R-08-83

Site engineering report Forsmark

Guidelines for underground design
Step D2

Svensk Kärnbränslehantering AB

November 2009

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Summary

The design and construction of an underground nuclear repository for spent nuclear fuel must consider the site conditions that may impact the long-term safety of a repository. Many of the constraints that are needed to ensure the safe performance of a final repository facility with respect to radionuclide containment are unique for the repository. The main purpose of this Site Engineering Report is to provide an overall framework for the designers responsible for the underground design and layout that meets both the operational requirements for such an underground facility and the long-term safety requirements related to nuclear-waste containment. The foundation for the development of this framework is the site descriptive model.

The Site Engineering Report builds on the extensive surface based site investigations carried out at the Forsmark site and the interpretation and evaluation of these data that are given in the site descriptive model. However, because the site descriptive model serves the needs of many users, and especially those of safety assessment, not all information contained in site descriptive model is needed for engineering design and layout purposes. The information obtained from site investigation phase and contained in site descriptive model for Forsmark must be in sufficient detail to enable SKB to: (1) develop a functional design and layout for the facility, (2) conduct a safety assessment for the site and identify the possible environmental impact of the final repository and its extent, and (3) develop an excavation strategy.

For the purpose of this report the final repository facility is divided into three functional areas that are referred to as: (1) repository access, including the access ramp and shafts, (2) central area, and (3) deposition area, including the deposition tunnels and deposition holes. Each of these areas has different design constraints and requirements. For design Step D2, the geological constraints and engineering guidelines provided in this Site Engineering Report cover the site adaptation of the final repository facility with respect to: (1) unsuitable deformation zones and rock mass conditions at depth, (2) parameters that affect the depth and areal size of the repository, and (3) description of ground conditions for assessment of constructability. The design process for the final repository facility must be in agreement with the European standard for construction, Eurocode, and in particular the standard for geotechnical design, EN 1997-1:2004, Section 2.7, which will be implemented in Sweden in 2009. This allows for the application of the Observational Method in underground design and construction. The Observational Method is a risk-based approach to underground design and construction that employs adaptive management to substantially reduce costs while protecting capital investment, human health, and the environment.

The inherent complexity and variability in the geological setting prohibits a complete picture of the ground structure and quality to be obtained before the facility is excavated. Thus during design, statistical methods will be required to evaluate the sensitivity of the design to this variability and for quantifying project risks.

There are several general engineering guidelines that should be considered in laying out the repository:

1. The depth of the repository shall be constrained between 450 and 500 m depth.
2. The deposition holes shall be located in sparsely fractured or massive rock within the Forsmark tectonic lens.
3. The central area can be located in any rock mass suitable for constructing large caverns.
4. The access tunnels and shafts should be located to minimise the potential for large groundwater inflows.
5. Layouts for tunnel and shaft access should be oriented such that the intersection lengths with major water bearing zones are as short as practical.
6. A respect distance of 100 m is required for major deformation zones (trace length at ground surface greater than 3 km).
7. The repository layout should minimise stress concentrations on the boundary of the underground excavations (deposition holes and deposition tunnels), unless it can be shown that such stress concentrations do not cause spalling.

In addition to the general guidelines given above there are several issues which need special consideration when designing the repository layout. These are highlighted below.

- The sub-horizontal fractures/sheet joints in the upper 40–200 m of the rock mass, within the target volume, inside the tectonic lens (fracture domain FFM02) may be highly transmissive. The layout of the access ramp should intersect these transmissive features at as large an angle as possible to improve the possibility to seal by grouting measures.
- The alignment of the ramp shall if possible avoid having long sections parallel with the NE-NNE trending fracture sets. This may cause systematic overbreak of the tunnel contour.
- The long walls of the rock caverns in the central area shall not be aligned parallel to the NE-NNE trending fracture sets, to decrease the need for bolting and reduce the risk for overbreak.
- The alignment of transport tunnels shall if possible avoid having long sections parallel with the NE-NNE trending fracture sets. This may cause systematic overbreak of the tunnel contour.
- The intersection of the deposition tunnels with the access tunnels will require special design attention, particularly the transition from the access tunnel to the deposition tunnel.
- The occurrence of water bearing fractures is expected to be very limited at the repository depth within the target volume. The few transmissive fractures found in the site investigation program in the target area, as well as observations from the SFR indicate that detecting these features with traditional probe hole drilling from the tunnel face may be very difficult. In addition, grouting methods from the tunnel where the flow from such features is highly channelized, may also prove challenging.
- The risk for local stress-induced problems (spalling) at any depth at Forsmark cannot be ruled out due to local heterogeneities in the rock mass. When minor spalling occurs worker safety will be an issue and roof support will be required.
- Circular openings excavated by mechanical means are particularly susceptible to construction issues associated with stress-induced spalling. The designer should consider alternative shapes for openings that are excavated at an unfavourable orientation relative to the maximum horizontal stress.

