partly open	6	10	0	0	0	1	0
Total fractures with aperture ≥x mm		161	65	10	42	68	71	11

1 Smallest aperture given in borehole KFM02A is 1 mm.

The investigated section 0 to 150 mbl. in borehole KFM01C is extreme in relation to other investigated borehole sections regarding:

- High average fracture frequency (11.0 fr/mbl.: others have 3.5 to 8.9 fr/mbl., Table 4-1).
- High proportion of partly open fractures (12.0 % of all fractures; others have 2.7 to 8.5 %, Table 4-2).
- Low relative proportion of fresh partly open fractures (33.8 % fresh of all partly open fractures; others have 49.2 to 86 %, Table 4-2).
- Low relative proportion of fresh sealed fractures (30.4 % fresh of all sealed fractures; others have 56.0 % to 98.2 %, Table 4-2).

Summary

In summary, it is a subtle distinction between an artificially broken sealed fracture and a thin naturally open fracture, especially if the fracture is slightly altered. Open fresh fractures with apertures equal to or greater than 1 mm should be studied separately as they could either be young and/or not connected to the network of fractures forming the conduits for circulating groundwater. Furthermore, study of separation of open altered fractures can be complemented by a similar study of open fresh fractures. One reason for doing this is that open fresh fractures may reflect late distortion in the rock adjacent to deformation zones.

Zone ZFMA2 in KFM10A

Borehole KFM10A intersects the brittle deformation zone ZFMA2 at about -300 to -332 m a.s.l., i.e. the greatest depth at which the zone is penetrated by any borehole. At this depth, the zone might be less affected by non-tectonic stress release related to the free ground surface. The distribution of open fractures in section 350 to 500 m along borehole KFM10A (Figs. 4-1 to 4-3) displays two clusters of open fractures at about 430 to 440 m and about 478 to 490 mbl. Both clusters are internally inhomogeneous and open fractures occur concentrated to narrower sections (cf. Figs. 4-1 to 4-3). In order to identify the clusters as brittle deformation zones there is a need for further analysis of the fracture populations inside the clusters but that is beyond the scope of this study. However, it is found that open altered fractures within these clusters are more inclined than the assigned dip of the gently dipping SKB zone ZFMA2 (cf. Fig. 4-3 and Fig. 3-5) and there are fractures with apertures greater than 1 mm located within the clusters. Open fractures with apertures (3 fractures ≥1 mm) located in the upper part of the investigated sections are fresh and may either be associated with thin fracture clusters or occur as discrete structures in the bedrock.

The locations of clusters outlined by all fractures with more than 10 fr/mbl. and clusters with at least 5 fr/mbl. do in many locations fully coincide (Fig. 4-3), i.e. mutually overlapping each other. Clusters containing more than two fractures per metre borehole length indicate that relatively thin damage zones along the two main swarms of clusters, representing the two branches of the SKB zone ZFMA2, may occur. These clusters indicate also that there are minor fractured sections, probably off-shots or bridges, between the two branches of zone ZFMA2 (cf. Figs. 4-1 to 4-3 and 3-133, if the lower zone is a branch).

The distributions of all open fractures and open altered fractures, respectively, in the investigated section of borehole KFM10A are very similar. The same result is obtained when using a minimum of four or five fractures in the classification system. This implies that open fresh fractures are not very common outside sections with open altered fractures; they may either represent non-connected fractures or fractures related to late stress release.

Displaying fracture frequency

A fracture frequency diagram, considering all fractures in a borehole, displays the distribution of fractures intersecting the borehole but gives limited information how fractures are spatially distributed in the rock. More detailed information is obtained by displaying sorted data, e.g. different groups of fractures (e.g. all fractures, open, open altered, partly open, and sealed fractures combined with selected sets of fractures), and by using different width of intervals for calculation the fracture frequency. The selection of interval widths affects the filtering of data. Using a moving average with relative wide sections and relative small steps (SKB 2006) will filter the background "noise" and indicate sections with generally enhanced fracturing (cf. Figs. 4-1b and 4-2b), i.e. can be insensitive to minor zones and locations of the zone boundaries.

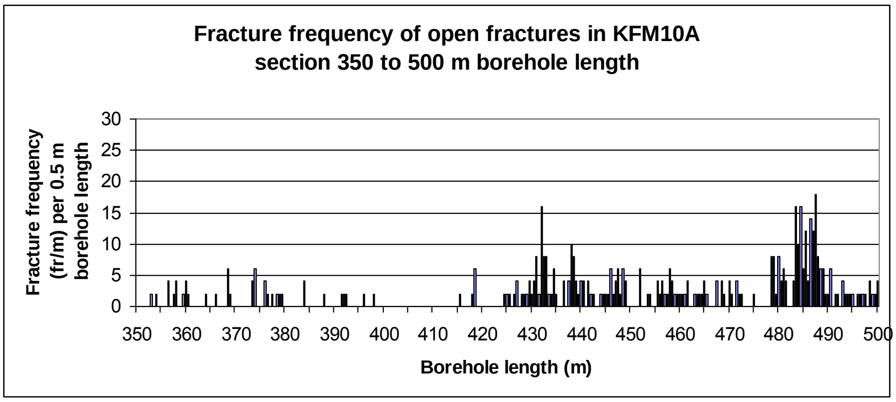
The method of using clusters (e.g. defined by a minimum number of fractures with a maximum mutual separation between the fractures – an "on-off" approach) can give detailed information about the locations of sections with enhanced fracturing, even when the sections are small (cf. Figs. 4-1c and 4-2c).

Refinement of cluster analysis

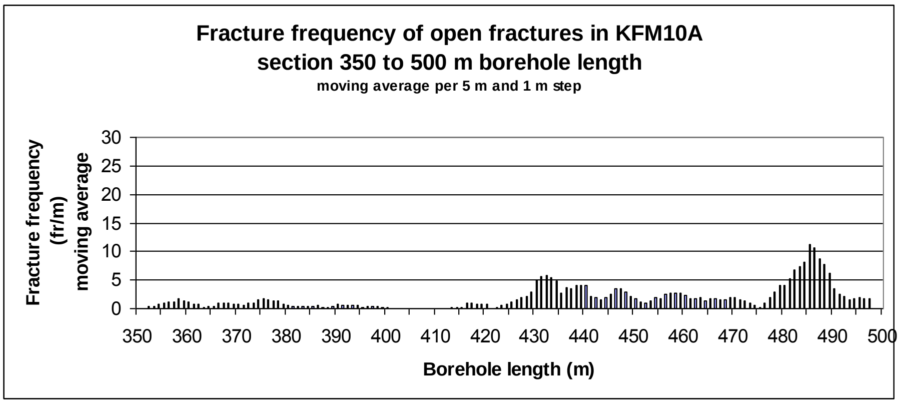
Some further complementary work (as described above) can be performed to modify the concept of identifying clusters by (cf. Fig. 4-3):

- Either change the minimum number of fractures that should be considered to define a cluster (e.g. considering 3 or 5 fractures instead of 4 generally used in this study), or
- change the maximum mutual separation of fractures to be identified as a cluster (e.g. increase the fracture separation distance giving a lower threshold for the fracture density in clusters, e.g. 0.50 m corresponding to fracture frequency ≥ 2 fr/mbl.).

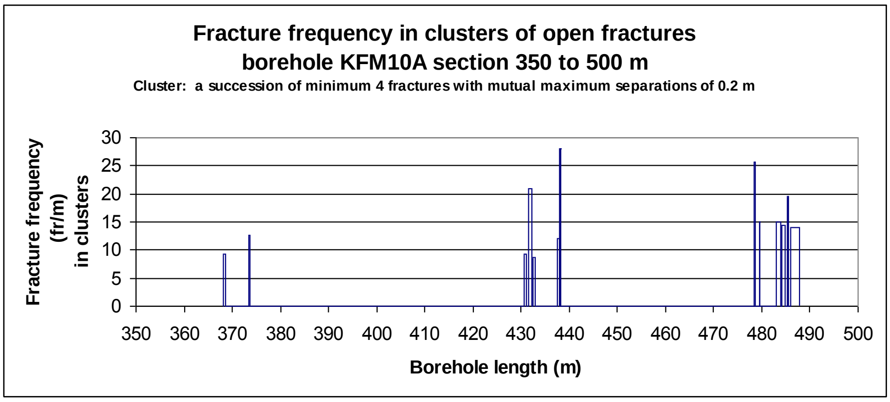
These types of modification (sensitivity tests) are applied on borehole data from borehole KLX10A including all fractures, all open fracture and open altered fractures (summarized in Fig. 4-3 and Table 4-4). Fractures of different sets (with sampling bias considered) is presented in the previous section of the report (Chapter 3; KFMA section 350 to 500 mbl.) and are only briefly discussed in this section.



a.



b.



c.

Figure 4-1: Distribution of open fractures along borehole KFM10A, section 350 to 500 mbl. (N=279):

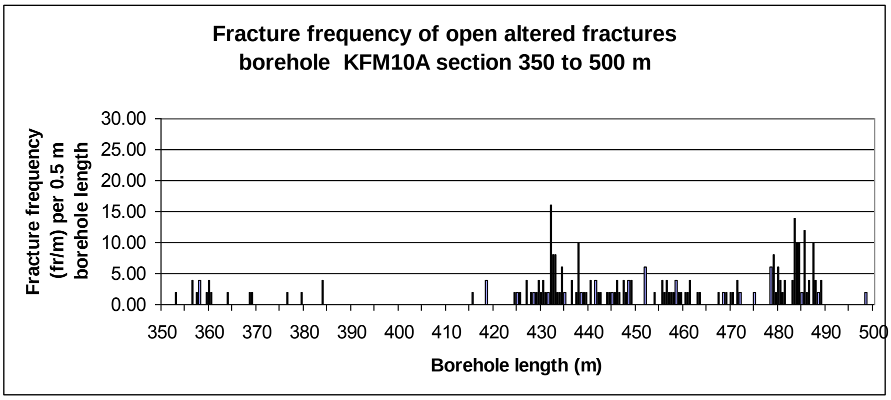
a. Fracture frequency (fractures per metre borehole length), the width of intervals is 0.50 m.

b. Moving average; fracture frequency per five meter boreholes length and one metre steps (cf. SKB SHI, SKB 2006).

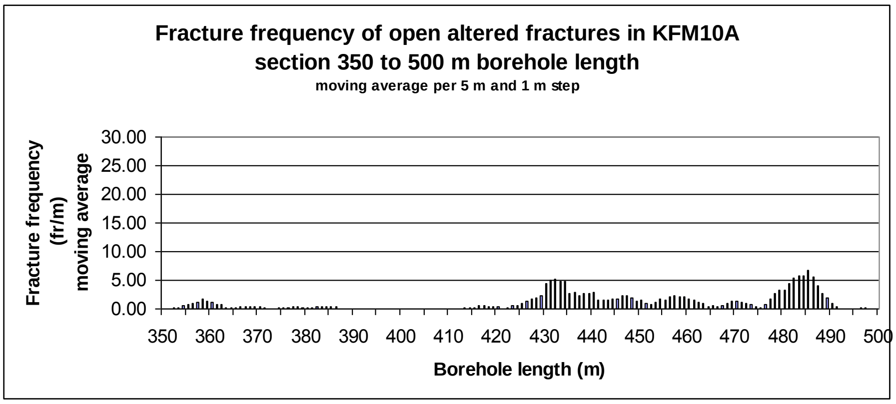
c. Fracture frequency in fractures per metre borehole length in clusters defined by a minimum of four fractures and the mutual separations of the fractures are maximum 0.20 m (i.e. 5 fr/mbl.).

Clusters versus fracture frequency diagrams

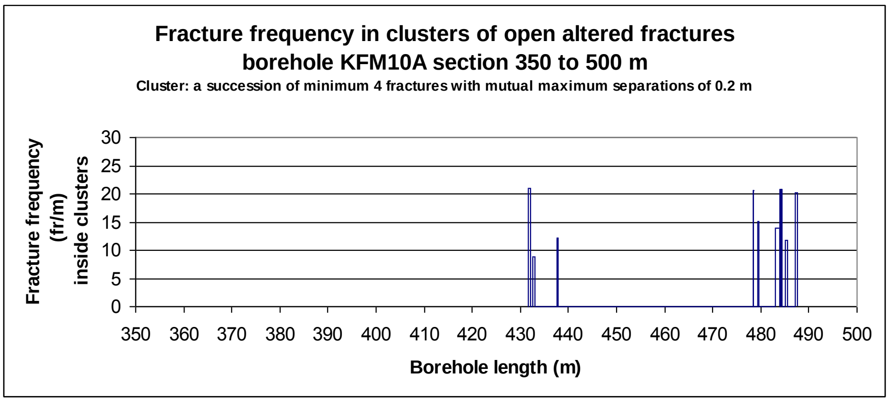
The applied methodology for sorting clusters of fractures based on fracture separation has a higher resolution than fracture statistics with fixed interval widths when considering outlining the cluster boundaries (cf. Figs 3-4 and Figs. 4-1 and 4-2).



a.



b.



c.

Figure 4-2: Distribution of open altered fractures along borehole KFM10A, section 350 to 500 mbl. (N=175):

a. Fracture frequency (fractures per metre borehole length), with of interval is 0.5m.

b. Moving fracture frequency per five meter boreholes length and one metre steps (cf. SKB SHI, SKB 2006).

c. Fracture frequency in fractures per metre borehole length in clusters defined by a minimum of four fractures and the mutual separations of the fractures are maximum 0.2 m (i.e. 5 fr/mbl.).

Classification based on mutual separation of a succession of three fractures has previously been discussed in this report. A comparison of ordinary diagrams showing fracture frequency (fr/0.5 mbl., cf. Fig. 4-1 to 4-2) and clusters (Fig. 4-3 and Table 4-4) is presented. It is indicated that applying cluster classification based on three fractures may identify small fractured sections. Furthermore, comparisons of the distribution and sizes of clusters based on different combinations of parameters (fracture characters and minimum number of fracture fractures together with maximum mutual

Table 4-4. Character of clusters of fractures in borehole KFM10A section 350 to 500 m borehole lengths. Three groups of fractures are treated: all fractures, open fractures and open altered fractures. Identification of clusters is based on two criteria: 1. a minimum mutual separation between fractures (given by the minimum fracture frequency; 10, 5 and 2 fr/mbl.) and 2. the minimum number of fractures to outline a cluster (3, 4 and 5 fractures).

Cluster				Borehole KFM10A					
ID[3]	Group of fractures	Criterion to identify clusters		Borehole section 350 to 500 m borehole length					
		Minimum number of fractures to outline a cluster[1]	Minimum fracture frequency (fr/mbl.)[3]	Number of clusters	Length of clusters (mbl.)	Length of clusters in percent of section length (%)	Mean fracture frequency in section (fr/mbl.)	Mean fracture frequency in clusters (fr/mbl.)	Fractures in clusters in percent of fractures in section (%)
1	All	3	10	72	12.4	8.3	4.5	28.6	62.5
2		3	5	55	25.0	16.7	4.5	18.4	75.7
3		4	10	46	10.5	7.0	4.5	28.7	50.7
4		4	5	40	23.6	15.7	4.5	18.1	68.3
5	All open	3	10	18	3.4	2.3	1.9	20.9	31.9
6		3	5	20	7.7	5.1	1.9	13.8	45.2
7		4	10	8	2.4	1.6	1.9	21.1	20.8
8		4	5	13	6.4	4.3	1.9	14.4	37.6
9		4	2	17	24.0	16.0	1.9	7.1	67.0
10		5	10	5	2.1	1.4	1.9	19.3	16.1
11		5	5	9	5.5	3.7	1.9	143	31.5
a	Open and altered	3	10	12	1.4	0.9	1.2	25.8	27.4
b		3	5	9	3.6	2.4	1.2	15.2	36.0
c		4	10	6	1.0	0.7	1.2	24.6	17.1
d		4	5	9	3.6	2.4	1.2	15.2	36.0
e		4	2	12	15.6	10.4	1.2	6.1	61.1
f		5	10	3	0.6	0.4	1.2	25.3	10.3
g		5	5	8	3.4	2.2	1.2	15.2	33.7

[1] Minimum number of fractures to outline a cluster – 3 fractures = 2 core pieces, 4 fractures = 3 core piece and 5 fractures = 4 core pieces. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of the clusters).
[2] Investigated section of the drill core is 150m, cf. Table 3-2.
[3] ID of group of clusters, cf. Fig. 4-3.

separation between fractures) give information about the general character of the brittle deformation in the rock.

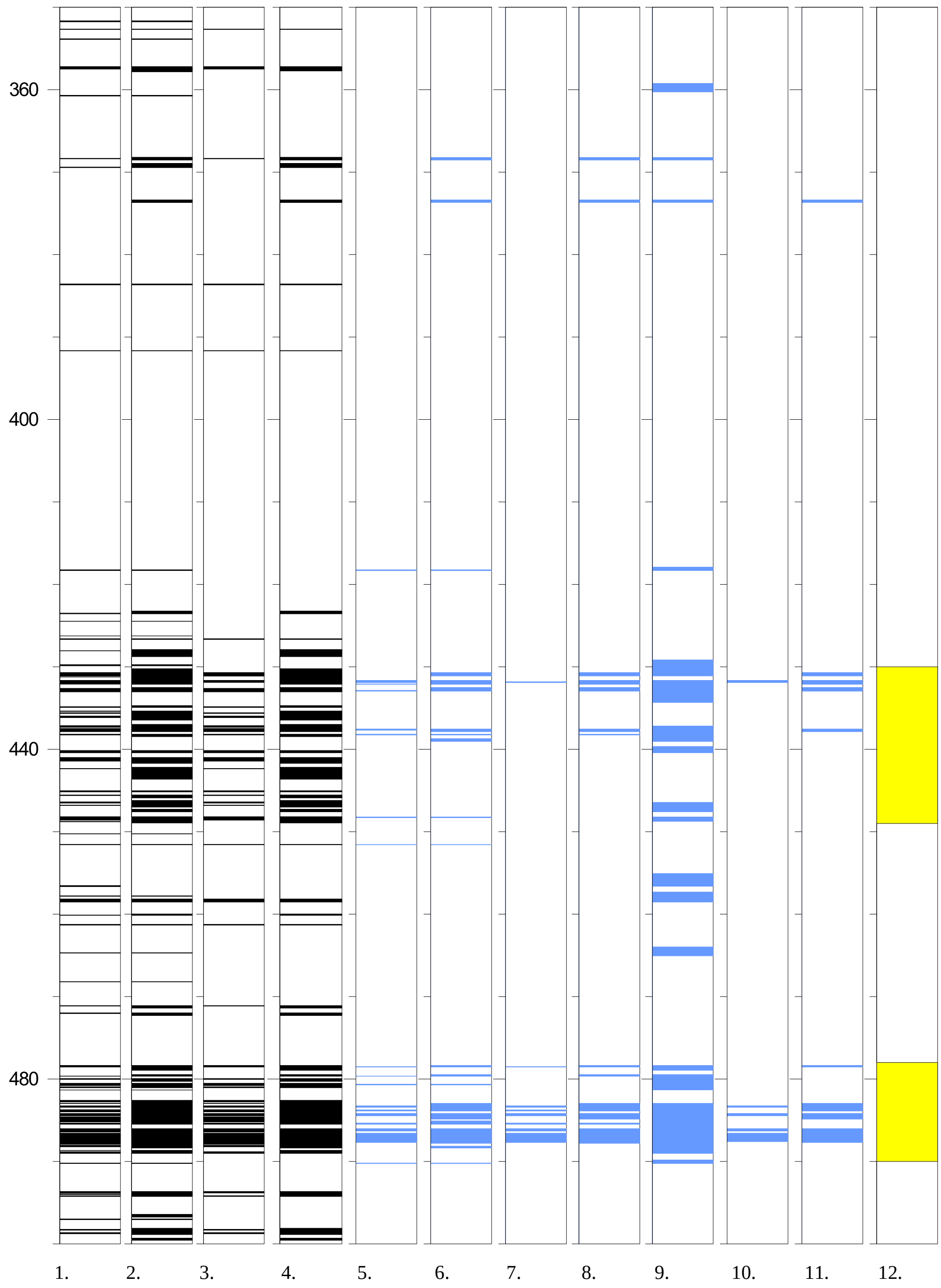


Figure 4-3: Sensitivity test displaying discrimination of the total fracture set in borehole KFM10A section 350 to 500 mbl. (Table 4-4; Same ID's are used in the figure):

Base data;

1 to 4. All fractures (black).
5 to 11. All open fractures (light blue).
12. SKB zone ZFMA2 (12 yellow).

Clusters are composed of;

1, 2, 5 and 6. At least 3 fractures.
3, 4, 7, 8, 9: At least 4 fractures.
10 and 11: At least 5 fractures (10, 11).

Fractures in the clusters have mutual separations that are;

1, 3, 5,7 and 10. ≤ 0.1 m (≥10 fr/mbl.).
2, 4, 6, 8 and 11. ≤ 0.2 m (≥5 fr/mbl.).
9. ≤ 0.5 m (≥2 fr/mbl.). (To be continued)

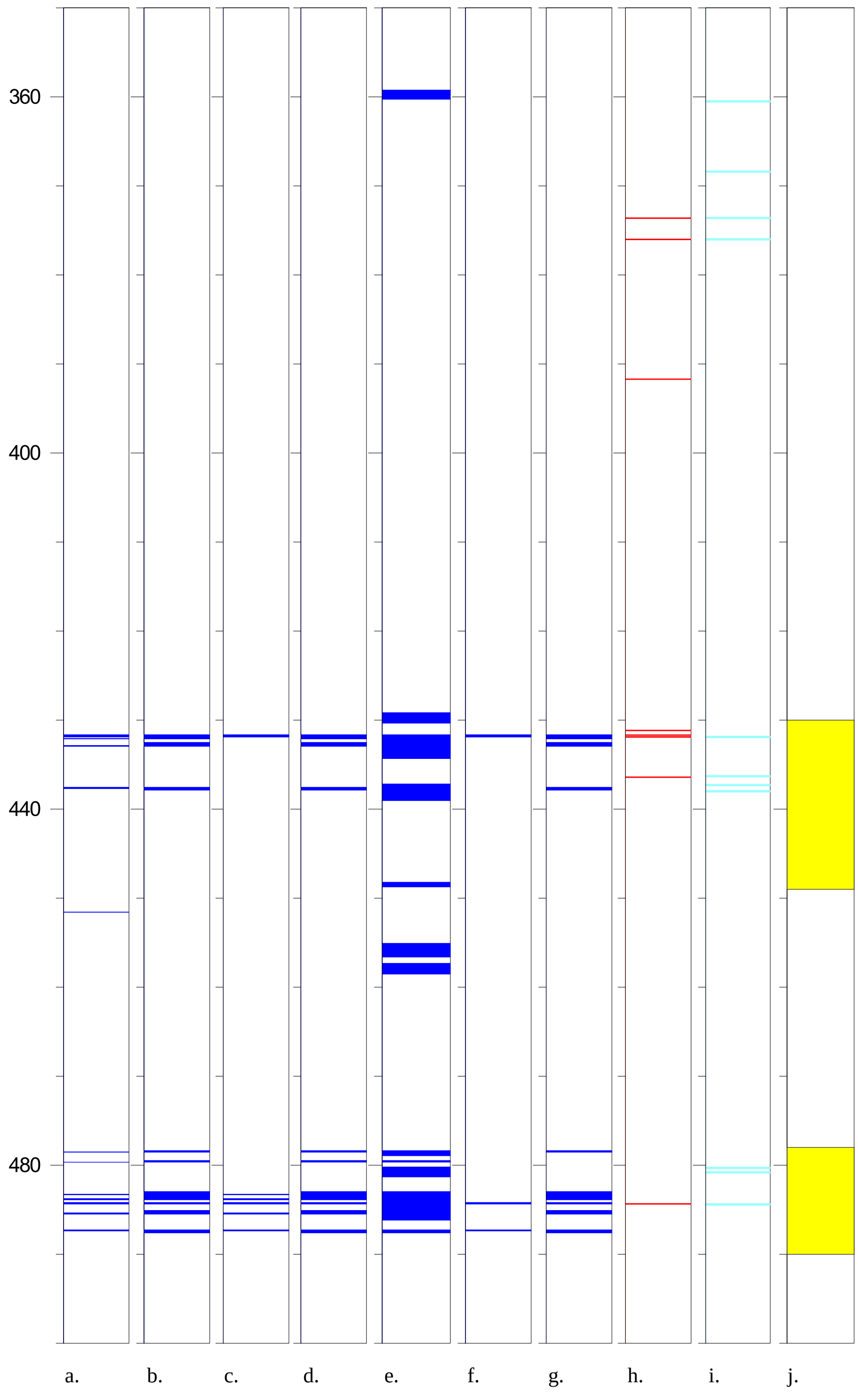


Figure 4-3 (continued). Sensitivity test displaying discrimination of the total fracture set in borehole KFM10A section 350 to 500 mbl. (Table 4-4; Same ID's are used in the figure:

Base data;

a–g. Open altered fractures (dark blue).
h. Discrete open fractures (fracture aperture ≥1mm, red).
i. Fractures with indicated groundwater flow (PFL anomalies, light blue).
j. SKB zone ZFMA2 (yellow).

Clusters are composed of;

a-b. At least 3 fractures.
c-e. At least 4 fractures.
f-g. At least 5 fractures.

Fractures in the clusters have mutual separation that are;

a, c and f. ≤ 0.1 m (≥10 fr/mbl.).
b, d and g. ≤ 0.2 m (≥5 fr/mbl.), e. ≤ 0.5 m (≥2 fr/mbl.).

Character of different types of fracture clusters

The character of fracture clusters in borehole KFM10A, section 350 to 500 mbl., has some distinct features (Table 4-4, c.f. Fig.4-3) in relation to the applied criteria for the cluster identification:

- *Minimum fracture frequency ≥ 10 fr/mbl.(i.e. minimum separation of fractures ≤ 0.1m), and minimum of 3, 4 or 5 fractures in clusters*;

    - average fracture frequency for clusters;
      cluster $_{\text{all fractures}}$ (c. 29 fr/mbl.) > cluster $_{\text{open altered fractures}}$ (25 to 26 fr/mbl.) > cluster $_{\text{open fractures}}$ (20 to 21 fr/mbl.)
    - total borehole length of clusters;
      cluster $_{\text{all fractures}}$ (11 to 12 m) >> cluster $_{\text{open fractures}}$ (2 to 3 m) > cluster $_{\text{open altered fractures}}$ (c. 1 m).

- *Minimum fracture frequency ≥ 5 fr/mbl.(i.e. minimum separation of fractures ≤ 0.2 m), and a minimum of 3, 4 or 5 fractures in clusters*;

    - average fracture frequency for clusters;
      cluster $_{\text{all fractures}}$ (c. 18 to 19 fr/mbl.) > cluster $_{\text{open altered fractures}}$ (15 fr/mbl.) > cluster $_{\text{open fractures}}$ (c. 14 fr/mbl.).
    - total length of clusters;
      cluster $_{\text{all fractures}}$ (24 to 25 m) >> cluster $_{\text{open fractures}}$ (6 to 8 m) > cluster $_{\text{open altered fractures}}$ (c. 3 to 4 m).

- *Minimum fracture frequency ≥ 2 fr/mbl.(i.e. minimum separation of fractures ≤ 0.5 m), and a minimum of 4 fractures in clusters*;

    - average fracture frequency for clusters;
      cluster $_{\text{open}}$ (c. 7 fr/mbl.) > cluster $_{\text{open altered fractures}}$ (6 fr/mbl.)
    - total length of clusters;
      cluster $_{\text{open}}$ (24 m) >> cluster $_{\text{open altered fractures}}$ (16 m).

Zone ZFMA2 in KFM010A

The location of the gently inclined brittle deformation zone ZFMA2 in borehole section 350 to 500 m borehole KFM10A (Stephens et al. 2007) is herein used as a reference when describing the distributions of fracture clusters (Fig. 4-3). The text given here is partly a repetition of descriptions given in the last sections of Chapter 3.

The clusters outlined by all fractures have very similar distributions regardless of the applied classification criterion (fracture separation and minimum number of fractures). An upper swarm of clusters (about 430 to 450 mbl.) appears to have more gradual boundaries compared to a lower, more distinct cluster swarm (about 480 to 490 mbl.). The deformation has a fairly regular appearance with bands of fractured rock mixed with bands of more solid rock. In the upper swarm of fracture clusters, the outer rims are composed of sealed fractures. There are also rims of sealed fractures in the lower, more distinct swarm of fracture clusters, but these rims have lesser extents.

Clusters with open fractures occur primarily in the upper part of the upper cluster swarm, while such clusters are concentrated to the central part of the lower cluster swarm. The distributions of clusters outlined by open and open altered fractures, respectively, are fairly similar (cf. Fig. 4-1 to 4-3). However, in the upper cluster swarm of the open fractures the open altered fractures are centred while in the lower cluster swarm of open fractures the open altered fractures are gathered in the upper part. Furthermore, open discrete fractures with measurable apertures (i.e. ≥ 1mm) are located immediately above the clusters of open altered fractures in the upper cluster swarm, while the only open discrete fracture with aperture in the lower cluster swarm is located in close association with the dense package of clusters outlined by open altered fractures.

The description above considers separation of fracture intersections in the borehole but does not consider sampling bias caused by fracture orientation. This is treated in the general description of fracturing in borehole sections containing the gently inclined brittle deformation zone (Chapter 3). In borehole KFM10A, the open altered fractures in the upper cluster swarm are generally gently inclined southwards (75/11) and sub-parallel to fractures with measurable apertures in the uppermost part of the upper cluster swarm, while in the lower part of the upper cluster swarm the fractures are mainly moderately to steeply inclined (for the most part south-westwards).

Moreover, open altered fractures in the lower cluster swarm are generally moderately inclined (115/40) and the open fractures with apertures found in this section of the borehole has similar orientation (105/56). The genetic relation between the upper cluster swarm and the lower cluster swarm may be studied further as it is not fully obvious that the gently and moderately to steeply inclined fractures are related. The relation between the upper and the lower cluster swarms is not clearly expressed in the SKB geological model of the Forsmark site as the lower cluster swarm, an interpreted branch of zone ZFMA2, is not visualized (cf. Fig. 3-5).

Summary

For identification and characterization of brittle deformation zones, the identification of clusters is the first step (see section below), which should be complemented by classifying the fracture data into fracture sets. The recognition of clusters should then consider the orientation of fracture sets relative to borehole orientation. This appears to be crucial in a bedrock environment such as Forsmark where the fracture frequency is relative low and fractures commonly occur as small clusters/swarms (e.g. less than 0.5 mbl. for all clusters defined by at least 4 fractures with mutual separations of maximum 0.2 mbl.). Compared to a standard fracture frequency diagram (fractures per 0.5 mbl., cf. Figs. 4-1 to 4-2), the fracture frequency in clusters give higher peak values, even when the mean section width is similar, because the applied cluster classification system selectively and effectively embraces anomalies (Figs. 4-3).

Relation between fracture sets

Interactive sorting of data, discrimination of data, can be performed in several ways. However, such a process should bring along all fracture characteristics given in the original data and the fracture characteristics may then be classified (for example, indicate different fracture sets by colour coding the original data). Such a procedure increases the readability of data and the understanding of the character of fracture clusters.

In the previous section the relation between gently inclined fractures and moderately to steeply inclined fractures in borehole KFM10A is discussed. Borehole KFM04A gives information about the relation between gently to horizontal fractures and steeply dipping NW-trending fractures (cf. Fig. 3-103).

From cluster classification to identification of brittle deformation zones

The identification of brittle deformation zones is a matter of definition and depends on the methodology employed to identify the structural features that meet the definition. However, it is not within the scope of this study to present a definition of the concept but to illuminate some matters related to the problems of presenting a universal concept of classifying a multivariable system.

What will be discussed in this section is an approach that in some sense helps to bridge the step from identification of anomalous fracturing to establish the location/character of brittle deformation zones formed by clusters of discrete fractures. The applied definition of a brittle deformation zone and the methodology to identify such a structure must be applicable, i.e. must meet the purpose of the investigation.

For example, the fault zone architecture model presented by Caine et al. (1996) include brittle structures containing at least one extensive shear surface (fault core – which can be represented by a discrete surface) while the damage zone (the subsidiary structures that bound the fault core) in the rock outside the shear surface might be absent. However, Cain et al. do not describe how such structures can be identified in a cored borehole (e.g. what is a zone and what is striated discrete fracture). Furthermore, Cain at al. do not consider brittle deformation zones with absence of displacements along any of the fractures outlining the zone. The definition of brittle deformation zones presented by Munier et al. (2003; cf. Fig. 2-1) gives some fixed values of fracture densities for the damage zone (called transition zone by Munier et al.) and the core zone; ≥4 fr/m for the damage zone and ≥ 9 fr/m for the core zone. Furthermore, Munier et al. include in a schematic illustration fault rocks in the core zone, e.g. fault gouge, without a discussion whether the fault rock is cohesive (sealed) or not.

Fracture clusters

Many of the early ductile deformation zones have also acted as precursor for later deformation. Character of fault rocks has been described and discussed by, for example Sibson (1977), Braathen et al. (2004) and Milnes (2006). In practice, the identification of deformation zones depends on the general character of the state of deformation of the rock. The SKB characterization of deformation zones are performed in two steps: 1) initial identification of possible deformation zones (SKB SHI phase; SKB 2006) and 2) a revisit to basic data during the geological 3D modelling (the SKB ESHI phase). However, neither Munier et al. (2003) nor SKB (2006) present any methodology describing the principles for locating the boundaries of a brittle deformation zone. Furthermore, the description of the relation between sealed structures and open fractures is sparse in the SKB description of deformation zones. This holds also for the description of the internal structural pattern in zones and the external structural pattern outside zones and how the two patterns are related. Without knowing the latter, the determination of the size of the damage zone may be difficult to judge.

Fracture clusters in investigated borehole sections, Forsmark

In the previous text, location and size of clusters based on different classification parameters (minimum fracture to define a cluster /mainly 4 fractures and 3 or 5 fractures in few cases/, minimum separation of fractures /0.10, 0.20 and in few cases 0.50 mbl./ or type of fractures /all, open and open altered fractures) are described. It is shown that all three parameters affect the location, number and width of clusters. There is, as could be expected, not a simple relation between size and location of different types of clusters. However, using different combinations of the fracture parameters, fractured sections in the rock can be classified and the weaker parts of the bedrock can be focused on.

In this case the weaker parts are assumed to be those with higher frequency of open altered rock. Other types of open fractures, for instance open fresh fractures (including fractures with no fill) are generally found associated with open altered fractures and they are often in a minority and might therefore not affect the results significantly (cf. Fig 4-3). However, this should be tested in each case.

To give some quantitative numbers on clusters, four types of clusters are compared and the clusters are:

- Clusters formed by successions of at least four fractures having mutual separations smaller or equal to 0.10 mbl.;
    - XY:1; cluster outlined by all fractures (clusters in boreholes FMXY; $_{\text{Xfor boreholes}}$=01, 02, 04, 05, or 10, $X_{\text{for clusters}}$=1, 2, 4, 5 and 10 and Y=A, B or C),
    - XY:3; clusters outlined by open altered fractures.

- Clusters outlined by sequences of successions of at least four fractures having mutual separations smaller or equal to 0.20 mbl.;
    - XY:2; cluster outlined by all fractures , and
    - XY:4; clusters outlined by open altered fractures.

Investigated sections in boreholes KFM01B, 01C, and 05A are all shallow (investigated depth interval located between -6 to -137 m a.s.l.), in borehole KFM04A at intermediate depth (-132 to -237 m a.s.l.) and boreholes KFM02A, 02B and 10A at deeper levels (located in interval -342 to -480 m a.s.l.). Each of the seven investigated section are intersected by the gently inclined brittle deformation zone ZFM02A (Figs. 3-4 and 3-5).

The general fracturing (all fractures) is enhanced in three of the shallow and intermediate sections (boreholes KFM01B, 01C and KFM04A; 7.5 to 16.5 fracture per metre borehole length), while it low in one (KFM05A; 4.0 fractures per metre borehole length). The fracture frequencies regarding open altered fractures vary: 0.5 to 3.7 fractures per metre borehole length (Table 4-5). The frequencies of open altered fractures are most pronounced in boreholes KFM01B, 01C and 05A (2.5 to 3.7 fractures per metre borehole length, Table 4-5).

The ratio between open altered fractures and all fractures varies strongly in the investigated boreholes: from 1.6 to 9.2 (Table 4-5). The highest ratio occurs in borehole KFM04A, located in the fringe zone of a regional northwest trending ductile, sub-vertical shear zone. The KFM04A borehole section is intersected by two brittle deformation zones; one sub-parallel to the regional NW-trending shear zone and the other is the gently inclined zone ZFMA2.

Fractures in different types of fracture clusters have some characteristics in common in the seven investigated borehole sections (Figs. 4-4 to 4-5 and 4-7 to 4-8 and Tables 4-5 and 4-6; no corrections of sampling biases made) and these are, for example:

- The mean fracture frequency for each type of cluster shows relative small variation (mean value/mdian value/standard deviation for XY:1 is 30.5/30.8/2.7 fr/mbl., XY:2 16.8/16.0/2.5 fr/mbl., XY:3 26.6/28.3/4.1 fr/mbl. and XY:4 14.9/14.5/1.6 fr/mbl.).
- The mean width of clusters shows small range in magnitudes for each type of cluster (mean value/median value/standard deviation for XY:1 is 0.22/0.23/0.02 fr/mbl., XY:2 0.69/0.60/0.20 fr/mbl., XY:3 0.18/0.18/0.02.1fr/mbl. and XY:4 0.47/0.40/0.18 fr/mbl.).
- The mean percent of fractures in each type of cluster in relation to fractures in investigated section shows some spread (mean value/median value/ standard deviation for XY:1 is 51.70/53.6/15.5 fr/mbl., XY:2 73.1/73.8/12.2 fr/mbl., XY:3 24.2/25.6/7.7 fr/mbl. and XY:4 46.9/45.0/10.2 fr/mbl.).

- No correlation is found between maximum width of clusters and fracture frequency in the investigated sections.

Table 4-5: Fracture frequencies (fractures per metre borehole length) in investigated borehole section. (Investigated sections are given in Table 3-1; light blue indicate depth intervals from 0 to -135 m a.s.l.; green -131 to -237 m a.s.l. and white -342 to – 466 m a.s.l.).

	Fracture frequency in investigated section in boreholes						
Borehole	**KFM01B**	**KFM01C**	**KFM02A**	**KFM02B**	**KFM04A**	**KFM05A**	**KFM10A**
All fractures (fr/mbl.)	7.5	12.0	3.5	4.7	16.5	4.0	4.0
Open altered fractures (fr/mbl.)	2.8	3.7	0.5	0.8	1.8	2.5	1.6
Open alt. fr./all fr.	2.7	3.2	6.7	5.9	9.2	1.6	3.8

Table 4-6: Maximum width of clusters in investigated borehole section (definition of cluster XY:1 and XY:2 is given in text, investigated sections are given in Table 3-1, colures indicate investigated depth intervals, cf. Table 4-5).

	Maximum width of clusters (metre borehole length)						
Borehole **Type of cluster**	**KFM01B**	**KFM01C**	**KFM02A**	**KFM02B**	**KFM04A**	**KFM05A**	**KFM10A**
All fractures, XY:1	0.73	1.54	0.53	1.36	0.95	0.28	1.36
All fractures, XY:2	4.43	10.65	3.30	4.53	3.11	2.16	2.92
Open altered fractures, XY:3	0.35	0.42	0.00	0.26	0.40	0.28	0.27
Open altered fractures, XY:4	2.55	1.90	0.00	0.70	1.28	0.75	0.94

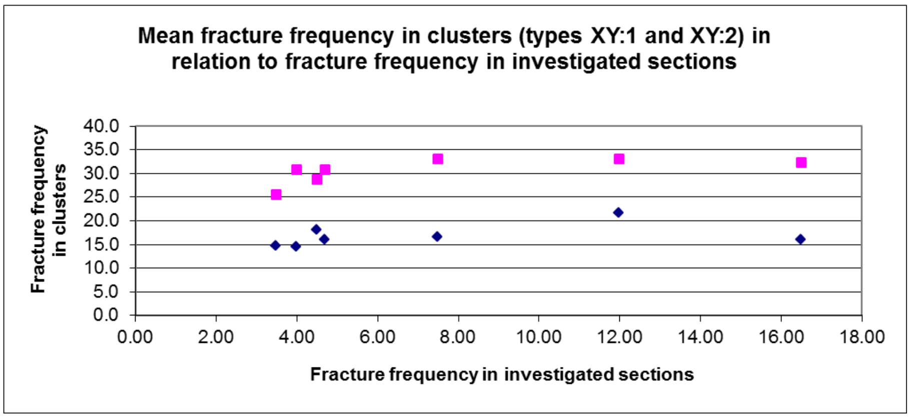


Figure 4-4: All fractures; relation between mean fracture frequencies (fr/mbl.) in clusters and fracture frequency in investigated borehole sections, seven borehole sections truncated by the gently inclined brittle deformation zone ZFMA2, Forsmark area (cf. Tables 4-4 and 4-5 and Figs. 4-33,4 and 4-3j). Definition of clusters (XY:1 red all, XY:2 dark blue), see text.