Sammanfattning

I projekteringen och uppförandet av en undermarksanläggning för använt kärnbränsle (slutförvarsanläggning) måste hänsyn tas till de platsförhållanden som kan inverka på förvarets långtidssäkerhet. Flera av de restriktioner som är nödvändiga för att garantera en säker funktion av förvaret med avseende på dess innehåll av radionuklider är unika för en slutförvarsanläggning. Det huvudsakliga syftet med rapporten *Site Engineering Report* (SER) är att tillhandahålla en övergripande struktur för projektörer ansvariga för undermarksprojektering och layout, och en struktur som uppfyller både driftkrav för en sådan undermarksanläggning och krav avseende långtidssäkerhet relaterat till använt kärnbränsle. Underlaget till framtagandet av denna struktur är den platsbeskrivande modellen.

Rapporten SER baseras på de omfattande platsundersökningar, som genomförts i Forsmark och på de tolkningar och utvärderingar av undersökningsdata, som redovisas i en platsbeskrivande modell. Den platsbeskrivande modellen utgör ett underlag till flera användare och då inte minst för säkerhetsanalys, men all information som inryms i den platsbeskrivande modellen är inte nödvändig för projekterings- och layoutarbetet. Informationen från platsundersökningen som finns redovisad i den platsbeskrivande modellen för Forsmark måste ha en tillräcklig detaljeringsgrad för att möjliggöra för SKB att: (1) ta fram en funktionell design och layout av anläggningen, (2) utföra en säkerhetsanalys av platsen och identifiera möjlig miljöpåverkan (och dess omfattning) av slutförvarsanläggningen, och (3) utarbeta en strategi för berguttaget.

I SER är slutförvarsanläggningen indelad i tre funktionsområden, som benämns: (1) tillfarter omfattande ramp och schakt, (2) centralområde och (3) deponeringsområde som inkluderar deponeringstunnlar och deponeringshål. För respektive område gäller olika restriktioner och krav. De geologiska förhållandena och den bergtekniska beskrivningen för projekteringssteg D2, som redovisas i SER, omfattar platsanpassningen av slutförvarsanläggningen med avseende på: (1) deformationszoner och bergmassans egenskap på djupet, (2) parametrar som påverkar förvarets djupförläggning och areella utbredning, och (3) bergteknisk beskrivning av bergmassan med avseende på byggbarhet.

Designprocessen för slutförvarsanläggningen skall anpassas till den europeiska standarden för byggande, Eurocode och särskilt till standarden för geoteknisk design, EN 1997-1:2004, sektion 2.7 som kommer att tillämpas i Sverige under 2009. Detta medger tillämpning av observationsmetoden för undermarksprojektering och bergbyggande. Observationsmetoden är tillämpning av en riskbaserad metod för projektering och byggande, som innebär anpassad styrning, kvalitetssäkrade kontroll- och analysmetoder för att väsentligt reducera kostnader, och samtidigt skydda kapitalinvesteringar, hälsa och miljö. Den komplexa sammansättningen av och variationen i bergmassan medför att en helhetsbild av geologiska strukturer och bergmassans kvalitet inte kan erhållas innan förvaret har byggts. Statistiska metoder måste därför användas under projekteringsskedet för att utvärdera känsligheten hos designen med avseende på den geologiska variationen i bergmassan och för att kvantifiera risker.

Det finns flera allmänna bergtekniska riktlinjer som skall tas i beaktande avseende förvarets placering:

1. Förvarsdjup skall begränsas till 450–500 m djup.
2. Deponeringshålen skall placeras i sprickfattig eller homogen bergmassa inom den tektoniska linsen i Forsmark.
3. Centralområdet kan placeras i en bergmassa lämplig för byggande av stora bergrum.
4. Ramp och schakt skall placeras på ett sådant sätt, att potentialen för stora grundvatteninflöden minimeras.
5. Layouterna för tunnlar och schakt skall orienteras så att längden av sektionerna, där tunnlar och schakt passerar större vattenförande zoner blir så korta som är praktiskt möjligt.
6. Ett respektavstånd av 100 m krävs för större deformationszoner (spårlängd på markytan längre än 3 km).
7. Förvarslayouten skall minimera spänningskoncentrationer i bergutrymmenas periferi (deponeringshål och deponeringstunnlar), om inte det kan visas att sådana spänningskoncentrationer inte orsakar bergspjälkning.