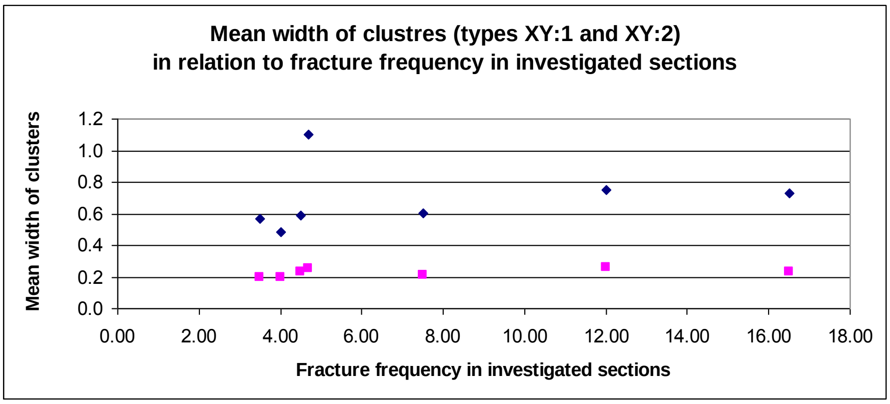


Figure 4-5: All fractures; relation between mean width of clusters (mbl.) and fracture frequency (fr/mbl.) in investigated borehole sections; seven borehole sections truncated by the gently inclined brittle deformation zone ZFMA2, Forsmark area (cf. Tables 4-4 and 4-5 and Figs. 4-33,4 and 4-3j). Definition of clusters (XY:1 red, XY:2 dark blue), see text.

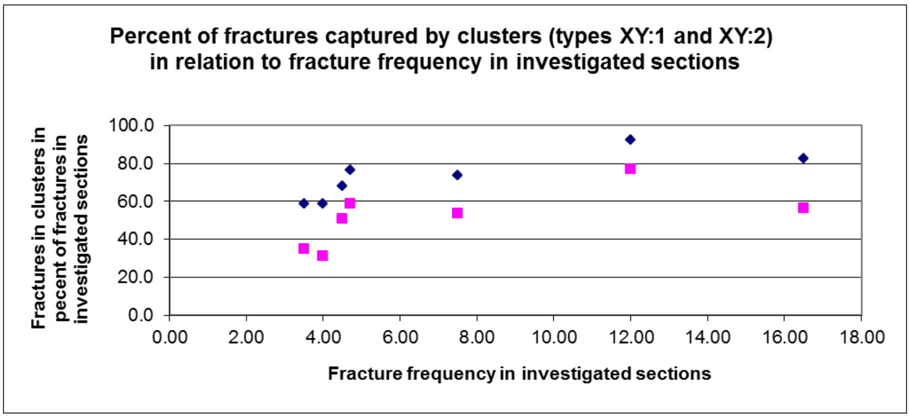


Figure 4-6: All fractures: fractures in clusters in per cent of all fractures in the investigated section in relation to the fracture frequency (fr/mbl.) in investigated borehole section; seven borehole sections truncated by the gently inclined brittle deformation zone ZFMA2, Forsmark area (cf. Tables 4-4 and 4-5 and Figs. 4-33,4 and 4-3j). Definition of clusters (XY:1 red /0.01 m separation/, XY:2 dark blue /0.2 m separation/), see text.

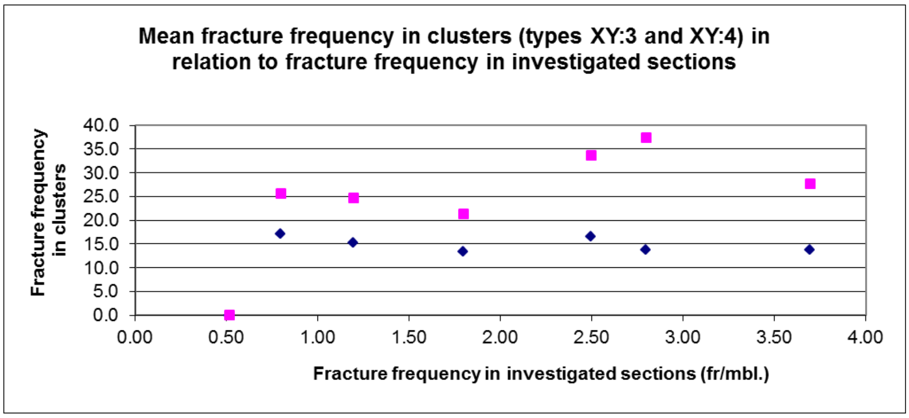


Figure 4-7: Open altered fractures; relation between mean fracture frequencies (fr/mbl.) in clusters and fracture frequency in investigated borehole sections, seven borehole sections truncated by the gently inclined brittle deformation zone ZFMA2, Forsmark area (cf. Tables 4-4 and 4-5 and Figs. 4-3c,d and 4-3j). Definition of clusters (XY:1 red /0.01 m separation/, XY:2 dark blue /0.2 m separation/), see text. (Point 0.50/0.0 indicates that no clusters formed by open altered fractures in borehole KFM02A, section 350 to 490 mbl.)

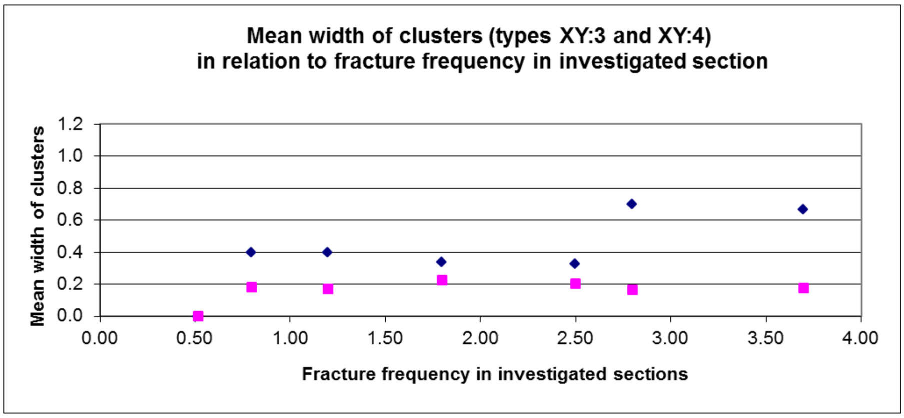


Figure 4-8: Open altered fractures; relation between mean width of clusters and fracture frequency (fr/mbl.) in investigated borehole sections; seven borehole sections truncated by the gently inclined brittle deformation zone ZFMA2, Forsmark area (cf. Tables 4-4 and 4-5 and Figs. 4-3c,d and 4-3j). Definition of clusters (XY:3 red /0.01 m separation/, XY:4 dark blue /0.2 m separation/), see text. (Point 0.50/0.0 indicates that no clusters formed by open altered fractures in borehole KFM02A, section 350 to 490 mbl.)

For all fractures, the percent of fractures captured inside clusters (XY:1 and XY:2) is somewhat lower in borehole sections with mean general fracture frequencies (all fractures) less or equal to 4.5 fractures per metre borehole length than in clusters located in sections with greater mean fracture frequencies (Fig. 4-6). For open altered fractures the relative amount of open altered fractures captured by clusters (XY:3 and XY:4) varies with the mean fracture frequency in the investigated borehole sections. However, there is an indicated tendency for the difference between the relative percentages of fractures captured by different clusters (XY:3-XY:4, Fig. 4-9) to increase with increasing fracture frequency in investigated sections (cf. Figs. 4-6 and 4-9).

The mean frequency of fractures in clusters and the mean width of clusters have very little, if any, relation to the mean fracturing in investigated borehole sections in Forsmark. This indicates that locations of sections with increased fracturing can be uniformly investigated, at least in the Forsmark area, by using a classification system with fixed parameters (minimum separation between adjacent fractures in a borehole and minimum number of fractures within a cluster).

The fracture groups (for example all fractures and open altered fractures) and applied parameters (minimum of 0.10 and 0.20 mbl. for the mutual separation of fractures) give, as pointed out above, swarms of clusters that coincide with the deformation zones (DZ) found by SKB and structures outside the SKB DZ (Figs. 3-49, 3-61, 3-72, 3-87, 3-102 and 3-118). The latter are mainly formed by single to a few closely located clusters, each less than some decimetre wide. Still, the latter may represent thin brittle deformation zones (for example: 80 to 100 mbl. in KFM01B /with only few XY:3 and XY:4, Fig. 3-48/, sections between SKB DZs in upper part of borehole KFM01C /with several XY:3 and XY:4, Fig. 3-61/ and in KFM04 between SKB DZs /with several XY:1 and XY:2, Fig. 3-102).

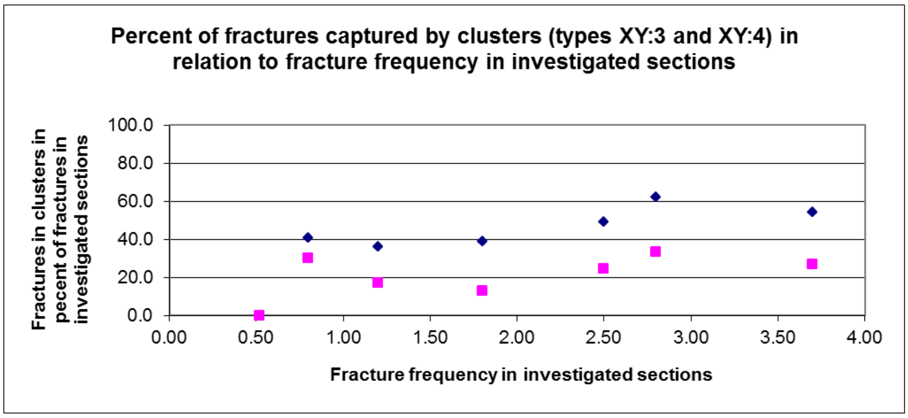


Figure 4-9: Open altered fractures: fractures in clusters in per cent of all fractures in the investigated section in relation to the fracture frequency (fr/mbl.) in investigated borehole section; seven borehole sections truncated by the gently inclined brittle deformation zone ZFMA2, Forsmark area (cf. Tables 4-4 and 4-5 and Figs. 4-3c,d and 4-3j). Definition of clusters (XY:3 red /0.01 m separation/, XY:4 dark blue /0.2 m separation/), see text. (Point 0.50/0.0 indicates that no clusters formed by open altered fractures in borehole KFM02A, section 350 to 490 mbl.)

Relations between different types of fracture clusters

The mean fracture frequency within clusters outlined by fractures with mutual separation less than or equal to Z mbl. will be higher than or equal to 1/Z fractures per metre borehole length. For the investigated sections in boreholes from Forsmark, the mean fracture density for clusters (Z=0.1 mbl.) regarding all fractures (XY:1) is greater than 25 fractures per metre borehole length and greater than 13 fractures per metre for open altered fractures (XY:3).

However, all type of clusters represent sub-population of all discrete fractures mapped in boreholes/on drill cores. This implies that there are some spatial relations between the four sets of clusters (XY:1 to 4), i.e. XY:2 clusters will embrace XY:1, XY.3 and XY:4 clusters, and XY:1 and XY:4 clusters will contain all XY:3, while there may only be overlaps between XY:1 and XY:4 clusters as XY:1 clusters can be formed both by open altered fractures and sealed fractures and XY:4 clusters contain only open altered fractures.

For example, the total width of XY:1 clusters in the seven investigated borehole sections constitutes 30.1 to 52.0 % of the width of XY:2 clusters (median is 36.8 %, Table 4-7). Corresponding values for XY:3 and XY:4 clusters are 20.8 to 45.0 % (median 25.0%; neither XY:3 nor XY:4 occur in the investigated section of borehole KFM02A, cf. Figs. 4-7 to 4-10). Comparing the total widths of clusters formed by open altered fractures (XY:3) with clusters formed by all factures (XY:1) it is found that the XY:3 clusters covers 5.8 to 45.5 % of the XY:1 clusters and XY:4 clusters covers 7.9 to 53.4 % of the XY:2 clusters (the anomalous value is from borehole KFM05A; cf. Table 4-7). Finally, only minor parts of XY:2 clusters are covered by XY:3 clusters, 2.1 to 13.7 %.

Furthermore, in shallow sections the relative proportion of the total length of clusters of open altered fractures in relation to the total length of clusters outlined by all fractures is indicated to be higher than in deeply located sections. However, the relative proportion of cluster lengths is also indicated to be related to the tectonic environment (e.g. vicinity of regional brittle deformation zones). Clusters outlined by open altered fractures are most commonly occurring in borehole sections with wider clusters outlined by all fractures or where such cluster form swarms (clusters of clusters; cf. Figs. 3-48, 3-61, 3-72, 3-87, 3-102, 3-118, 3-133 and 4-15). Though, increased density in the general fracturing of the rock (considering all fractures) does not necessarily indicate the locations of enhanced density of open altered fractures.

Table 4-7: Comparison between the total length of different types of clusters of fractures (cf. text above) in the seven investigated borehole section crossing the brittle deformation zone ZFMA2. (Base data are given in Tables 3-4, 3-6, 3-8, 3-10, 3-12, 3-14 and 3-16, colures indicate investigated depth intervals, cf. Table 4-5).

	Relation between total length of different types of fracture clusters in investigated sections in cored boreholes (%)				
Borehole ID	XY:1/XY:2	XY:3/XY:4	XY:3/XY:1	XY:4/XY:2	XY:3/XY:2
KFM01B	40.6	24.4	22.8	38.0	9.27
KFM01C	52.0	23. 6	11.9	26.3	6.20
KFM02A	32.2	-	-	-	
KFM02B	33.5	45.0	10.6	7.9	3.54
KFM04A	36.8	20.8	5.8	10.3	2.14
KFM05A	30.1	25.6	45.5	53.4	13.70
KFM10A	44.5	27.8	9.5	15.3	4.24
For all boreholes					
mean	38.5	27.9	17.7	25.2	6.52
median	36.8	25.0	11.3	20.8	5.22
std	7.8	8.7	14.8	7.9	4.64
max	52.0	45.0	45.5	53.4	13.70
min	30.1	20.8	5.8	7.9	2.14

Clusters of fractures and brittle deformation zones

To identify the locations of potential deformation zones the definition presented by, for example, Munier et al. (2003) can be applied (to test the SKB identification of DZ). The first step could be to locate the core zones, which have a lower limit greater than 9 fr/m (cf. RQD=0, Deere 1964). If the core zone is defined by the distribution of all fractures, then all SKB DZs contain high proportions of core zones, even though each of them may be thin, and “core zones” are even locally frequent outside the SKB DZ (Figs. 3-48, 3-61, 3-72, 3-87, 3- 102, 3-118 and 3-133). However, some additional guidance is needed to identify the boundaries of the core zones (analogous to the identification of brittle deformation zones), i.e. which clusters of fractures could be grouped together in larger structural units (merged together) and which clusters represent solitary structures.

Clusters reflecting different parts of brittle deformation zones

The core zones of brittle deformation zones may be composed of XY:1 clusters. However, the parameters used to identify clusters representing core zones have also to be set in relation to the fracture distribution in the rock. The damage zone (the transition zone according to Munier et al. 2003) may then include XY:2 clusters where they are not overlapped by XY:1 clusters (or core zones, cf. text below). For the average damage zone in the seven investigated borehole sections, the fracture frequency shall then be less 9 fractures per metre borehole length (cf. Fig. 4-10) and greater than a threshold value (e.g. 4 fr/m according to Munier et al. 2003). The mean and median fracture frequency in XY:2 clusters outside XY:1 clusters are 9.0 and 9.1 fr/mbl., respectively, and the standard deviation is 0.7 fr/mbl.

The same calculation for XY:4 clusters (borehole KFM02 excluded; no XY:4 detected) gives somewhat higher values for the fracture frequency in XY:4 clusters outside XY:3 clusters (Fig. 4-10); mean and medium values are 9.9 and 10.4 fr/mbl., respectively, and the standard deviation is 2.0 fr/mbl. However, fractures associated with a brittle deformation zone (a planar to semi-planar domain outlined by a sequence of fractures) are genetically related why good knowledge of fracture sets outlining clusters is needed. There may also be anomalous fracturing in general formed by interference between fracture sets (irregular fracture domains) and a special case is the "columnar" fracture domains (cf. channels) formed at the intersection of brittle deformation zones.

Each cluster having fracture frequencies greater than, for instance 4 fractures per metre (if this value is set to represent the threshold value to sort out anomalous fracturing in the rock[15]) and without considering its width (cf. Table 4-6), may solitarily or in combination with adjacent clusters represent a brittle deformation zone. A general guidance is that sections of the rock located between clusters of fractures can form parts of brittle deformation zones if the combined sections (clusters and intercalated sections of less fractures rock) fulfil the criterion for fracture densities within a brittle deformation zone. The process involves a decrease in fracture frequency, a dilution, as borehole sections between clusters will be incorporated; the process is described in detail in the following section.

Furthermore, each step in the evaluation process of locating brittle deformation zones gives information about the character of the zones and their relation to the general fracturing in the host rock. However, the statistical treatment of fractures should, if possible, be related to the geometrical and genetic relation of fractures in the rock. The proposed approach to locate brittle deformation zones implies that the boundaries of brittle deformation zones and core zones are located at fracture clusters.

[15] A comprehensive description of fracture statistics and fracture simulation is given by, for example Chen (2010)

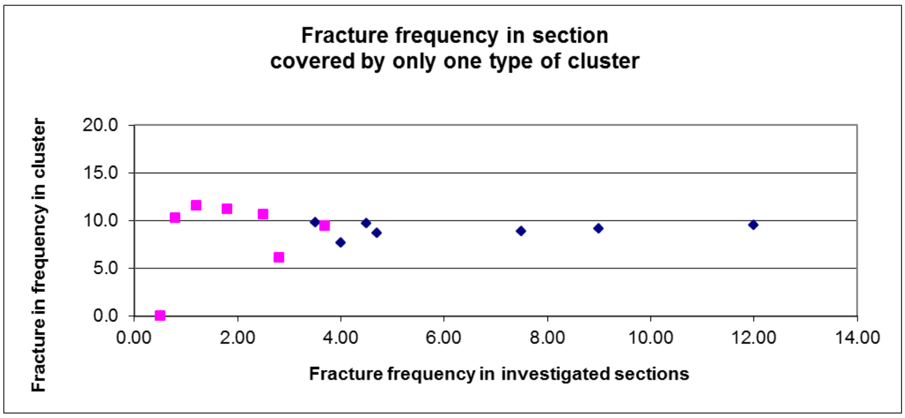


Figure 4-10: Fracture frequency (fr/mbl.) in parts of investigated borehole sections comprising XY:2 and XY:4 cluster segments with no overlaps of XY:1, alternative XY:3 clusters, i.e. segments that correspond to SKB transition zones (the damage zone) when defined either by all or open altered fractures (XY:2-XY:1= dark blue and XY:4-XY:3=red). When the fracture frequency is zero the zone. (Point 0.50/0.0 indicates that no clusters formed by open altered fractures in borehole KFM02A, section 350 to 490 mbl.)

General character of brittle deformation zones in SKB local models

The SKB nomenclature applied to denote brittle structures of different scales (cf. Andersson et al. 2000) is as follows:

- A fracture is a brittle structure with a width less that 0.1 m and extension less than 10 m.
- A local minor “fracture zone” (brittle deformation zone) is a brittle structure that varies in width from 0.1 to 5 m and from 10 m to 1 km in length.
- A local major “fracture zone“(brittle deformation zone) is a brittle structure that is 5 to 100 m wide and has an extension of 1 to 10 km.
- A regional “fracture zone” (brittle deformation zone) is a large-scale brittle structure that is more than 100 m wide and has an extension exceeding 10 km.

This type of classification of brittle structures has to be verified (especially regarding the fractures) and it may affect the communication of information and the modelling of structures. For example, the length of an observed structure may be affected by faulting and the length of discrete fractures may exceed 10 m.