Förutom de allmänna riktlinjerna ovan, finns flera frågeställningar, som kräver speciellt hänsynstagande i samband med designen av förvarets layout:

- De horisontella/subhorisontella bankningssprickor i bergmassans övre del, 40–200 m inom undersökningsområdet och i den tektoniska linsen (sprickdomän FFM02) kan ha hög vattentransmissivitet. Tillfartsrampen och schakten skall passera partier som innehåller dessa vattenförande sprickor med så stor vinkel som möjligt för att underlätta tätning genom injektering.
- Rampen skall om möjligt placeras, så att långa sektioner parallella med sprickgrupperna NE-NNE undviks. Detta kan annars förorsaka systematiskt överberg av tunnelkonturen.
- De långa väggarna i bergrummen i centralområdet skall inte orienteras parallellt med sprickgrupper med strykningen NE-NNE, för att därigenom minska behovet av bultning och reducera risken för överberg.
- Transporttunnlarnas skall om möjligt placeras så att långa sektioner parallellt med sprickgrupper med strykning NE-NNE undviks för att minimera överberg av tunnelkonturen.
- Deponeringstunnlarnas skärning med tillfartstunnlarna kommer att kräva speciell uppmärksamhet vid designen, i synnerhet vid övergången från tillfartstunnel till deponeringstunnel.
- Förekomsten av vattenförande sprickor förväntas vara mycket begränsad på förvarsdjupet inom den tektoniska linsen. De få flödande sprickor som identifierats inom ramen för programmet för platsundersökningen, såväl som de observationer som finns dokumenterade från SFR, indikerar att det kan bli mycket svårt att detektera dessa sprickor med traditionell försondering från tunnelgaveln. Injektering från tunneln där inflödet från sådana sprickor uppträder starkt kanaliserat kan också visa sig komplicerat.
- Risken för lokala spänningsinducerade problem (bergspjälkning) på olika djup i Forsmark kan inte uteslutas beroende på lokala heterogeniteter i bergmassan. Arbetarskyddsfrågor kommer att bli en viktig fråga när mindre spjälkning förekommer. Bergförstärkning av tak kommer att krävas.
- Cirkulära öppningar som tas ut med mekaniska metoder är särskilt känsliga för spänningsinducerad spjälkning. Projekteringen skall därför ta hänsyn till alternativa geometrier för öppningar med en ogynnsam orientering relativt till den största horisontella spänningen.

Contents

1 Purpose and scope

The design and construction of a repository for spent nuclear fuel at depths of 400 to 700 m may appear similar to the development of an underground mine. However, unlike an underground mine, which typically lasts from 10 to 100 years for the purpose of mineral extraction, the design of a facility for spent nuclear fuel must consider the site conditions that may impact the long-term safety of a repository. Many of the constraints that are needed to ensure the safe performance of a repository with respect to radionuclide containment are unique for the final repository facility. The design of such an underground facility cannot be simply based on traditional empirical rules that have been developed from previous underground projects.

The main purpose of this Site Engineering Report (SER) is to provide an overall framework for the designers responsible for the underground design and layout that meets both the operational requirements for such an underground facility and the long-term safety requirements related to nuclear-waste containment. This is done by presenting a rationale and guidelines for the design that are focused on constructing a repository. These guidelines also incorporate the operational and safety assessment issues that may impact construction and facility layout.

1.1 Background

The overall purpose of the final repository facility is to isolate the spent fuel so that unacceptable quantities of radionuclides do not migrate to the biosphere. The design of the final repository facility must address a number of considerations related to the project objective that are not faced in traditional mining or civil engineering underground projects. This involves the characterisation of a large volume of rock, assessment of thermal effects, the construction of underground openings that meets strict quality control requirements, and the need to consider an extremely long design life. The major tasks of the underground design for the final repository facility are described in /SKB 2007/ and are summarised below:

- Outline a design for the site, considering site adaptation, functional requirements and step-wise development in parallel to operation of the final repository facility.
- Examine the feasibility for grouting, and estimate the required grout quantities.
- Establish the rock support required and estimate the support quantities.
- Perform a technical risk analysis of the potential hazard(s) for the project that are considered in the design process, and propose measures to reduce the risk from these hazards within the next design step.

A Site Descriptive Model (SDM) in the context of the final repository facility refers to the integration and interpretation of multidisciplinary data to develop a geoscientific description of a site /Munier et al. 2003/. The Site Descriptive Model for the Forsmark site in this report will be referred to as SDM-Site Forsmark /SKB 2008/. Site investigations have been in progress in the Forsmark area since February 2002, and have provided data to two data freezes during the initial site characterization phase and three during the complete site characterization phase. The design work and the adaptation of the layout of the repository has been running in parallel with the Site Investigation Phase. The preliminary layouts were given in design step D1 /Brantberger et al. 2006/. As demonstrated during design step D1, there was a need to extract the data contained in the site descriptive model into parameters that are required for the design and layout. This Site Engineering Report (SER) is focused on this task.