Furthermore, SKB have in their evaluation of possible intersections of brittle deformation zones in boreholes (SHI; boreholes KFM01A-10A, SICADA data) within the Forsmark area detected 113 structures (DZ) with the following width data: mean 33.0 mbl., median 21.5 mbl., and range from 1 to 215 mbl. with a standard deviation of 39.7 mbl. The number of SHI DZ with widths from 1 to 5 mbl. and from 5 to 10 mbl. are 10 and 21 (the peak value), respectively. In the extended version of SHI (ESHI: boreholes KFM01A-10A, SICADA data) produced during modelling 126 structures (DZ) are included with following width data: mean 32.6 mbl., median 21.8 mbl. and with standard deviation of 39.0 mbl. The number of ESHI DZ with widths from 1 to 5 mbl. and from 5 to 10 mbl. are 16 and 22 (the peak value), respectively. The total width of ESHI DZ (tot length 4112 mbl.) is 9.3 % longer than for the SHI DZ.

Applying the relation between length and width of brittle structures (Andersson et al. 2000, see above) the ESHI interpretation gives 16 samples of borehole intersections of local minor zones, 103 samples of local major brittle deformation zones and 7 samples of regional brittle deformation zones. Most probably the number of detected intersection of local minor brittle deformation zones (MDZ) is too low as such structures can be expected to exceed the number of local major brittle deformation zones (cf. Fox et al. 2007). However, the objectivity of the SKB surface based site characterization of Forsmark site was to detect local major and regional deformation zones (extension greater than 1000 m).

Summary

The applied approach using fracture clusters can be used to locate and characterize sections of anomalous fracturing in the Forsmark area. However, to recognize different parts of brittle deformation zones such as the core zones, the damage/transition zones and the external boundaries of the zones may need some complimentary processing. The outcome of the presented cluster analysis has a relatively high resolution thus some systematic generalizations may be needed. In other words, there is a need to go a step further by smoothing the results. An approach to do this is presented in the following section and considers premises for connecting clusters with minor separations. Furthermore, a method to calculate the fracture frequencies in different parts of brittle deformation zones should be presented.

Extension of cluster patterns – a step to brittle deformation zone identification

Brittle deformation is discontinuous by nature and brittle deformation zones are inhomogeneous. The visual impression of the degree of inhomogeneity depends to some extent on the scale of observation. A fracture is a structure along which loss of cohesion has taken place (Dennis 1967), a break. A zone of fractures, a brittle deformation zone, is a planar to semi-planar domain outlined by a sequence of fractures, an anomaly. Furthermore, the character of fractures found within a brittle deformation zone represent a mix of accumulated tectonic distortion of the rock combined with effects of sealing processes. In general terms the character of fractures in brittle deformation zones are related to:

1. The formation of the zones, i.e. the fractures inside a zone are genetically related.
2. Modification of existing fractures and formation of new fractures during reactivation of the zones, which is steered by the stress field, the external geometry and internal character of the reactivated zones.
3. Fractures that overprint zones, i.e. not structurally related to the zones.

The latter (item 3) may only locally affect the (present) character of the zones if not associated with pervasive deformation.

Fracture distribution and width and separation of clusters or fractures

The previous sections of the report have mainly considered the identification of borehole sections with enhanced fracturing. All of the investigated borehole sections contain the deformation zone ZFMA2. The average fracture frequency for all mapped discrete fractures does in some of the sections exceed the fracture density for a brittle deformation zone according to the SKB definition. However, despite of a generally high density of fractures it is found that fracture characteristics may reveal the locations of zones.

Clusters of fractures occur locally as swarms and separations of XY:2 clusters outlined by all fractures (cf. Fig. 4-11) have a mean and median separation of 1.8 and 0.6 m, respectively, and a standard deviation of 4.1 m. More than half of all separations between XY:2 clusters (52.9 %) are shorter or equal to the mean width of XY:2 clusters (0.7 m).

The mean and median separation of clusters outlined by open altered fractures (XY:4, cf. Fig. 4-12) are 3.8 and 1.4 mbl., respectively, with a standard deviation of 7.1 m. The mean width of clusters outlined by open altered fractures is 0.5 mbl. and 27.1 % of all separations are shorter than or equal to the mean width of clusters outlined by open altered fractures.

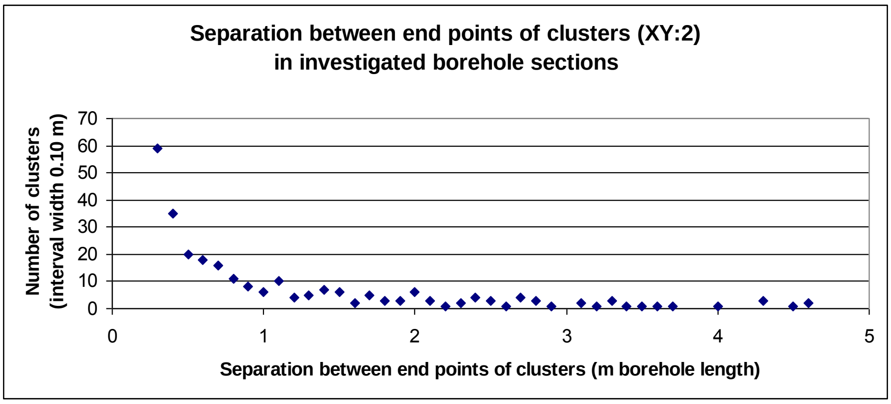


Fig 4-11. Distribution of separations of XY:2 clusters in the seven investigated borehole sections in Forsmark, N=280 (263 with separations less than 5 mbl. and the mean width of clusters is 0.7 mbl.).

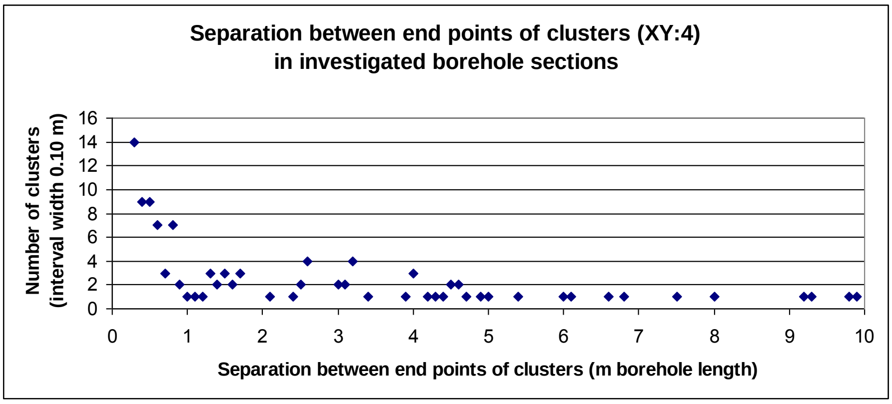


Fig 4-12. Distribution of separations of XY:4 clusters in the seven investigated borehole sections in Forsmark, N=280 (109 with separations less than 10 mbl. and the mean width of clusters is 0.5 mbl.).

Merging cluster of fractures to outline zones, principles

A simple test of joining/merging adjacent clusters in a borehole in order to locate sections of increased fracturing, potential brittle deformation zones, is here performed for borehole KFM10A. The maximum separation of clusters to be merged is here chosen to be less than the mean width of the clusters in the investigated borehole section (cf. Fig. 4-11 and 4-12). The merging process is interactive and ends when the mean width of merged clusters is less than the separation between the merged clusters (Fig. 4-13). However, the merging should also stop when merged clusters do not meet the applied definition of a brittle deformation zone (the section containing merged cluster should have a fracture frequency greater than, for example 4 for all fracture in sets related to fractures zones /cf. Munier et al. 2003/: cf. Items 1 and 2 on the previous page). This involves four steps:

1. Locate fractured sections in the borehole (clusters of fractures: Fig. 4-13).
2. Present the premises for merging clusters (cf. Fig. 4-11 and 4-12).
3. Perform a systematic classification of fractures into clusters (merged or solitary clusters) in order to distinguish whether or not the clusters contain fracture geometries and characteristics reflecting systematic deformation (cf. Fig. 3-133).
4. Add information about fault rock, information acquired during the core logging. All section of fault rock are to be considered as core zones within brittle deformation zones and incohesive fault rock are also considered together with open altered fractures (described further on). Adjust the merged pattern of cluster if the adding of sections of fault rock affects the separations between clusters (e.g. fill in gaps).

The principle here is, as pointed out above, to start and end all fractured sections that may represent a brittle deformation zones at a cluster of fractures. This does not necessarily imply that a zone will start/end at a peak value in the fracture frequency. It only implies that the mean fracture frequency will correspond to the value determined for the disturbed zone, according to the applied definition of brittle deformation zones, from the border of the zone to its core or across the zone if the zone has no core zone. The outcome of the merging of clusters is a simplification; obtained by "dilution" (including sections between clusters). The definition of brittle deformation zones given by Munier et al. (2003) have here been applied in order to get information about the width of fractured sections (all fractures) corresponding to the "statistical definition" of a brittle deformation zone in a selected section of borehole KFM10A and to compare the outcome with the SKB location of potential brittle deformation zones (DZ in ESHI). The distribution of open altered fractures and incohesive fault rock is used to locate weakness zones.

The used borehole section to perform a test on, KFM10A, 350 to 500mbl.

The two investigated groups of fractures in borehole KFM10A, section 350 to 500 mbl., are (1) all fractures and (2) open altered fractures. The reason for selecting these two groups of fractures is to get a picture of the full set of mapped discrete fractures in the section and fractures that have been affected by fluids. Within the investigated borehole section there are no sections mapped as crushed rock (cf. Fig. 3-133) and there are two thin sections of cataclastic rocks (2 sections; ≤ 0.02 m), a brittle-ductile shear zone (1; 0.004 m wide), a few ductile shear zones (3; ≤0.04 m) and one core loss (1; <0.09 mbl.).

Clusters of type 10A:1 (an assembly of at least four clusters with mutual separations of maximum 0.1 mbl., considering all fractures) incorporate the most intensely fractured sections. These clusters are relatively thin and occur mainly as swarms. The 10A:1 clusters have been interactively merged three times (stopped when all separation of merged cluster are greater than the mean width of merged clusters). The repeated merging (three times) of 10A:1clusters (Table 4-8) give a cluster pattern that is fairly similar to the unmerged pattern outlined by 10A:2 clusters (cf. Fig. 4-13).

The 10A:2 clusters (a succession of at least four fractures with mutual separations of maximum 0.2 mbl., considering all fractures) are interactively merged four times (Fig. 4-13 and Table 4-8). The two major merged 10A:2 clusters agree to some degree with the SKB identification of potential brittle deformation zones (DZ) in the investigated borehole section; the upper is larger while the lower is somewhat smaller than the SKB DZ's. However, there are several merged clusters that are few metres wide and not identified by SKB.

Clusters outlined by open altered fractures (10A:3 and 10A:4, Fig 4-13 and Table 4-8) are relatively sparse in the investigated section of borehole KFM10A and focused to two borehole levels 432 to 438 m and 478 to 487 mbl. The separations of all XY:3 clusters are greater than any of the widths of XY:3 clusters, why no merging has been performed. The XY:4 clusters have been merged twice. The location of merged 10A:4 clusters are fully located within 10A:1 clusters, except for a cluster at about 479.5 mbl. and the overlap at about 432 mbl.(Fig. 4-13).

Character of sections with merged clusters in KFM10A, 350 to 500 mbl.

Without going into details regarding orientation of fractures in and outside clusters it can be said that the density of gently inclined (dip < 30º), moderately inclined (30<x<60º) and steeply (70º<x) inclined fractures are all increased in the two major sections formed by merged 10A:2 clusters (all fractures, no correction for the sampling bias is performed). In the upper merged 10A:2 cluster (423 to 452 mbl. – denoted cluster section A in the text below) the frequencies of fractures are similar regardless fracture inclination (3-4 fractures per metre borehole lengths per set) and the contrast to the fracture frequency in the surrounding rock is three times greater or more. In the lower merged 10A:2 clusters (478 to 489 mbl. – denoted cluster section B in the text below) the frequency of moderately inclined fractures dominates (about 6.5 fr/mbl.) and is two times higher than in cluster section A. The frequency of moderately inclined fractures is of the same magnitude below cluster section B as in cluster section A. The frequency of gently inclined fractures in cluster section B is slightly increased compared to the frequency in the surrounding rock and lower than in cluster section A. The frequency of steeply dipping fractures is similar in cluster section A and cluster section B, less

than one fracture per metre borehole length, and at least four times higher than in the bedrock above and below cluster sections A and B.

Another way of describing the difference in fracture frequency in cluster section A and cluster section B is to give the relative proportion of 10A:1 and 10A:2 clusters in the two clusters. Cluster section A contains 14.4 % 10A:1 clusters and 40.0 % 10A:2 clusters, while cluster section B contain 43.9 % 10A:1 clusters and 68.9 % 10A:2 clusters.

Clusters outlined by open altered fractures occur only inside Cluster section A and B and are thin (Fig. 4-13). Gently inclined open altered fractures dominate in the upper part of cluster section A (cf. Fig. 3-133e,f), while open moderately dipping fractures strongly dominate cluster section B (cf. Fig. 3-133g). Steeply dipping open altered fractures are slightly enhanced in cluster sections A and B, and to a somewhat lesser degree enhanced in the borehole section between cluster sections A and B, compared to what is found in the rock above cluster section A and below cluster section B.

In order to find the structural relation between cluster section A and cluster section B further studies are needed. For example, study the clustering of fractures of each fracture set (cf. Figs. 3-120, 3-121 and 3-133e-g), correct the data for sampling bias and correlate data between boreholes.

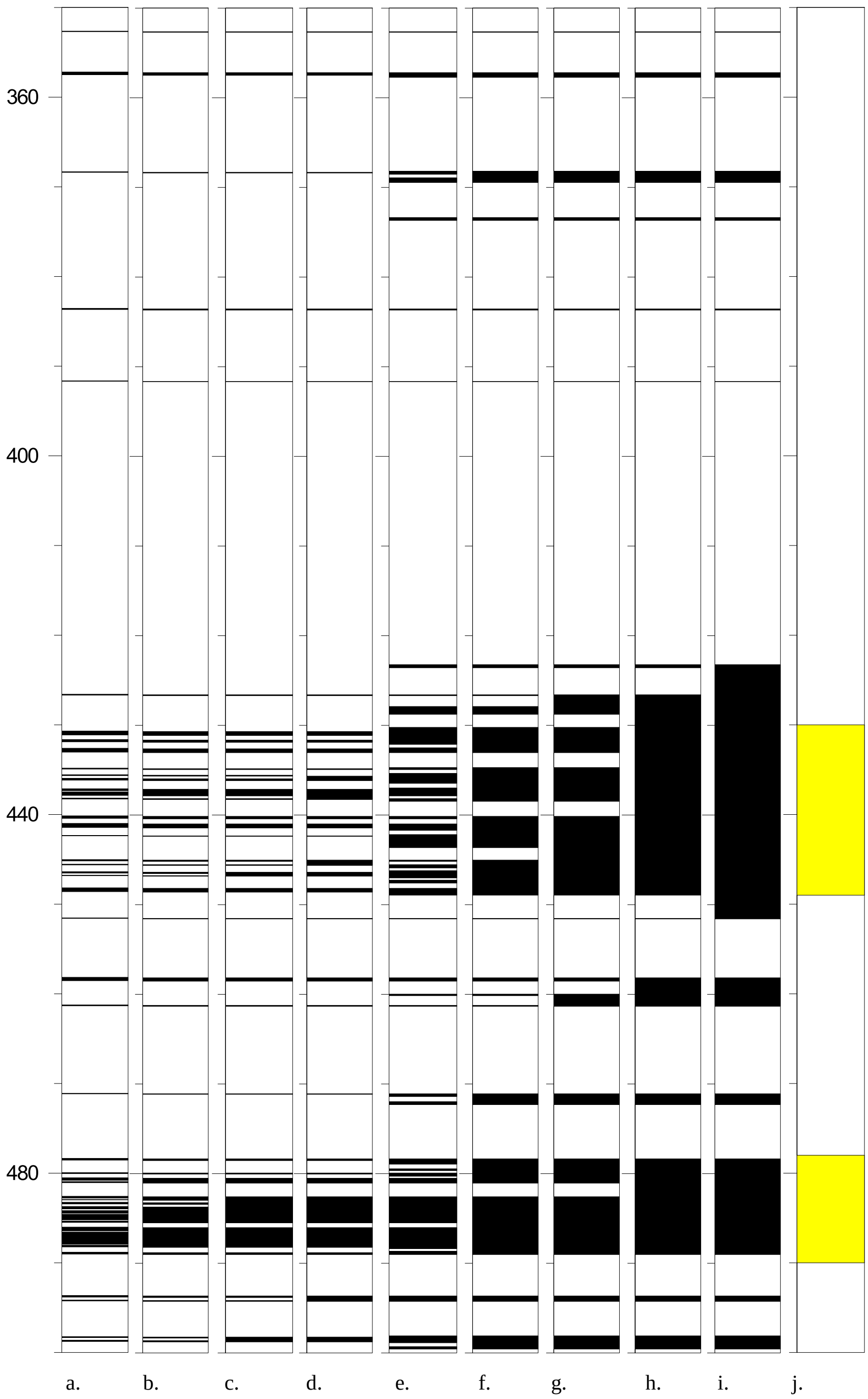


Figure 4-13: Borehole KFM10A section 350 to 490 mbl., comparison between primary clusters (10A:1 to 10A:4) and the result of step-wise merging of clusters (see text and Table 4-8):
a. Clusters (10A:1), clusters outlined by all fractures (succession of at least four fractures with mutual separation less than 0.1m).

b-d. Three successive steps of merging 10A:1 clusters; clusters are merged where separation between adjacent clusters are less than the mean width of clusters.
e. Clusters (10A:2), clusters outlined by all fractures (succession of at least four fractures with mutual separation less than 0.2m).

f-i. Four successive steps of merging 10A:2 clusters; clusters are merged where separation between adjacent clusters are less than the mean width of clusters.

j. SKB's interpreted location of the gently inclined zone ZFMA2 (upper branch /430-449m/ and lower branch /476-490 mbl. /).

(To be continued.)

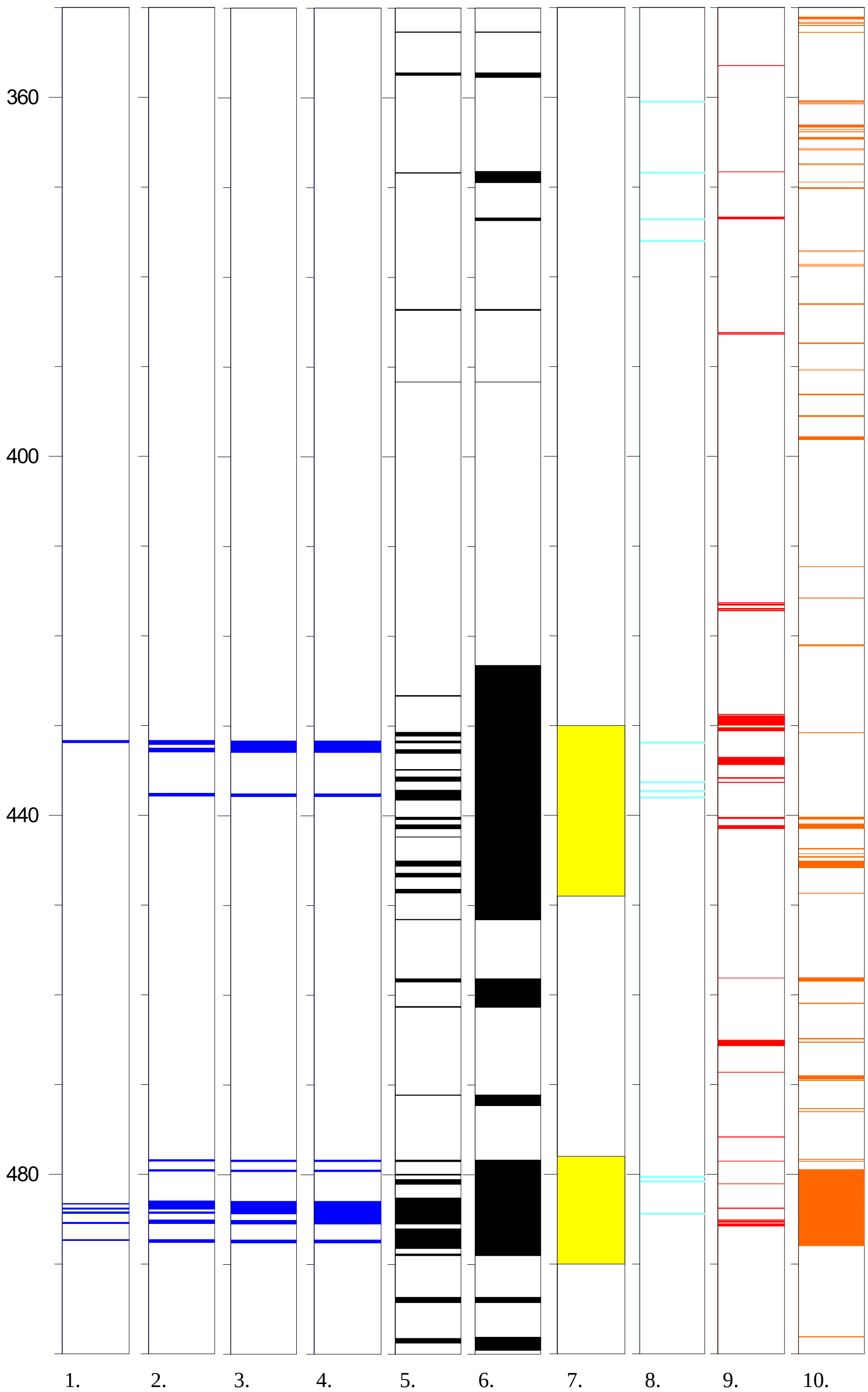


Figure 4-13 (Continued): Borehole KFM10A section 350 to 490 mbl., comparison between primary clusters (10A:1 to 10A:4) and the result of step-wise merging of clusters (see text and Table 4-8):
1. Clusters (10A:3), clusters outlined by open altered fractures (succession of at least four fractures with mutual separation less than 0.1m; mean width of clusters less than all separations – no merging of clusters performed).
2. Clusters (10A:4), clusters outlined by open altered fractures (succession of at least four fractures with mutual separation less than 0.2m).
3-4. Two successive steps of merging 10A:4 clusters; clusters are merged where separation between adjacent clusters are less than the mean width of clusters (stopped at the second step).
5. Merged 10A:1 clusters (included for comparison, cf. Fig. 4-13a).
6. Merged 10A:2 clusters (included for comparison, cf. Fig. 4-13i).
7. SKB's interpreted location of the gently inclined zone ZFMA2 (upper branch /430-449 m/ and lower branch /476-490 mbl. /).
8. PFL anomalies.
9. Sealed network of fractures. 10. Sections with altered host rock, oxidized (cf. Fig. 3-132).