The information obtained from the Complete Site Investigation phase and contained in the SDM-Site Forsmark must be in sufficient detail to enable SKB to:

1. develop a functional design and layout for the facility,
2. conduct a safety assessment for the site,
3. identify the possible environmental impact of the final repository facility and its extent,
4. develop an excavation strategy.

For the purpose of this report the final repository facility is divided into three functional areas that are referred to as:

1. **repository access**, including the access ramp and shafts,
2. **central area**,
3. **deposition area**, including the deposition tunnels and deposition holes.

Each of these areas has different design constraints and requirements, and hence the discussion of these functional areas has been separated in this report. Figure 1-1 provides a general overview of these functional areas.

1.2 Objectives

The Site Engineering Report builds on the extensive surface based site investigations carried out at the Forsmark site and the interpretation and evaluation of these data that are given in the SDM-Site /SKB 2008/. However, because SDM-Site serves the needs of many users, and especially those of safety assessment, not all the information contained in SDM-Site is needed for engineering design and layout purposes. Figure 1-2 illustrates the role of this report which was to extract the relevant information and parameters/values from SDM-Site and summarise them in a format suitable for developing a ground engineering model. Parameters that are recommended in this report for engineering purposes are based on the SDM-Site Forsmark and in some cases these parameters may be modified to reflect modern engineering practice. Geological conditions that may constrain the layout from the safety assessment point of view are also provided.

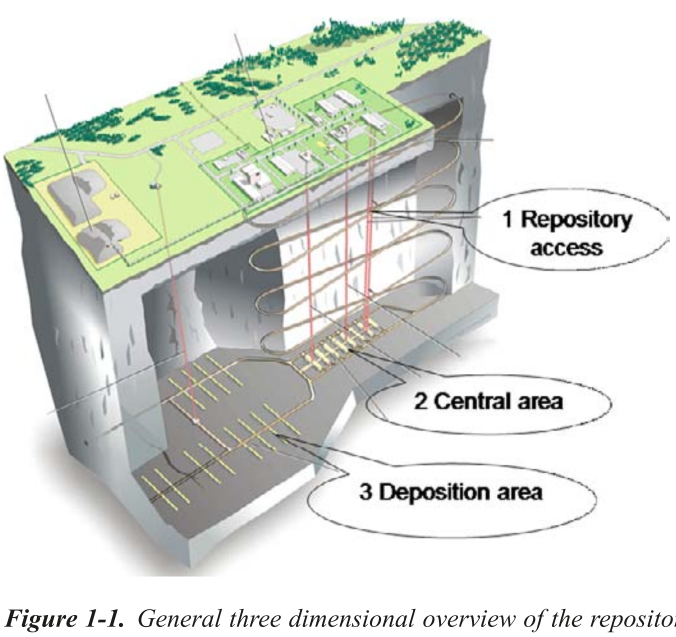


Figure 1-1. General three dimensional overview of the repository layout showing the three major functional components.

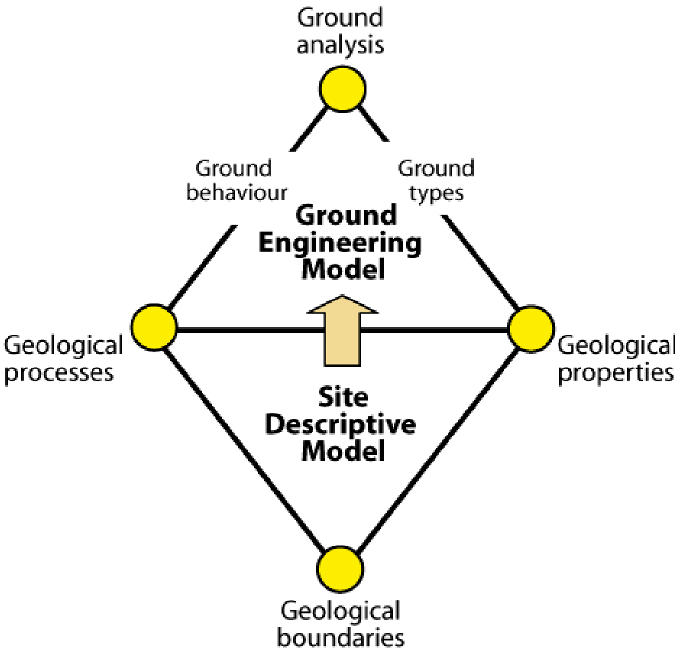


Figure 1-2. *Illustration of the interface (Site Engineering Report – represented by the arrow) between the Site Descriptive Model (SDM) and the Ground Engineering Model. The Site Engineering Report translates and summarises the relevant information contained in the SDM into numbers/values that are used in the analyses to develop the Ground Engineering Model.*

The main users of the Site Engineering Report will be the engineers responsible for the repository design and layout during various design stages. As such the major objectives of the Site Engineering Report are to:

1. present an engineering description of the rock mass for the design of the underground openings associated with the deep geological repository,
2. derive and present site specific requirements and constraints on the design related to long-term safety,
3. establish geological engineering parameters for the rock mass that should be used in the repository design and layout stage D2,
4. highlight issues that require special attention during the repository design and layout,
5. establish a procedure for dealing with uncertainties and potential hazards in some elements of the design process.

1.3 Long-term safety and design

The long-term safety is assessed using site specific data including the layout of the facility. As a consequence, long term safety requirements can impact the design of the underground openings and the layout of the facility. For design Step D2, the geological constraints and engineering guidelines provided in SER cover the site adaptation of the final repository facility with respect to: (1) unsuitable rock mass conditions and deformation zones at depth, (2) parameters that affect the depth and areal size of the repository, and (3) description of ground conditions for assessment of constructability. The final design will be optimised for these restrictions.

Figure 1-3 provides an overview of the main content of this Site Engineering Report. The input for this report comes from SDM-Site Forsmark /SKB 2008/, as well as from the main conclusions from the preliminary Safety Assessment (SR-Can) carried out for the site /SKB 2006b/. The major long-term safety elements considered in this Site Engineering Report and shown in Figure 1-3 are:

- Facility depth which is determined and justified in Chapter 8.
- Constraints for the layout which are discussed in Chapter 7. These constraints identify deformation zones that require a respect distance and specific site conditions that shall be considered in the design, such as recommended alignment of the deposition tunnels, and the distribution of ground types within each functional area.
- Chapter 7 also deals with the site conditions that affect the areal size of the final repository facility. The areal size is a function of the recommended canister spacing which is dependent upon the thermal properties of the rock domains (see also Appendix A). The fracturing and hydraulic conditions are analysed to assess the loss of deposition holes which also impacts the areal size of the final repository facility.
  The design tasks in accordance with /SKB 2007/ are based on the input from this report and the input from the general requirements on the final repository facility. The output from the design will be audited by the final Safety Assessment prior to the application for siting of the final repository facility.

1.4 Design strategy and observational method

One of the design methodologies used in underground design and construction to address the uncertainty and variability in the geological setting and ground structure interaction is the Observational Method. The Observational Method is a risk-based approach to underground design and construction that employs adaptive management, including advanced monitoring and measurement techniques, to substantially reduce costs while protecting capital investment, human health, and the environment. Development of the Observational Method in geo-engineering is generally attributed to /Terzaghi and Peck 1967/ and /Peck 1969/ initially outlined the essential elements of the methodology and /Stille 1986/ described the adaptation of the method in Sweden under the name "Active Design".