Table 4-8: Character of clusters of fractures and merged fracture clusters in borehole KFM10A section 350 to 500 mbl. (cf. Fig. 4-13).

Borehole KFM10A

350 to 500 m borehole length

Group of fractures	Sections within 10A:X clusters[1] (X=1&3)	Sections within 10A:X-10A:Y clusters[2] (Y=2&4)	Average fractures frequency in borehole sections outlined by single clusters (cf. core[1] and transition[2] zones within a brittle deformation zone). (fractures per metre borehole length)				
			Unmerged clusters	1st merger of clusters	2nd merger of clusters	3rd merger of clusters	4th merger of clusters
All	10A:1		28.7	26.7	25.1	23.4[3]	23.4
		10A:2-10A:1	6.1	5.4	5.1	4.9	4.5[6]
Open altered	10A:3		24.6[4]	24.6	24.6		
		10A:4-10A:3	9.3	8.0	7.1[5]		

[1] May represent the core zone of a brittle deformation zone, see text.

[2] May represent the damage zone of a brittle deformation zone, see text.

[3] The merging of 10A:1 clusters stops at the 3rd round as the separations between merged clusters are all greater than the mean width of the merged clusters.

[4] 10A:3 clusters are not merged as the mean width of 10A:3 clusters are less then all separations of clusters.

[5] The merging of 10A:1 clusters stops at the 2nd round as the separations between merged clusters are all greater than the mean width of the merged clusters.

[6] A 5th merge of clusters will give a mean value of fracture densities in 10A:2-10A:1 sections that is equal to 4.0 and the repeated merge will not affect the two greater sections with merged clusters. A 5th merge of clusters will only unite two pairs of clusters in the uppermost and lowermost part of the investigated section.

Sections of merged clusters and indicated flowing structures

The relation between the general fracturing in borehole KFM10A and water-conductive intervals indicated by, for example the PFL log, is complex. The number of PFL anomalies located in merged clusters of fractures is the same as for unmerged clusters. This holds both for clusters formed by all fractures and open altered fractures in borehole KFM10A. Most of the PFL anomalies can be related to general increase in fracturing of the rock (in unmerged/merged 10A:1 clusters 7 out of 11 PFL anomalies are located; for 10A:2 clusters the number is 9) and some PFL anomalies are associated with clusters of open altered fractures (unmerged/merged 10A:4 clusters contain 3 out of 11 PFL indications; for XY:3 clusters the number is 2) while the remaining number of PFL anomalies are not associated with any cluster of fractures (2 out of 11). It is here indicated that most of the flowing structures are located outside clusters of open alter fractures and may take place along solitary/discrete fractures (cf. Chapter 3, KFM10A section 350 to 500 mbl.) especially along channels or discrete planes in mainly sealed brittle deformation zones. Indicated flowing structures in the upper parts of the two wider sections of merged clusters (cluster section A) are gently inclined (Fig. 4-13; at 431 mbl. within a cluster of open altered fractures). Other flowing structures in the two wider sections (cluster sections A and B) are moderately to steeply dipping.

Concluding remark

A conclusive remark is that the potential locations of brittle deformation zones can be determined using the methodology presented in this report. However, it is of importance to quantify parameters, such as fracture frequencies in absolute or relative terms, and define how to distinguish the borders of a zone. A definition of a brittle deformation zone could be based on both sealed and weak structures. An alternative approach is to focus on fractures with low tensile strength and consider the rock composed of sealed fractures as a separate tectonic rock type.

Fractures and borehole geophysics

In the cored boreholes in Forsmark several different types of borehole geophysical logs have been used. In this section the fracture population, represented by clusters, are briefly compared to a combination of selected geophysical borehole logs. The test is performed on borehole data from borehole KFM09A. The borehole is located in the central western part of the detailed study area (cf. Fig. 3-3) and is drilled southwards (200/60; swings about 25º giving a more south-westerly trend in the lower part of the borehole) towards a regional NW-trending deformation zone located outside the detailed study area.

Selection of borehole KFM09A

One reason for choosing borehole KFM09A in this test is that selected borehole geophysical data from this borehole have been processed in a previous study (Tirén et al. 2009) using a statistical method, K-mean cluster analysis (cf. Sträng et al. 2010), in order to locate sections having increased porosity (Fig. 4-16), i.e. section affected by brittle deformation or some type of alteration. The geophysical boreholes logs used are the gamma log, magnetic susceptibility log, sonic log and two resistivity logs (Res 140 and Res 300; cf. SKB data base SICADA activity type). In the following text the anomalous sections found by the K-mean cluster analysis are denoted geophysical clusters. In the performed study of correlation between geophysical clusters and clusters of fractures are accepted where there are spatial overlaps. Another reason for selecting borehole KFM09A is that the borehole intersects a regional brittle deformation zone (oriented 138/85) in its lowermost parts (at about – 600 m a.s.l.).

Structural description of the rock penetrated by borehole KFM09A

Borehole KFM09A displays three main orientations of fractures and the sets are formed by sub-horizontal fractures and steeply dipping to vertical fractures trending NNW-SSE to NW-SE and ENE-WSW to E-W (Fig. 4-14). The open altered fractures mirror the orientation of all fractures.

However, all the three sets are not uniformly distributed along the borehole. The set of fractures with ENE-WSW to E-W trending fractures are most common in the upper and central parts of the borehole (Fig. 4-14). Although the distribution of fractures of the different sets and the density of fractures vary along the borehole, the proportion between all fractures and open fractures together with partly open fractures are fairly similar within each 150 m sections of the borehole. The proportions vary from 3.4:1 to 5.8:1 (base data given in Fig. 4-14) with the highest ratios in the deepest parts of the borehole and low ratios (3.4:1 and 3.5:1) in the upper part of the borehole (0-300 mbl.). However, the ratio between all fractures and open altered fractures varies from 4.5:1 to 7.1:1 with high ratios in the lowest section (7.1:1, 750 to 800 m) and the uppermost section (6.6:1, 0 to 150 mbl.).

Fractures (all mapped discrete fractures) are unevenly distributed along borehole KFM09A. Lower fracture frequencies (meaning a frequency lower than 5 fr/mbl. within a 30 m long interval) are found from about 140 to 245 m (3.6 fr/mbl.) and 510 to 625 m (2.9 fr/mbl.). Most frequent are fractures in the upper part of the borehole (0 to 140 m; 9.4 fr/mbl.) and in the lower part (627 to 800 m; 8.0 fr/mbl., 10.2 fr/mbl. in section 750 to 800 m). In the middle part of the borehole (245 to 510 m) the fracture frequency is somewhat lower (6.7 fr/mbl.).

The frequency of open fresh fractures decreases from about 1.0 fr/mbl. in the first 150 m of the borehole and decreases to 0.4 fr/mbl. in the next 150 m and thereafter shows a smooth decrease from 0.3 to 0.1 fr/mbl. in the lowermost 50 m of the borehole. This may imply that the distribution of open fresh fractures is not related to the overall fracture distribution in the borehole.

Open/partly open fresh fractures (368; 93 are partly open) are most frequent in the upper part of the borehole (1 fr/mbl.) and relatively evenly spread in the remaining part of the borehole except for a smaller anomaly at about 245 mbl. (5 fr/mbl.).

Open altered fractures (cf. Fig. 4-15) may represent fractures that are or have been connected. They (795) occur as peaks (one metre sections with more than 5 fractures) in the uppermost (0 to 121 mbl.) and lowermost parts of the borehole (557 to 738 m). Open altered fractures have mean and median separations in the order of 1.0 and 0.4 m (standard deviation 1.7 m) and the maximum separation is 20.7 m. Corresponding data for all fractures are: maximum 3.8 m, mean 0.2 m, median 0.1 m and standard deviation 0.2 m.

Structural and geophysical parameters included in the test

In this test geological features that may increase the porosity in the rock are considered and compared to a combination of selected geophysical data, geophysical clusters (see text above).

Structural data

The following fracture clusters are presented in Figure 4-15 (cf. Table 4-10):

- 4 types of clusters outlined by all fractures (clusters outlined by sequences of at least 3 or 4 fractures having a minimum mutual separation of 0.10 and 0.20 mbl. in a total population of 5 062 fractures; clusters 9A:1-9A:4 in Tables 4-9 and 4-10).
- 4 types of cluster outlined by open altered fractures (clusters outlined by sequences of at least 3 or 4 fractures having a minimum mutual separation of 0.10 and 0.20 mbl. in a total population of 1 105 fractures; clusters 9A:5 to 9A:8 in Table 4-10).

The borehole geophysical measurements are sensitive to porosity in rock. Therefore, open fresh fractures (310) and partly open fractures (93; 58 are noted as fresh and the aperture of partly open fresh fractures are in two cases 8 to 11 mm) are included when geophysical clusters are compared to fracture clusters. The differences between clusters outlined by all open fractures and open altered fractures are small as many of the open fresh fractures are located inside clusters outlined by open altered fractures. Correlation between discrete fractures with aperture and geophysical clusters is also studied.

The correlation between geophysical clusters also considers, except for clusters outlined by discrete fractures, other structural features that may affect the porosity in the rock, i.e. zones of crushed rock, brittle-ductile shear zone and sections within which the host rock is altered. The most extensive type of alteration of the rock is oxidation (Fig. 4-15).

Included is also the identification of deformation zones performed by SKB (SHI DZ Carlsten et al. 2006), and ESHI in SKB database SICADA (file p_eshi-KFM09A.xls), which is based on the complete core log, all geophysical borehole logs and also an ocular inspection of the drill core (Fig. 4-15).

Geophysical clusters

There are 30 geophysical clusters (analysed section is 24 to 782 mbl.) and they are generally thin (mean 1.6 m, median 1.1 m, standard deviation 2.2 m, and maximum width is 10.3 mbl.). The locations of geophysical clusters are generally given by their mid-points. The largest geophysical cluster is located in the lower part of the borehole, between 731 to 741.3 m, and represents a larger WNW-trending deformation zone (Stephens et al. 2007), while the second largest geophysical cluster is located between 511.1 to 519.1 mbl. and agrees in position with a section with oxidized rock having a modest

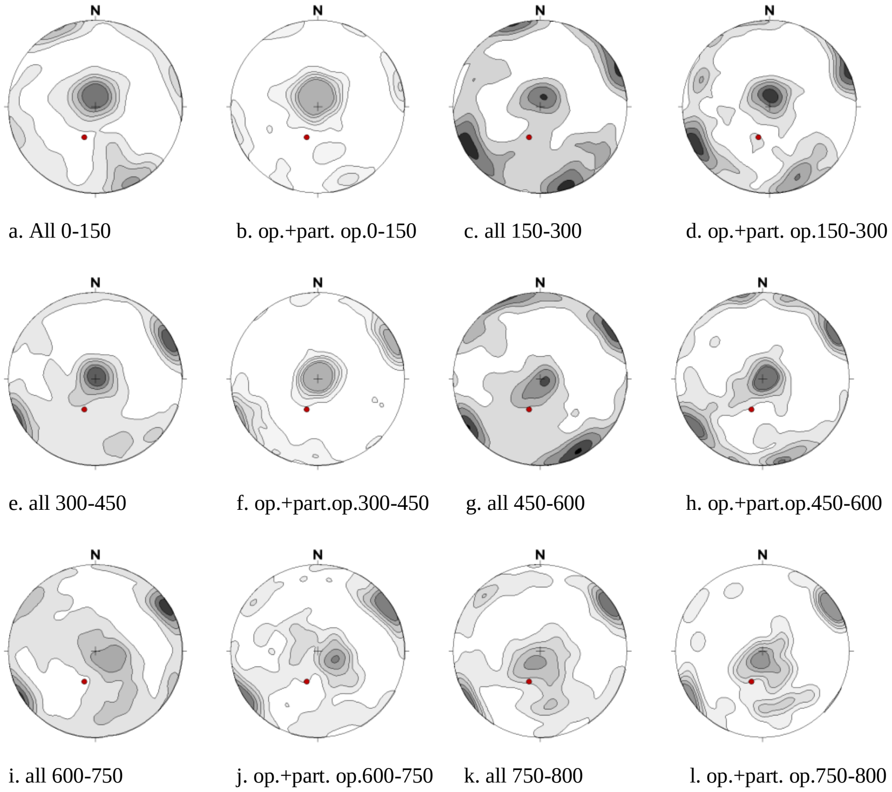


Figure 4-14: Orientation of fractures in cored borehole KFM09A (for comparison the number of open fractures and open altered fractures are giving in parenthesis):

a. All fractures, section 0 to150 mbl., N=1286.

b. Open and partly open fractures, section 0 to150 mbl., N=371 (N_{open}=341, $N_{open\ altered}$=195).

c. All fractures, section 150 to 300 mbl., N=747.

d. Open and partly open fractures, section 150 to 300 mbl., N=217 (N_{open} =202, $N_{open\ altered}$=145).

e. All fractures, section 300 to 450 mbl., N=937.

f. Open and partly open fractures, section 300 to 450 mbl., N=204 (N_{open} =189, $N_{open\ altered}$=145).

g. All fractures, section 450 to 600 mbl., N=648.

h. Open and partly open fractures, section 450-600 mbl., N=137 (N_{open} 125, $N_{open\ altered}$=100).

i. All fractures, section 600 to 750 mbl., N=646.

j. Open and partly open fractures, section 600 to 750 mbl., N=183 (N_{open} =169, $N_{open\ altered}$=142).

k. All fractures, section 750 to792 mbl., N=453 (in section 791.6 -799.4 m all 45 fractures are missing orientations).

l. Open and partly open fractures, section 750 to 792 mbl., N=78 (in section 791.6-799.4 m all 8 fractures are missing orientations) (N_{open} =71, $N_{open\ altered}$ 64).

fracture density (Fig. 4-15). An extraordinary feature of this section is that the quartz in the rock have been dissolved giving a porous rock (vuggy granite/episyenite).

Discrete fractures and geophysical clusters

Some information should be given about the relation between discrete fractures with apertures greater or equal to one millimetre and geophysical and fracture clusters (cf. Table 4-9), before going into more detail about the relation between geophysical clusters and fracture clusters, different types of brittle deformation zones and alteration of the bedrock.

The minimum measurable fracture width, applying SKBs borehole investigation programme, is 1.0 mm (the resolution of the borehole TV-set, the BIPS instrument). In the SKB core logging system, thinner open fractures are given a width of 0.5 mm.

About half of all open and partly open fracture with apertures greater or equal to one millimetre are noted as fresh in the SKB core log (92 out of 179). The relative number of fractures in the fracture clusters (for example 9A:2, Table 4-9) or geophysical clusters increase with the aperture of the fractures.

Open and partially open fractures with apertures larger than three millimetres (12) are either identified by the fracture cluster analysis or by the geophysical clusters; 8 open fractures, 4 of them are fresh, with apertures up to 6 mm and 4 partially open fresh fractures with apertures up to 11 mm. Two discrete open fractures with apertures of 3.5 and 6 mm, fresh and slightly altered, are found at relative deep levels (-228 and -389 m a.s.l).

The discrete fractures, open and partly open, with apertures equal to two millimetre are all, except for four (19 out of 23), identified by either fracture cluster analysis or geophysical clusters. Three out of the remaining four are open; one of these is fresh and the other two are altered. The fourth fracture is partly open and fresh. The deepest located open fractures with an aperture of 2 mm is altered and found at -434 m a.s.l.

There are 144 fractures with apertures equal to 1.0 or 1.5 mm (17 are partly open fractures and 127 are open fractures). Amongst the partly open fractures few are altered (2), while amongst the open fractures the corresponding number is much higher (73). The number of fractures with apertures between 1.0 and 1.5 mm not covered by fracture cluster analysis or geophysical clusters is 32 (30 open fractures and 2 partly open fractures). Open fresh fractures with apertures of one millimetre is found along the entire borehole, i.e. to a depth of - 619 m a.s.l.

On the other hand, the number of open and partly open fractures in the geophysical clusters varies from zero (zero in one cluster, see text above) to 55 fractures (in the most extensive geophysical cluster at 731 to 741 mbl. /located -575 to -582 m a.s.l./; containing 4 open fresh fractures, 4 partly open fresh fractures and 47 open altered fractures). Most of the geophysical clusters contain one to four open or partly open fractures. Nine geophysical clusters contain no fresh fractures.

The main part of the geophysical clusters (29 out of 30) contains mixes of sealed and open fractures. Except for the 10 m wide geophysical cluster at about 735 mbl. (containing 150 fractures of which 110 are open), single geophysical clusters embrace smaller number of fractures (2 to 31 fractures and not more than 7 open fractures in each cluster: one geophysical cluster have no open fractures).

Table 4-9: Fractures with apertures greater or equal to one millimetre in borehole KFM09A and such fractures relation to fracture clusters and geophysical clusters.

Number of open and partial open fractures with apertures ≥1.0 mm in borehole KFM09A

Fractures with aperture	≥ 1 mm	≥ 2 mm	≥ 3 mm
In the borehole	179	35	12
In fracture clusters (9A:2, Table 4-10)	132	25	8
In geophysical clusters	29	15	7
In overlaps between fracture clusters and geophysical clusters	17	9	3
In fracture clusters or geophysical clusters	144	31	12

Geophysical clusters and fracture clusters

Correlation of geophysical clusters with fracture clusters outlined by all fractures (Fig. 4-15 and Table 4-10) shows that 26 of the 30 the geophysical clusters coincide or overlap clusters outlined by all fractures. The two largest geophysical clusters are located from 731 to 741.3 m and from 511.1 to 519.1 mbl., respectively. The geological signatures of these two sections differ remarkably. The lower of the two is densely penetrated by fractures with clusters of open fractures primarily located in the upper and lower part of the geophysical cluster.

The upper of the two large geophysical clusters has no apparent relation to fracture clusters (only the upper part of the geophysical cluster contains fracture clusters). However, as described above it correlates very well with a strongly oxidized porous section in the rock. The remaining 28 geophysical clusters range in width from 0.4 to 3.1 mbl. (mean, median values and standard deviation are 1.1, 0.9 and 0.7 mbl., respectively). Note that fracture clusters 9A:1 to 9A:4 are related to all fractures in the borehole and fracture clusters 9A:5 to 9A:8 are related to open altered fractures.

Geophysical clusters not primarily related to discrete fractures

There are four geophysical clusters that do not correlate with any fracture cluster (group A). The upper two geophysical clusters (at 95 and 240 mbl.) contain oxidized rock and the lower of the two clusters has also brittle-ductile shears and both are located in close connection to interpreted brittle deformation zones (one contain brittle-ductile shear zones and both are located in SKB DZ, see text below). The other two geophysical clusters are fairly closely located (at about 477 and 489 mbl.) and contain no noted structural features indicating increased porosity.

The section at 477 mbl. (0.6 m wide) is located between two sections with oxidized rock while the section at 489 mbl. (0.5 m wide) has no oxidized rock in its closest surroundings. Although, the two geophysical clusters are relatively closely located above the major section of vuggy granite at about 510 to 520 mbl. and the absence of open fractures in the two geophysical clusters indicates that the increased porosity may be due to alteration.

Geophysical clusters related to general fracturing

Amongst the 26 geophysical clusters (group B clusters) that coincide with clusters outlined by all fractures (23 agree with 9A:1 fracture clusters, 21with 9A:3, 26 with 9A:2 and 24 with 9A:4), there are 7 geophysical clusters (sub-group B1) that coincide with clusters outlined by open altered fractures (all 7 agree with 9A:1 to 9A:4 clusters and, regarding open altered fractures, 4 of them agree with 9A:5 clusters, 2 with 9A:7, 7 with 9a:6 and 5 with 9A:8, cf. Table 4-10) while 3 geophysical clusters (sub-group B2) contain sections of crushed rock[16] (all 3 agree with 9A:1 to 9A:4 clusters). Notable is that only two sub-group B1 clusters and one sub-group B2 clusters are located at levels above -500 m a.s.l. (corresponds to 625 mbl.: two B1 sub-clusters at about 230 and 335 mbl. and one B2 sub-cluster at 264 mbl.) while 5 sub-group B1 clusters and one sub-group B2 cluster are located below -500 m a.s.l. (clusters of the B1 sub-group at about 641, 658, 736, 743 and 778 mbl. and a clusters of the B2 sub-group at 644 mbl.).

Amongst sub-group B1 clusters, two clusters are associated with brittle-ductile shears and oxidation (at 230 and 641 mbl.). In the remaining five sub-group B1 clusters two display alteration (oxidation; at 736 and 743 mbl.). The fractures in the B2 sub-group of clusters, i.e. fractures in crushed zones, are all altered and one cluster contains also brittle-ductile shears (at 644 mbl.).

A third sub-group of clusters belonging to the B group can be distinguished (sub-group B3: 16 clusters). This sub-group constitutes group B clusters that belongs to neither sub-group B1 nor sub-group B2 of the geophysical clusters (sub-group B3: 13 agree with 9A:1 fracture clusters, 9 with 9A:3, 16 with 9A:2, 14 with 9A:4 and none correlates with 9A:5 to 9A:8 fracture clusters); i.e. the group B clusters that do not coincide with clusters outlined by open altered fractures or crushed rock. Amongst sub-group B3 clusters, three are associated with brittle-ductile shears (at 104, 248, and 479 mbl.), 7 with oxidation of the host rock (at 31, 102, 233, 245, 475, 479 and 515 mbl.), 7 contain neither brittle-ductile shears nor oxidized rock (at 65, 70, 75, 99, 179, 344, 421 mbl.) and one sub-group 3 cluster has both alteration and brittle-ductile shears (at 479 mbl.). All sub-group B3 clusters are located from 30 to 520 mbl., i.e. located above -500 m. a.s.l.

Summary

In summary, correlation between geophysical clusters and fractures clusters are uncertain as, for example, the fracture clusters 9A:2 (all fracture data; 523 clusters outlined by at least 3 fracture with mutual separations less than

[16] According to the SKB nomenclature applied in geological core-logging (SKB 2004) the term “crush” is used for a highly fractured section formed by open fractures. Furthermore, the separation of fractures is less than 5 cm and performing any restoration of the core is difficult to impossible. In practice a section of crushed rock contains more the one set of fractures (note made by the author of the present report.

0.2 mbl.) cover about 30 per cent of the borehole (cf. Fig. 4-15 and Table 4-10) whereas the geophysical clusters (30) cover 6.4 % of the investigated part of the borehole. Of the geophysical clusters, 26 coincide with clusters outlined by all fractures. The "clusters" outlined by open altered fractures (cf. 9A:6 clusters, 46 clusters outlined by similar clustering criteria as 9A:2 and cover 1.4% of the borehole as well as 5 sections of crushed rock) coincide with a third of the geophysical clusters (7 9A:6 clusters and 3 sections of crushed rock). This study should be complemented with studies of clusters outlined by fracture sets and sampling bias should then be considered.

Tectonic zones and geophysical clusters

In borehole KFM09A, seven zones of crushed rock are mapped. The zones are all thin (0.01 to 0.89 m wide; mean width is 0.17 m, median 0.04 m and standard deviation 0.32 m). Three of the crushed zones (0.12, 0.89 and 0.02 m wide at about 35, 263 and 645 mbl., all containing altered fractures) agree in position with geophysical clusters (Fig. 4-15j). The remaining four crushed zone have widths of few centimetres (0.01 to 0.06 m; two with fresh fractures and two with altered fractures).

The number of brittle-ductile shear zones is large in borehole KFM09A (73; zones, 0.004 to 0.4 m wide, mean width 0.08 m, median width 0.05 and standard deviation 0.08 m). The brittle-ductile shear zones are generally subvertical and trend NW to NNW. Nine brittle-ductile shear zones correlate with geophysical clusters (Fig. 4-15k) and the widths of these zones are all less than 0.20 mbl. The zones are located at 94 m (3 zones), 104 m, 229 m, 248 m, 479 m, 640 m and 645 mbl.

Alteration of bedrock and geophysical clusters

The different types of alteration recorded in borehole KFM09A are albitization, argitillization, chloritization, epidotization, laumontization, oxidation, quartz dissolution, saussuritization and sericitization. The dominating type of alteration is oxidation followed by albitization. Other types of alterations are sparse. Different types of alteration may overlap each other. The number of sections with oxidation in the borehole is 120; having mean and median widths of 0.7 and 0.3 mbl. and associated standard deviation and maximum length are 0.9 m and 5.3 m, respectively.

There are 13 geophysical clusters overlapping borehole sections with oxidation and the width of the oxidized sections range from 0.1 to 5.3 m (9 are wider than 0.85 m). As already pointed out, the widest oxidized section (actually two sections in close connection), located between 513.2 to 520.4 mbl., display dissolution of the quartz grains (so called "vuggy granite" or episyenite). Other oxidized sections at about 475 to 480 mbl., having few fractures, may also be affected by quartz dissolution (no notations are found in the core log) as it is indicated by the geophysical logs to be porous.

Oxidized sections correlated with geophysical clusters are located at about 30 m, 94 m, 101 m, 228 m, 232 m, 239 m, 244 m, 464 m, 479 m, 515 m, 640 m, 733 m, and 743 m and borehole length. The two widest borehole sections with oxidized rock not correlated to geophysical clusters have widths of 3.8

and 3.0 mbl. and are located at about 114 m and 698 mbl., respectively. There are also some 20 sections of oxidized rock wider than 0.9 mbl. that do not overlap with the geophysical clusters.

Interpreted brittle deformation zones and geophysical clusters

There are 6 deformation zones interpreted by SKB (DZ in SKB data base SICADA file p_eshi-KFM09A.xls) in borehole KFM09A. The widths of the DZ range from 1.0 to 63.0 mbl.; the 1.0 m wide DZ is an ESHI DZ (unreported data) while deformation zones inferred during the geological Single Hole Interpretation range in length from 20 m to 63 mbl. (cf. Stephens et al. 2008). The total borehole length of DZs is 170 m, which is about 20% of the total length of the borehole. The total width of the 30 geophysical clusters is about 49 mbl. and the DZs that are wider than 20 mbl. contain one to six geophysical clusters.

The one metre wide DZ is the only DZ that does not contain any geophysical cluster. There are 15 geophysical clusters located outside DZ's ranging in width from 0.2 two metres to 2 mbl. (mean and median widths are 0.8 and 0.6 mbl.), excluding the 8 m wide geophysical cluster that coincides with the vuggy granite.

Summary

In summary, the objective of this section of the report is to identify borehole intervals with increased porosity based on structural data and relate these sections with porous sections indicated by geophysical measurements.

The distribution of all fractures (including the categories sealed, partly open and open fractures) may give limited information about locations of increased porosity. However, most of the geophysical clusters (28 out of 30; the missing two are about 0.5 m wide) can be correlated with structures in the rock. However, fracture data need more sorting. In addition, fracture sets and fracture classes (for example size of aperture and degree of alteration of fractures) have to be treated separately in order to locate and understand weak parts in the rock. Notable is that the porosity in the rock can also be caused by chemical processes, for example alteration associated with dissolution of minerals and mass transport.

Table 4-10. Character of clusters of fractures in borehole KFM09A section 7 to 800 m borehole lengths. Two groups of fractures are treated: all fractures and open altered fractures). Identification of clusters is based on two criteria: 1. The minimum mutual separation between fractures (given by the minimum fracture frequency; 10 and 5 fr/mbl.) and 2. The minimum number of fractures to outline a cluster (3 and 4 fractures).

Cluster				**Borehole KFM09A**					
ID[3]	**Group of fractures**	**Criterion to identify clusters**		**Borehole section about 7 to 800 m borehole length**					
		Minimum number of fractures to out-line a cluster[1]	**Minimum fracture frequency (fr/mbl.)**[3]	**Number of clusters**	**Length of clusters (mbl.)**	**Length of clusters in percent of section length (%)**	**Mean fracture frequency in section (fr/mbl.)**	**Mean fracture frequency in clusters (fr/mbl.)**	**Fractures in clus-ters in percent of fractures in sec-tion (%)**
9A:1	*All*	3	10	602	98.1	12.4	6.4	24.1	58.7
9A:2		3	5	522	253.1	32.0	6.4	14.5	82.8
9A:3		4	10	364	78.8	9.9	6.4	24.0	44.6
9A:4		4	5	406	236.5	29.9	6.4	14.5	75.9
9A:5	*Open altered*	3	10	29	3.3	0.4	1.0	26.1	14.6
9A:6		3	5	46	11.3	1.4	1.0	13.3	24.8
9A:7		4	10	14	2.4	0.3	1.0	24.2	8.9
9A:8		4	5	26	7.4	0.9	1.0	15.1	17.2

[1] Minimum number of fractures to outline a cluster – 3 fractures = 2 core pieces and 4 fractures = 3 core pieces. Fracture frequency in a cluster is (number of fractures outlining the cluster – 1)/(borehole length of the cluster); the mean fracture frequency in clusters is (number of fractures outlining the clusters – number of clusters)/(total borehole length of the clusters).

[2] Investigated section of the drill core is about 792.

[3] ID of group of clusters, cf. Fig. 4-15.

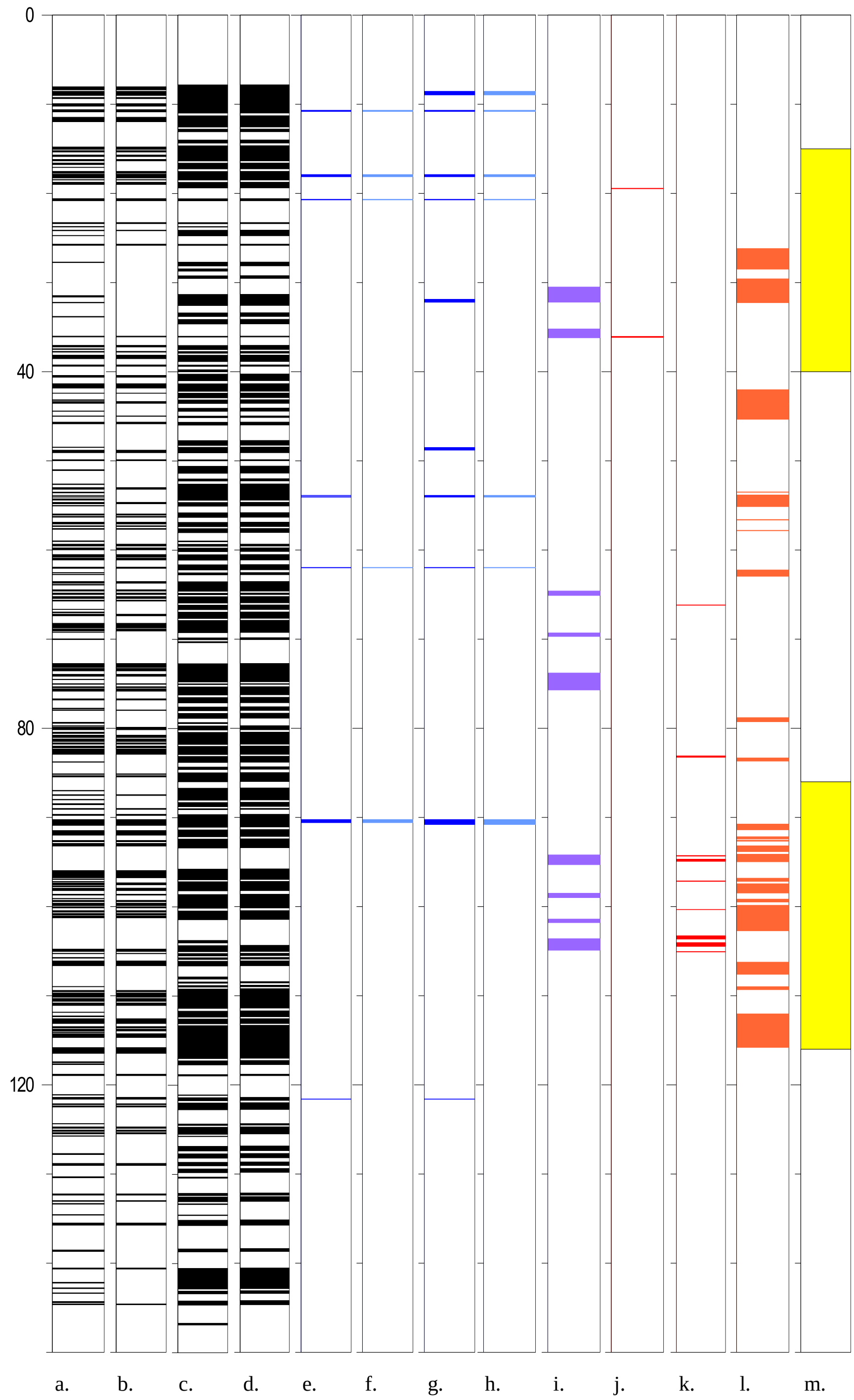


Figure 4-15: Borehole KFM09A, section 0-150 mbl.; fracture clusters (Table 4-10) brittle structures, borehole geophysics, and location of SKB interpreted brittle deformation zones (ESHI DZ):

a. Cluster 9A:1, b. 9A:3, c. 9A:2, d. 9A:4, e. 9A:5, f. 9E:7, g. 9a:6, h. 9A:8 (cf. Table 4-10),

i. Combined borehole geophysics, K-mean cluster analysis (Tirén et al. 2009, cf. text),

j. Sections with crushed rock.

k. Sections with brittle-ductile deformation zones.

l. Host rock alteration, oxidation.

m. SKB's interpretation of brittle deformation zones (ESHI DZ: DZ1, 15-40m, ZFMENE1208A and DZ2, 86-116 m, ZFMENE1208B, Stephens et al. 2008).

(To be continued).

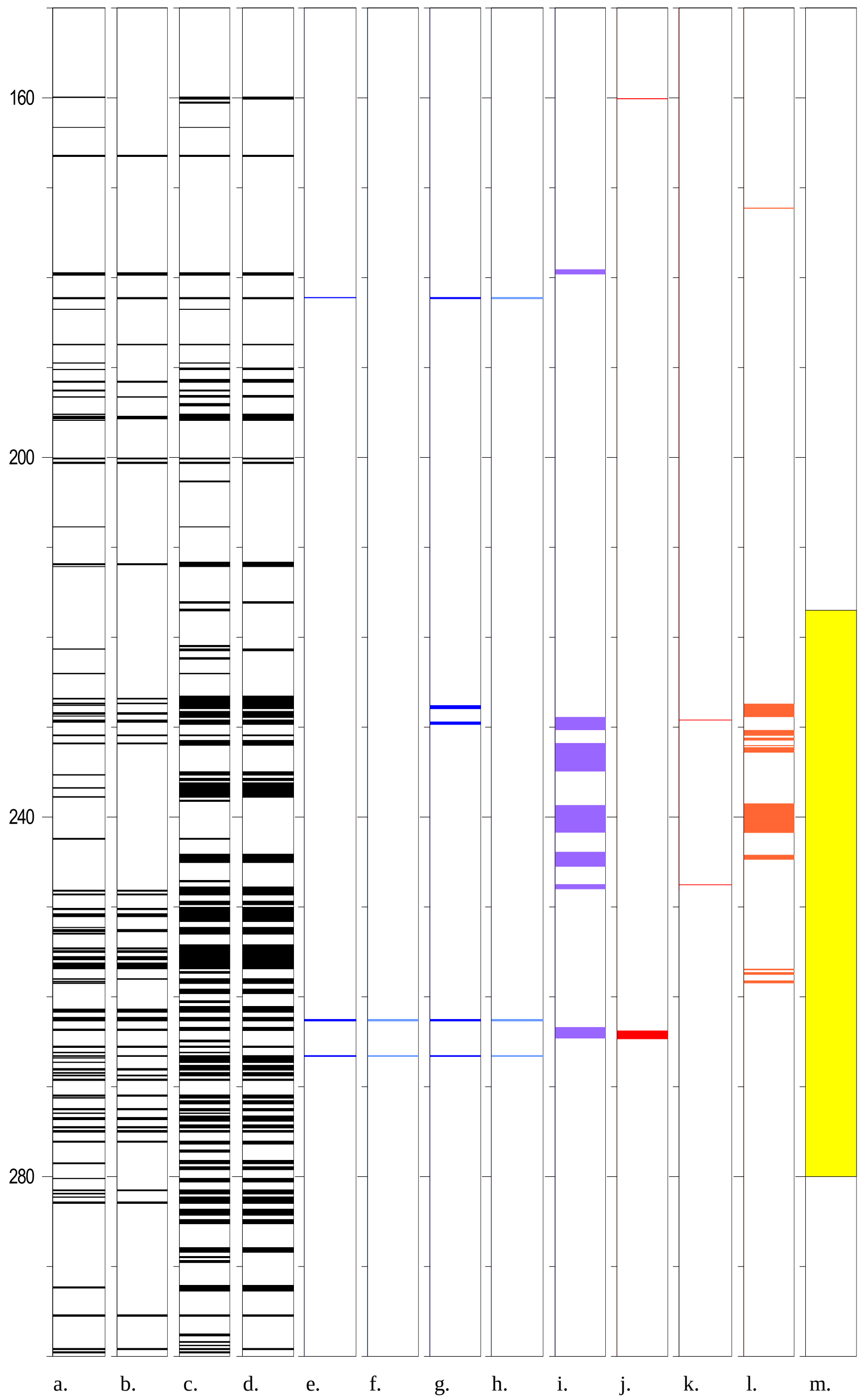


Figure 4-15 (continued): Borehole KFM09A, section 150-300 mbl.; fracture clusters (Table 4-10) brittle structures, borehole geophysics, and location of SKB interpreted brittle deformation zones (ESHI DZ):

a. Cluster 9A:1, b. 9A:3, c. 9A:2, d. 9A:4, e. 9A:5, f. 9E:7, g. 9a:6, h. 9A:8 (cf. Table 4-10).

i. Combined borehole geophysics, K-mean cluster analysis (Tirén et al. 2009, cf. text).

j. Sections with crushed rock.

k. Sections with brittle-ductile deformation zones.

l. Host rock alteration, oxidation.

m. SKB's interpretation of brittle deformation zones (ESHI DZ: DZ3, 217-280m, ZFMENE0159A, Stephens et al. 2008).

(To be continued).