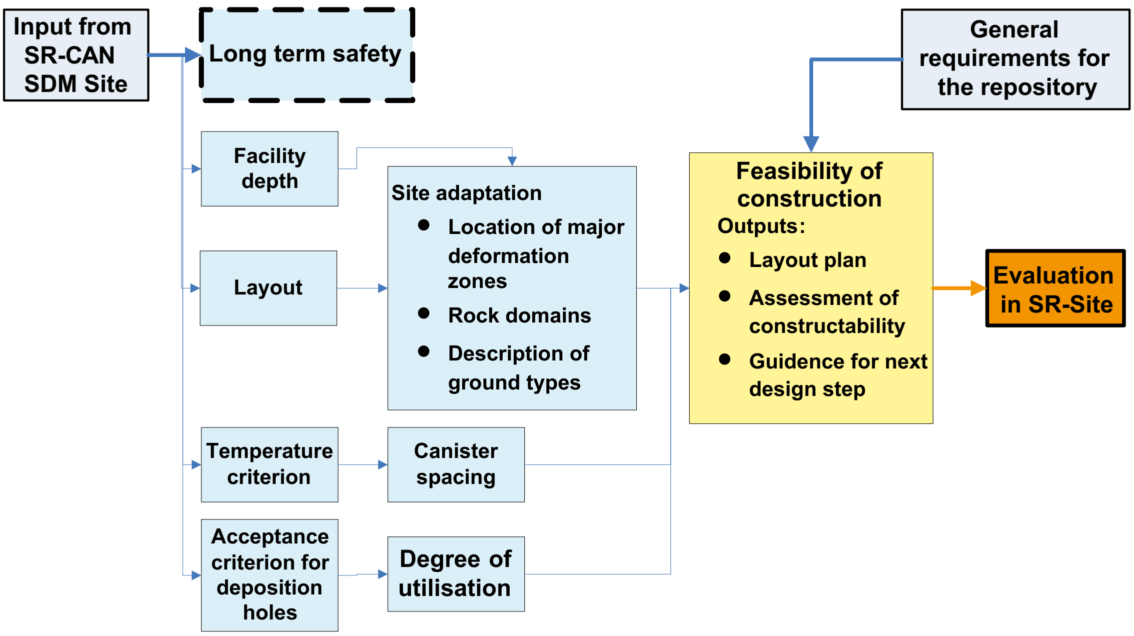


Figure 1-3. *Overview of main deliverables from the Forsmark Site Engineering Report with respect to long-term safety (blue) and major outputs from design (yellow) to Safety Assessment (red).*

As outlined in Underground Design Premises D2 /SKB 2007/, in underground engineering there are some major aspects that must be addressed during the design phase. The repository design must meet the requirements from long term safety, operation safety and be economically feasible, based on a realistic estimate of the expected ground conditions and their potential behaviour as a result of the excavation. The design process using the Observational Method has several steps and is constantly updated during each step, as more information becomes available. During the design steps, the inherent complexity and variability in the geological setting prohibits a complete picture of the ground structure and quality to be obtained before the facility is excavated. Thus during design, statistical methods may be used to evaluate the sensitivity of the design to the variability as well as the quality of the existing data. This is most important during the early stages of design when trying to quantify project risks and cost estimates. As new data are acquired during subsequent investigations the site descriptive model will systematically be updated, and the parameter distributions refined.

The SKB design strategy is outlined in the Underground Design Premises D2 report, /Section 5.7 in SKB 2007/. SKB plans to carry out the design process for the final repository facility project in agreement with the European standard for construction, Eurocode, and in particular the standard for geotechnical design, Section 2.7 in Eurocode EN 1997-1:2004, which will be implemented in Sweden in 2009. This allows for the application of the Observational Method in underground design and construction. In /SKB 2007/ is presented how the Observational Method shall be applied in design stage D2 and an overview of the design in relation to the Observational Method is given in Table 1-1. The scope of the design tasks in design stage D2 will be primarily limited to the following five requirements of the Observational Method stated in Eurocode EN 1997-1:2004, Section 2.7:

1. Establish acceptable limits of behaviour.
2. Assess the range of possible behaviour and show that there is an acceptable probability that the actual behaviour will be within the acceptable limits.
3. Develop a plan for monitoring the behaviour, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully.
4. the response time of the monitoring and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system.
5. Develop a contingency plan which may be adopted if the monitoring reveals behaviour outside acceptable limits.

The Observational Method has several caveats. One must be able to define an action plan for every possible adverse condition based on current site understanding. The method cannot be used if a predictive model for the behaviour cannot be developed, i.e. it is necessary to establish a model that can calculate the parameters that will subsequently be monitored during construction. This is not a trivial problem as long as we can measure what we cannot calculate and vice versa. This means that the monitoring plan must be chosen very carefully with a good understanding of the significance to the problem.

The construction of the access shafts and tunnels will rely on the Observational Method and the method will also be used to ensure that the facility layout will meet the requirements of the safety analysis. For example, the Observational Method will be used to decide the orientation and location of the deposition tunnels, and to locate the deposition holes in suitable rock conditions. A requirement with the Observational Method is the on-going underground characterization that will go hand-in-hand with choosing the final layout for the facility. Hence it is important that the Observational Method is considered as a key component of all stages of the design, and that those key parameters that can be used for monitoring are identified during the design steps.

This report is limited to preliminary assessments of the first two requirements of the Observational Method as stated in Eurocode EN 1997-1:2004, Section 2.7.

Table 1-1. Design documents in an iterative design process; focus on SKB design stage D2.

Design documents	General content	SKB document corresponding to design document
Background documents.	Description of rock domain distribution and properties, deformation zones, fracture domains, hydrogeology and hydro-geochemistry conditions in the target volume.	Site description of Forsmark at completion of the site investigations (SDM-Site Forsmark) /SKB 2008/.
Engineering characterization and classification documents.	The rock mass is divided into separate ground types that meet the objectives of SER. The description of the ground types considers geological conditions, rock mechanics, hydrogeology, hydro-geochemistry and thermal issues.	Forsmark Site Engineering Report Guidelines for underground design stage D2 *(this report).* Construction and engineering experiences are compiled in CECR. /Carlsson and Christiansson 2007/.
Design documents for excavation, rock support, grouting.	Description of possible construction-, support- and grouting solutions. Assessment of the rock mass response to the excavation based on the proposed support and grouting measures.	The design works for this preliminary design shall be described in the Underground Design Premises D2 /SKB 2007/. The design methodology is summarized in Chapter 5 in /SKB 2007/. Chapters 7–10 describe the design studies in this design stage.
Control programme.	Outline which parameters that may be monitored and observed during construction. Such parameters shall relate to the critical issues described in the design documents.	This is handled on a general level in design stage D2, cf. Chapter 10 in /SKB 2007/.
The procedures in the Observational Method that address the construction phase will be regarded in future design stages.		