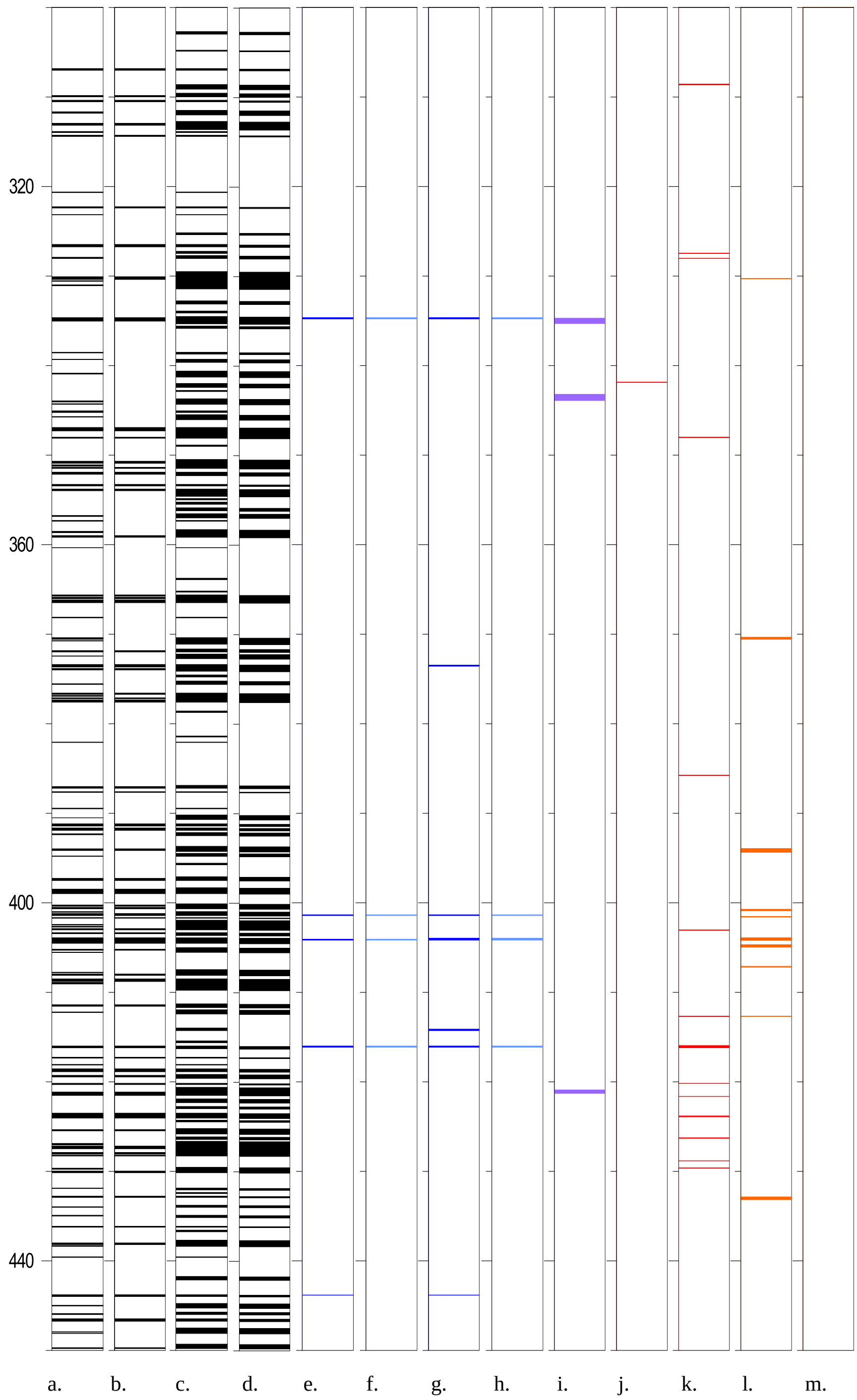


Figure 4-15 (continued): Borehole KFM09A, section 300-450 mbl.; fracture clusters (Table 4-10) brittle structures, borehole geophysics, and location of SKB interpreted brittle deformation zones (ESHI DZ):

a. Cluster 9A:1, b. 9A:3, c. 9A:2, d. 9A:4, e. 9A:5, f. 9E:7, g. 9a:6, h. 9A:8 (cf. Table 4-10).

i. Combined borehole geophysics, K-mean cluster analysis (Tirén et al. 2009, cf. text).

j. Sections with crushed rock.

k. Sections with brittle-ductile deformation zones.

l. Host rock alteration, oxidation.

m. SKB's interpretation of brittle deformation zones (ESHI DZ: No DZ in this section of the borehole, Stephens et al. 2008).

(To be continued).

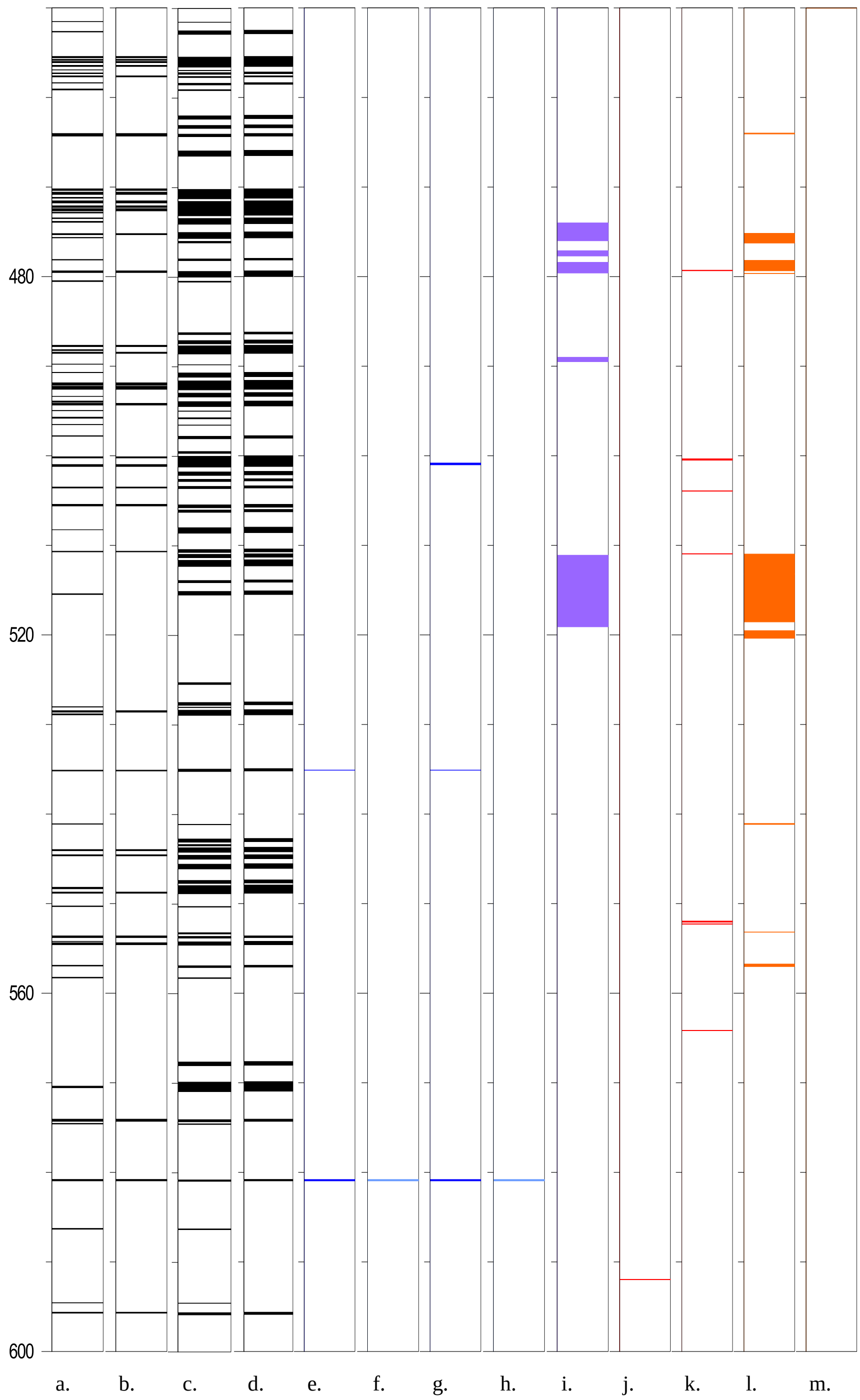


Figure 4-15 (continued): Borehole KFM09A, section 450-600 mbl.; fracture clusters (Table 4-10) brittle structures, borehole geophysics, and location of SKB interpreted brittle deformation zones (ESHI DZ):

a. Cluster 9A:1, b. 9A:3, c. 9A:2, d. 9A:4, e. 9A:5, f. 9E:7, g. 9a:6, h. 9A:8 (cf. Table 4-10).

i. Combined borehole geophysics, K-mean cluster analysis (Tirén et al. 2009, cf. text).

j. Sections with crushed rock.

k. Sections with brittle-ductile deformation zones.

l. Host rock alteration, oxidation.

m. SKB's interpretation of brittle deformation zones (ESHI DZ: No DZ in this section of the borehole, Stephens et al. 2008).

(To be continued).

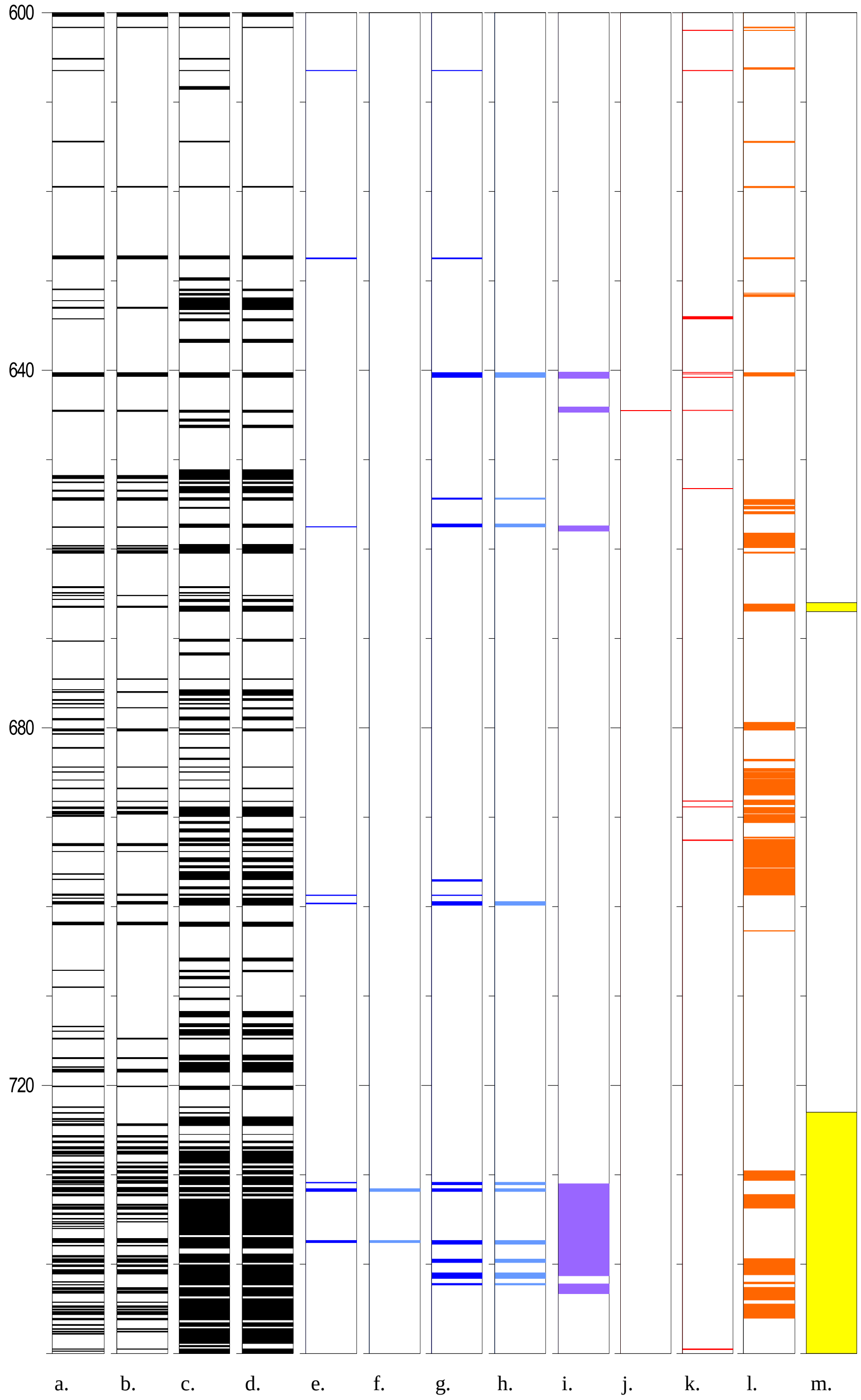


Figure 4-15 (continued): Borehole KFM09A, section 600-750 mbl.; fracture clusters (Table 4-10) brittle structures, borehole geophysics, and location of SKB interpreted brittle deformation zones (ESHI DZ):

a. Cluster 9A:1, b. 9A:3, c. 9A:2, d. 9A:4, e. 9A:5, f. 9E:7, g. 9a:6, h. 9A:8 (cf. Table 4-10).

i. Combined borehole geophysics, K-mean cluster analysis (Tirén et al. 2009, cf. text).

j. Sections with crushed rock.

k. Sections with brittle-ductile deformation zones.

l. Host rock alteration, oxidation.

m. SKB's interpretation of brittle deformation zones (ESHI DZ: DZ6, 666-667 m, DZ4, 723-754 m, ZFMNW1200, Stephens et al. 2008).

(To be continued).

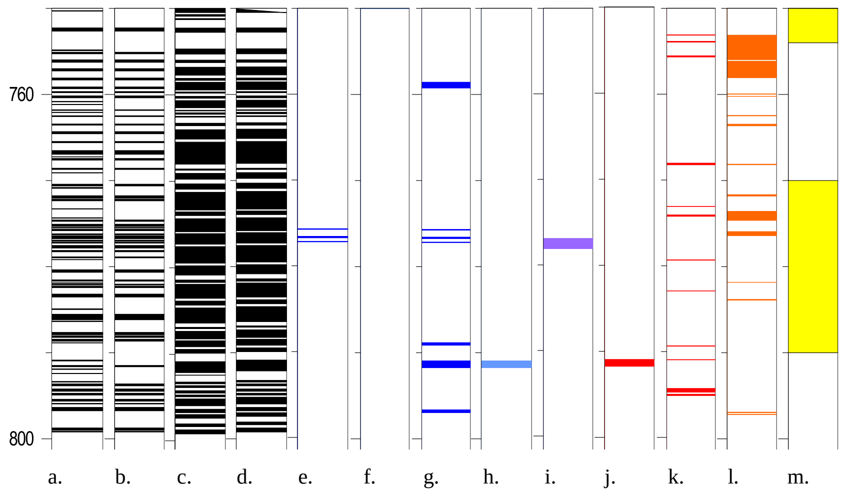


Figure 4-15 (continued): Borehole KFM09A, section 750-800 mbl.; fracture clusters (Table 4-10) brittle structures, borehole geophysics, and location of SKB interpreted brittle deformation zones (ESHI DZ);

a. Cluster 9A:1, b. 9A:3, c. 9A:2, d. 9A:4, e. 9A:5, f. 9E:7, g. 9a:6, h. 9A:8 (cf. Table 4-10).

i. Combined borehole geophysics, K-mean cluster analysis (Tirén et al. 2009, cf. text).

j. Sections with crushed rock.

k. Sections with brittle-ductile deformation zones.

l. Host rock alteration, oxidation.

m. SKB's interpretation of brittle deformation zones (ESHI DZ: DZ4, 723-754 m, ZFMNW1200, and DZ5, ZFMWNW1200, Stephens et al. 2008).

5. Results and conclusions

The objective of the present study is to give alternative descriptions of brittle deformation zones (location and internal character) and also try to describe the geological zones in terms of their competence, i.e. input data to rock mechanical analysis. In other terms, what is the difference between a brittle deformation zone and a related weakness zone (cf. Palmstrøm 1995)?

Detection of zones

It is obvious that a given definition of, for example, a geological feature should give a description of the feature but this does not imply that the definition itself give enough support to identify and locate the feature (give its position, its boundaries). Furthermore, the character of geological features may change over time. For example, a brittle deformation zone may seal or reactivate. The present character of a zone may in many cases be a result of repeated combinations of both processes.

In the Forsmark area, i.e. within the local SKB site, fractures are the most widely spread brittle structure in the rock while non-cohesive fault rock, except for crushed rock, is found more rarely. Borehole sections with crushed rock are mappable units and they are relatively few and have wel-defined widths. Guidelines and definitions useful for locating and describing brittle deformation zones and weakness zones in the Forsmark bedrock based on fracture distributions are needed (crushed rock are at a first stage not included as they are obvious weak features). The chosen definitions should be widely excepted/well described and the approach to locate zones should be simple and reproducible. Furthermore, generalizations, if needed, should be performed at a late stage of the process, which ensures that primary data are brought along during identification of zones allowing the zones to be described in detail.

The purpose of this work is not to define brittle deformation zones or weakness zones. However, it is necessary to have numerical values on fracture frequencies inside a zone and within its different parts as well as a tool to calculate fracture densities. Furthermore, premises for locating zone boundaries (internal as well as external) should be presented.

The chosen values for brittle deformation zones, 10 fracture per metre borehole length for the core zone and 5 fractures per metre for the damage zone (transition zone), are magnitudes fairly similar to those stated in the SKB definition of a brittle deformation zone (Munier et al. 2003). However, selecting other values for these parameters does not affect the approach to locate zones presented in this study. Moreover, the definition used for weakness zones (cf. Palmström 1995) does not comprise any numerical values on fracture densities. A weakness zone can be considered as a particular type of structural feature that generally is to some degree formed by brittle deformation, possibly accompanied by alteration, and includes a sub-group of all fractures; unsealed fractures, i.e. fractures having low tensile strength. Therefore, the same nomenclature for the different parts of a zone can be used both for brittle deformation zones and for weakness zones: core (e.g. 10

fractures per metre borehole length) and damage zone (transition zone; e.g. 5 fractures per metre borehole length). The difference is the base data.

The approach to locate brittle deformation zones[17] and weakness zones developed in this study contain several clearly outlined steps. The process involves discrimination of data (selecting sub-sets of fractures according to their characteristics) and classification of data (separation of fractures along boreholes). The characteristics of all fractures in all sub-sets of data are brought along in the process. Simplifications are only performed at a late stage of the process. Furthermore, no other information about geological features other than borehole logs has been used.

Proposed methodology

The approach to identify brittle deformation zones and weakness zones that was developed at an early stage of this study, presented in Chapter 2 and applied in Chapter 3, is here presented in a slightly upgraded version based on the experience gained during the evaluation of borehole data in this study. The different steps in the evaluation process are also discussed.

The steps are:

1. *Selection of fracture data to evaluate – main groups and sub-groups of data.*

   The detection of brittle deformation zones and weakness zones generally need sorting of base data as all clusters of fractures within, for example, a borehole may not be related to zones.

   A. In this study all discrete fractures are first analysed. If distinct sets of fractures exist then each set is treated as a separate group if fractures within the set appears as swarms in the drill core. Together these groups form the main groups of fractures (all fractures and set of fractures).

   B: Within each identified main group of fractures, sub-groups containing weak fractures are looked for. The identification of weak fractures is a critical issue and need a good understanding of the primary data.

   In this study weak fractures are indicated by the occurrence of open altered fractures. The outcome of selecting fractures with other characteristics to represent weak fractures can be tested (cf. Step 3, sensitivity tests).

   It is found helpful to give, for example, different fracture sets separate colour codes (noted in the columns giving the orientation) to get a visual overview of fracture orientations in the data file.

   Other types of brittle structures than discrete fractures are not considered in this step. Such brittle structures and ductile structures are added later (Steps 3 and 5).

[17] Strictly, what are defined are fracture zones as the zones are solitarily outlined by fractures. However, the term fracture zone was used by SKB prior to about 2000 (cf. Andersson et al. 2000 and Stråhle 2001) and thereby a redefinition have to be performed if the term should be reintroduced.

2. *Classification of fracture separation – location of clusters*

Brittle deformation zones constitute planar or semi-planar cluster domains of fractures. The same relates to weakness zones associated with brittle deformation. In a borehole the clusters are displayed by the separations of fractures. The calculations of fracture separation along the borehole are made by straight-forward subtraction[18]. The classification of fracture separations is not an intricate procedure, although it needs measures to relate to. These measures or parameters are partly given by the applied definition of brittle deformation zones and weakness zones.