1.5 Design methodology

A general flow chart for the design of the layout and the various underground openings for this design stage is outlined in Figure 1-4. A detailed description of the approach outlined in the flow chart to underground design is given by /Palmström and Stille 2006/ and additional background information for Figure 1-4 is given by /Goricki 2003/.

The SDM-Site Forsmark provides the detailed geoscientific description of the site obtained from the Complete Site Investigation phase /SKB 2008/. The primary purpose of this site descriptive model is to provide data for the design of the facility site and for the safety assessment. The SER has extracted the relevant data from the SDM-Site Forsmark that pertains to the design of underground openings and repository layout and integrated it with the construction experiences from the nearby Forsmark facilities to develop the underground design guidelines contained in this report for design stage D2. The SER also includes current engineering practice for the design and construction of underground openings in hard rock. As shown in Figure 1-4 the first phase of the underground design is to develop an engineering description of the rock mass (Engineering Ground Description) based on the site descriptive model. This description considers the rock domains (based on intact rock properties), fracture domains, major deformation zones, groundwater conditions and in situ stress conditions, obtained from the SDM-Site /SKB 2008/, and incorporates parameters that are required to provide an engineering description of the rock mass. The product of this description is an account of the ground types (GT) which will be encountered during construction. The number of ground types is project and site specific, and depends on the design stage, as well as on the complexity of the geological conditions. The ground types used for design stage D2 are described in Chapter 4 of this report.

The second step in Figure 1-4 (determine ground behaviour) involves evaluation of the potential ground behaviour considering each ground type. The ground behaviour must be evaluated for the underground opening in each of the functional areas without considering the effect of support, or the benefit of any modifications including the excavation method and/or sequence, and support or other auxiliary measures. The ground behaviour must also consider the influencing factors, as well as the relative orientation of relevant discontinuities to the excavation, ground water conditions and/or in situ stresses.