A: The first parameter is the mutual separation of fractures, which is the inverse of the fracture frequency. The damage zone (transition zone) should have a fracture frequency that differs from that in the host rock and should also differ from that in the core of the zone. Using RQD equal to zero to define a core zone gives a fracture frequency of 10 or more fractures per metres for the core zone (separation 0.1 mbl. or less). The corresponding value for the damage zone (transition zone) could then be 5 fractures per metre borehole length (separation of 0.2 mbl. or less). However, crucial is here the applied principle for determining the fracture frequency (number of fractures within a distance along the borehole, a fix distance or a fracture distribution related distance). As pointed out several times the separation of fractures in boreholes (along scan-lines) is here used as a relative measure to locate increased fracturing.

To simplify the classification of separation of fractures along boreholes two classes are used:

Class 1. The range in separation of fractures is 0.1 m or less.
Class 2. The range in separation of fractures is 0.2 m or less.

When classified groups of fractures consisting of a fracture set the ranges in separation of fractures along the core for the two classes may be corrected for sampling bias. This improves the possibility to detect fracture swarms intersecting the borehole at small angles. Furthermore, the second class will include all fractures embraced by the first class (see text below).

The selection of separations of 0.1 m and 0.2 m to distinguish clusters is found appropriate and the actual location of a zone (its core and damage zones) need further interactive processing of data (Step 4). Adding a third class of fracture separation with greater fracture separation (e.g. 0.5m) still implies that the interpretation of zones should harmonise with the applied definition of brittle deformation zones/weakness zones. In borehole KFM10A it may slightly affect the location of boundaries of zones when a third class (0.5m; note that the mean and median separation of fractures is 0.22 and 0.07 mbl., respectively, and the standard de-

[18] Treatment of sampling bias imposed by linear sampling see, for example, Priest 1985.

viation is 0.47 mbl.) is used and the definition of zones is kept (cf. 4-3 and 4-13 and text below).

B. How few fractures could a brittle deformation zone and weakness zone contain to be identified as a zone? In principle, a fault zone could contain a single fracture (cf. Caine et al. 1996), a fault plane. To calculate a separation two fractures are needed. To identify a cluster at least three fractures are needed.

There are some advantages of having a high resolution in the classification system:

a. Thin structures will be detected.
b. Simple to change to a higher number of fractures to outline a structure.
c. It gives a good base for sensitivity tests (cf. Fig. 4-3 and Step 3 below).

Furthermore, the classification system outlined above (considering separation and number of fractures) is very sensitive to detect clusters of fractures. Brittle deformation zones and weakness zones are all more or less heterogeneous, which implies that segments with low fracture densities occurring inside zones will be indicated. This implies that an additional step is needed to determine the total width of as zone (Step 4).

Table 5-1: Fracture frequency in clusters in seven borehole sections (65 to 150 m long) containing a gently inclined brittle deformation zone, zone ZFMA2 in the SKB site at Forsmark (see text for complimentary explanation).

Fracture frequency in different classes of fracture clusters

	Classification of clusters		Group of fractures	
Depth of section (- m a.s.l.)	**Minimum number of fractures**	**Minimum separation of fractures (mbl.)**	**All Fracture (fr/mbl.)**	**Open altered fractures (fr/mbl.)**
		Class 1		
0-137	4	0.1	28-33	27-34
132-237	4	0.1	28	21
248-480	4	0.1	25-31	0-26
		Class 2		
0-137	4	0.2	15-22	14-17
132-237	4	0.2	16	13
248-480	4	0.2	15-18	0-17

The average fracture densities in clusters within the seven investigated borehole sections located across the gently inclined brittle deformation zone ZFMA2 in Forsmark (Table 5-1, cf. Tables 5-2 and 5-3; note that 4 fractures are used to outline a cluster) are for clusters of class 1 type much higher than the given minimum value for core zones (10 fr/mbl.). The fracture frequencies in class 2 clusters (class 2 clusters contain the class 1 clusters), are about half (0.4 to 0.7 times) of the values for corresponding class 1 clusters. Nevertheless, the frequencies in those parts of class 2 clusters that correspond to the damage zones (transition zones) are enhanced (about two times higher) compared to the threshold value for the damage zone (transition zone).

In some of the investigated borehole sections, the applied classification of clusters incorporate more than 80 percent of all fractures and more than 40 % of the length of investigated borehole sections (Tables 5-2 and 5-3). These sections may contain several fracture sets indicating that zones of different orientation may interfere within the sections. Each fracture set should be tested separately and the outcome of the analysis should include a geological interpretation clarifying the structural relations.

Table 5-2: The relative length of fracture clusters in seven borehole sections (65 to 150 m long) containing a gently inclined brittle deformation zone, zone ZFMA2 in the SKB site at Forsmark (see text for complimentary explanation).

Relative coverage of borehole length for different classes of fracture clusters

	Classification of clusters		**Group of fractures**	
Depth of section (- m a.s.l.)	**Minimum number of fractures**	**Minimum separation of fractures**	**All fracture (% of investigated borehole sections)**	**Open altered fractures (% of investigated borehole sections)**
		Class 1		
0-137	4	0.1	3-25	2-3
132-237	4	0.1	16	1
248-480	4	0.1	4-7	0-1
		Class 2		
0-137	4	0.2	12-48	6-13
132-237	4	0.2	43	4
248-480	4	0.2	13-22	0-2

Table 5-3: The relative percent of fractures within fracture clusters in seven borehole sections (65 to 150 m long) containing a gently inclined brittle deformation zone, zone ZFMA2 in the SKB site at Forsmark (see text for complimentary explanation).

Relative percent of fractures in clusters for different classes of fractures clusters				
	Classification of clusters		Group of fractures	
Depth of section (- m a.s.l.)	Minimum number of fractures	Minimum separation of fractures	All Fracture (% of all fractures in investigated borehole sections)	Open altered fractures (% of all open altered fractures in investigated borehole sections)
		Class 1		
0-137	4	0.1	31-77	25-33
132-237	4	0.1	56	13
248-480	4	0.1	45-59	0-30
		Class 2		
0-137	4	0.2	59-92	49-62
132-237	4	0.2	83	39
248-480	4	0.2	59-77	0-41

Within Step 2, when considering all fractures, the characteristics of fractures inside clusters should be noted and also related to fractures outside clusters. Of special interest is to note these relations for clusters outlined by weak fractures (in this case open altered fractures). Clusters of fractures may either be due to random interferences between fracture sets or reflect the existence of brittle deformation zones.

3. *Sensitivity tests*

Including sensitivity tests early in the process can be advantageous as the selection of fracture data and threshold values of cluster parameters form the basis for further processing of data in order to determine the location of the core zones and borders of the zones (Step 4).

A test may consist of changing the minimum number of fractures to form clusters (for example 4±1 fractures, cf. Figs. 4-3 and 4-15) or to vary the minimum mutual separation between fractures to outline clusters (for example, from 0.1 and 0.2 to 0.5 mbl.; the latter corresponding a minimum fracture frequency of 2 fr/mbl., cf. Fig. 3-72). Of these two types, the second (changing the boundary for accepted separation between fractures) may have the greatest effect, at least in the Forsmark area.

A sensitivity test could also consider alternative selections of fractures to represent weak structures. Open altered fractures constitute a sub-group of all fractures parting the core. Some of the latter may be fractures that are broken during drilling or handling of the core. There may also be fresh open fractures and the relevance of these fractures is uncertain (cf. Chapter 4 section “Broken fractures and open, partly open and seal fractures”). They could represent natural fractures, but as they are fresh they are either late or not connected. It could be of interest to test if ‘open fresh fractures’ are related to any structural features outlined by, for example other types of fractures, ductile deformation, rock types or lithological contacts.

4. *Location of brittle deformation zones and weakness zones*

Clusters of fractures in boreholes, determined by the approach given above, do in many cases appear as swarms (higher order of clusters) and by that indicating inhomogeneous brittle deformation zones or weakness zones (a self-similar type of appearance).

The question is then what rules should be applied to outline inhomogeneous zones and where to locate the borders of such zones. In other words, principles for determining the architecture of zones are needed. That is, to locate core zone/-s, the damage zones (transition zones) and to present the width of the zones.

Merging clusters to form a zone implies dilution of the fracture frequency data, as parts of the rock located outside clusters will be included (the same holds for the core zone).

It is here determined that the boundaries of a zone and a core zone should be located at clusters of fractures. This is not a fully obvious decision, but it is practical. A cluster contains a number of fractures and the fractures may or may not have characteristics indicating whether they are related to the main part of fractures in the zone or not. If the fractures are related to the zone and located within a reasonable distance (see below) to the main body of clusters forming the zone, the cluster could be used to define the boundary of the zone.

The main question is which clusters should be merged in order to outline a zone. Clusters to be merged should contain fractures with similar character. The merging could of course be done by hand, but such a procedure may not be fully reproducible.

It is found in boreholes from Forsmark that class 2 clusters with separations equal to or smaller than their mean width could be merged, giving meaningful geological structures (Chapter 4 section “Extension of cluster patterns – a step to brittle zone identification”). This is an interactive repetitive process and it should stop when there are no more clusters to connect or when the fracture frequency in the damage zones reaches its minimum value.

However, calculations of fracture frequency in the damage zone (see below) require that class 1 clusters should first be merged in a similar manner. The class 1 clusters (affected or not affected by the merging process) together with sections of crushed rock and fault rocks (in this step introduced in the location/characterization of brittle deformation zones and weakness zones; weakness zones will only incorporate incohesive fault rock) will form the core zones. This procedure has been tested in one borehole section (Fig. 4-13). Furthermore, for bedrock comprising rock masses (domains) with contrasting general fracture characteristics, this step should be carried out separately for each domain. For example, the upper part of the basement rock in the Forsmark site has a general increase of fractures and a higher density of open fractures compared to deeper levels. Clusters outlining weak parts of the rock in Forsmark are generally wider in the upper part of the bedrock compared to similar clusters at depth.

Many brittle deformation zones are heterogeneous structures, which imply, for instance, that they may contain several parts recognisable as core zones. The core zone/-s may occur within the damage zones (transition zones) and some may occur at the border of brittle deformation/ weakness zones.

The fracture frequency within the damage zone can be calculated as the mean value for fractures inside a zone by excluding the core zone/-s (number of fractures in and total length of core zone/-s). The mean fracture frequency for core zones within a brittle deformation zone or a weakness zone can also be presented. However, the fracture frequency for each core zone is of interest as it may give information about the intensity and heterogeneity of deformation within a brittle deformation zone and also that it indicates the weakest part of a weakness zone. In Forsmark it is generally found that the weakness zones constitute minor parts of the studied brittle deformation zones and weakness zones may also occur outside the brittle deformation zones identified or modelled by SKB.

The final comment regarding this step in the zone identification regards a general geological consideration: Is the performed interpretation plausible? This question should be asked because the performed analyses of zones are based on simple statistics and the outcome should be considered as a guide.

5. *Presentation of results – compilation of data*

Presentation of results should be performed so that the results can easily be used by other geodisciplines and also in such a way that it communicates the essence of the results of the classification. The former can be done by presenting data in tables, while the latter can be a visualization of results (composite logs or three-dimensional figures showing, e.g., structural relationships). Both presentations should be accompanied by descriptive text.

In the present study the results are presented in composite borehole logs presenting distribution of clusters of fractures together with sections of core loss, crushed rock, brittle-ductile shears, ductile shears, different types of fault rock (mainly cataclastic rocks and breccias), networks of sealed fractures, host rock alteration, hydraulic log (PFL), and existing interpretations of brittle deformation zones (cf. 3-48, 3-72, 3-87, 3-101, 3-117 and 4-159). Geophysical logs should also be presented (cf. Fig. 4-15).

6. *Compilation of description of zones – an interactive process*

   Within the framework of brittle deformation zones in the bedrock different sets can generally be distinguished, including sets of zones that have typical characteristics and relations to other structures. Furthermore, structures may primarily change character along their extension and they can also be distorted, partly reactivated to extended, by subsequent tectonic events. A single set of brittle deformation zones may contain structures on different scales, which could be of interest to understand. Tectonic zones generally form traces in the terrain where they outcrop (lineaments), especially when a brittle deformation zone contains a distinct weakness zone or several weakness zones. However, generally the traces are covered by soil, i.e. not exposed. A borehole, on the other hand, represents a linear survey and that line provides a continuous exposure of the rock and its structures.

   By listing all characteristics of brittle deformation zones it should be possible to sort out which characteristics are primary, secondary (related to reactivation) and which features in the rock are not related to the zones. Identification of brittle deformation zones is a learning process and a systematic description of different sets of zones improves prediction and outcome studies; what do we know and what can we expect/predict?

It is beyond of the scope of this study to make a detailed catalogue describing the character of the investigated gently inclined zone ZFMA2 in Forsmark. However, based on the performed study a brief summary of the characteristics of ZFMA2 is given below. Before doing this it is stressed that the approach to locate brittle deformation zones and weakness zones presented here have the following advantages:

- It brings all fracture characteristics along during the process of locating zones although discrimination of fractures is performed (for example: all data –>open fractures –> open altered fractures –> sets of open altered fractures).
- A systematic approach to sorting and classifying borehole fracture data is established.
- The selection types and of ranges of parameter data, i.e. the fracture separation along boreholes, become clear and the arguments for the selections transparent.
- The process is reproducible.
- The analysis is relatively time-consuming, but as it is mainly a matter of sorting data.

Finally, in order to increase the traceability of data processing, all steps should be documented and a general plan of the processing should be established before starting the main work. This is a necessity as the work is a learning process and new ideas will emerge and be tested during the progress of the investigation. It is also important to establish an applicable nomenclature and to present relevant tools/processes to quantify parameters typical for the object.

A gently inclined brittle deformation zone and associated weakness zones

The object studied in this study is a gently inclined brittle deformation zone (ZFMA2), which is one of several modelled structures within the SKB site at Forsmark, eastern central Sweden. The zone (DZ) is interpreted to be penetrated by seven boreholes. In most boreholes, zone ZFMA2 is identified as a single zone (DZ widths: 12 to 37 m along the boreholes), while in three boreholes the zone appears to haves two branches (DZ widths: upper branch 11 to 25 m and lower branch 10 to 37 m along the boreholes). At deeper levels (below – 250 m a.s.l.), the range in the width of the zone (and its branches) is 12 to 25 mbl.

The investigation performed on the brittle zone ZFMA2 comprises Steps 1, 2 and 5 (see text above) for all seven borehole sections. Sensitivity tests and determination of zone location (Steps 3 and 4) are performed for the deepest location where the zone is penetrated by a borehole inside the local model area.

The character of ZFMA2 is summarized at the end of Chapter 3 and is not repeated here. Instead the overall picture of zone ZFMA2 is complemented by some notes regarding the variability of the zone in the different boreholes.

The orientations of fracture clusters within zone ZFMA2 in the boreholes (DZX[19]) show that it is evident that the typical orientations for fractures inside the zone is sub-horizontal to gently inclined eastwards. These are also the dominant orientations in the bedrock in the investigated borehole sections. It is also apparent that the fracture clusters inside the DZXs locally contain fractures with divergent orientation, i.e. where the zone ZFMA2 interferes with other zones, primarily with NW-SE:ly or ENE-WSW:ly trends (in boreholes KFM01C and 04A, respectively). However, in the lower branch of zone ZFMA2 in borehole KFM10A, fractures are dominantly dipping moderately southwards while fractures are sub-horizontal to gently dipping in the upper branch of the zone. A re-interpretation of the lower DZ may be possible.

Other structural features than discrete fractures are not considered when outlining clusters of fractures. However, when outlining brittle deformation zones (based on fracturing of the core), zones of crushed rock should also be considered (given in SKBs database SICADA is, for example the size of core pieces and orientation of upper and lower fractures and two dominant

[19] DZ does in this part of the text refer to the borehole intersection of zone ZFMA2 in boreholes according to SKB. DZX; X= 1 to 6 (cf. Stephens et al. 2008)

fracture orientations inside the zone). Sections mapped as crushed rock are generally thin and in four boreholes there is no crushed rock associated with zone ZFMA2. Where zones of crushed rock occur, they are generally bordered by fracture clusters. Parts of the bedrock mapped as sealed network of fractures are not considered as the fractured are generally very thin and small. Fractures intersecting sealed network of fractures are mapped as discrete fractures. Furthermore, sealed networks may in some of the investigated borehole sections be associated with zone ZFMA2 but may also occur outside the actual zone outlined by discrete fractures and are missing in some boreholes. There are other types of deformed rock (fault rock) expressing the structural evolution and as these structures are cohesive they are not considered (cf. sealed network of fractures) in the fracture analysis. However, they form a part in the definition of brittle deformation zone given by Munier et al. (2003) and they may also be a part of weakness zones (if incohesive) and constitute parts of the core zones. Brittle-ductile shears are very thin and are scarce inside zone ZFMA2. Ductile shears are not found to be associated with zone ZFMA2. In other words, zone ZFMA2 is a structure defined by its fractures, i.e. *stricto sensu* a fracture zone.

In this study the only type of alteration studied is oxidation. The oxidation varies strongly within each of the seven studied borehole sections. In some boreholes, oxidized rock is more or less bounded to zone ZFMA2. In other boreholes, oxidation is associated only with one of the two branches of the zone. There are also boreholes dominated by oxidation without apparent association to zone ZFMA2, while in one of the boreholes oxidation is scarce. Oxidation of the bedrock can be looked upon as a tracer test, i.e. it may indicate where there has been transport of hydrothermal fluids. If the latter is the case then it is apparent that zone ZFMA2 was only partly open during the event (-s) of the oxidation and that networks of open fractures locally occurred also outside the zone.

In the detailed study performed in borehole KFM01C it is found that steeply dipping fractures (dips >60°) within shallow parts of the borehole (upper 55 m of borehole KFM01B) often are open and altered while at deeper levels these fractures are sealed. This condition appears also to hold for most gently inclined fractures at deeper levels. The weaker parts of zone ZFMA2, outlined by open altered fractures in the deepest location penetrated any borehole (KFM10A) inside the local Forsmark area, are:

1. In the upper branch (SKB DZ2 430 to 449 mbl. /about -297 to -308 m a.s.l./ and 423 to 452 mbl. in this study /cf. Fig 4-13/) there are two weak parts:
    a. The first part is a zone at about 432 m, with a width along the borehole of 1.3 m, dominated by gently inclined fractures. The zone is indicated to be a part of the system of structures controlling the flow of groundwater.
    b. The second part is at about 437 mbl. and is 0.3 m wide along the borehole. The weak section is a crossing of gently inclined fractures and sub-vertical fractures. Indicated conduits of groundwater are located above, in and below the weak zone.

2. In the lower branch (SKB DZ3 476 to 490 mbl. /about -324 to -332 m a.s.l./ and 478 to 489 mbl. in this study, cf. Fig. 4-13) there are four weak parts:
    a. Two upper sections at 478 and 479 mbl., each having widths of 0.2 mbl. The upper section is dominated by moderately inclined fractures dipping southwards. The lower section contains a mix of moderately and steeply dipping fractures. Groundwater flow is indicated below the lower of the two sections.
    b. A central section at 483 mbl. having a width of 2.6 m along the borehole and interpreted as a zone. Fractures are dominantly dipping moderately southwards. Two water-conductive sections at about 244 mbl. are indicated.
    c. A lower minor section at 487 mbl. is about 0.3 m wide and contains mainly fractures dipping moderately to steeply southwards. No groundwater flow is associated to this section.

The wider zones of weakness (>1 mbl.) in the two branches of the brittle deformation zone are asymmetric and contain upper sections which represent core zones (more than 10 open altered fractures per metre borehole length; 0.3 m and 1.4 m wide in the upper and lower branches) and a lower section representing the damage zone (between 5 and 10 open altered fracture per metre borehole length; 1.0 m and 1.1 m wide in the upper and lower branches). The other weak sections associated with zone ZFMA2 are so small that it is not meaningful to divide them into core and damage zones (transition zones).

In the investigated section above zone ZFMA2 in the cored borehole KFM10A (350 to 423 mbl., Fig. 3-133) there are four section with indicated water-conductive fractures (at 360, 368, 374 and 376 mbl). Two of these sections (at 368 and 374 mbl.) coincide with minor clusters outlined by all fractures (containing gently inclined fractures) and of the remaining two (at 360 and 376 mbl.) are related to related to moderately to steeply inclined fractures, one (at 360) coincides with the location of a borehole radar reflector dipping steeply southwest. All flowing sections in the investigated borehole section of borehole KFM10A (3050 to 500 mbl.) can be correlated with open fractures, discrete fluid conduits, although some of these are noted as fresh.

Concluding remark, detailed investigations contribute to the general understanding or the structural framework in the bedrock and form a base for generalization of geodata.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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