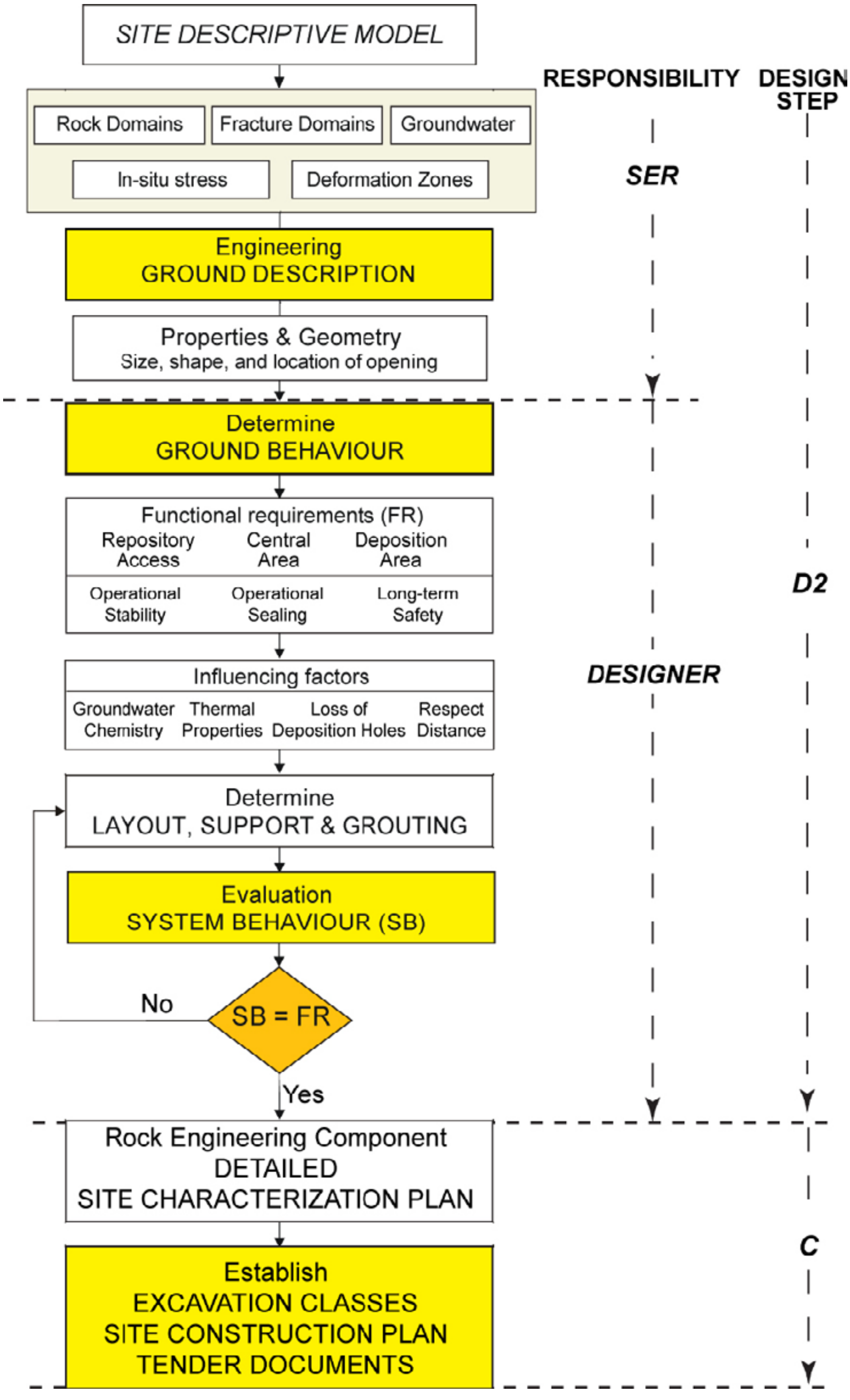


Figure 1-4. *Flow Chart for the design of underground openings associated with the repository for spent nuclear fuel. Modified from /Schubert and Goricki 2004/.*

The final step in Figure 1-4 (evaluation system behaviour) requires an assessment of the system behaviour, i.e. the interaction between the ground behaviour and construction measures. After the ground types and the ground behaviour have been determined, appropriate construction methods (excavation sequence, support methods, and auxiliary measures such as grouting) are determined. The system behaviour can be assessed using analytical methods, numerical methods, and/or comparative studies, based on experience from previous similar projects. For example it may be acceptable to use the Construction Experience Compilation Report /Carlsson and Christiansson 2007/ for the existing facilities at or near the site, such as the SFR Facility, to evaluate the system behaviour for the Access Area at this stage of the design. The analysis of the system behaviour shall assess the range of possible behaviour and show that there is an acceptable probability that the actual behaviour will be within the acceptable limits in terms of:

- stability of underground openings,
- repository design requirements, i.e. that the layout complies with constraints imposed by respect distance, loss of deposition holes, canister spacing and the required number of deposition holes,
- acceptable seepage limits.

All analyses used to assess the system behaviour should be documented in a way that is traceable and auditable in accordance with /SKB 2007/.

In Figure 1-4 there is a final stage in the design process called detailed site characterisation and the requirement to develop Excavation classes, Site Construction Plan and Tender Documents. This and the next step are included in the design activities (inside the yellow box in Figure 1-3). The excavation classes are defined based on the evaluation of the support, excavation and grouting requirements. The distribution of the expected ground behaviour and the excavation classes in the repository provides the basis for establishing the construction plan and tender documents. This stage of the design is not described in this SER and would take place during design stage C /SKB 2007/.

1.6 Terminology

The site descriptive model may use terms that are not generally used in underground engineering or have restricted definitions. A brief summary of these terms, taken from Section 1.6.5 SDM-Site Forsmark, is provided below.

- **Candidate area:** The candidate area refers to the area at the ground surface that was recognised as suitable for a site investigation, following the feasibility study work /SKB 2000/. The extension at depth is referred to as candidate volume.
- **Target area/volume:** The target area/volume refers to the north-western part of the candidate area and the rock volume beneath that was selected during the site investigation process as potentially suitable for hosting a final repository facility for spent nuclear fuel.
- **Rock unit (RU):** A rock unit is defined on the basis of the composition, grain size and inferred relative age of the dominant rock type. Other geological features including the degree of bedrock homogeneity, the degree and style of ductile deformation, the occurrence of early-stage alteration (albitization) that affects the composition of the rock, and anomalous fracture frequency also help define and distinguish some rock units.
- **Rock domain (RD):** A rock domain refers to a rock volume in which rock units that show specifically similar composition, grain size, degree of bedrock homogeneity, and degree and style of ductile deformation have been combined and distinguished from each other.
- **Deformation zone (DZ):** Deformation zone is a general term that refers to an essentially 2D structure along which there is a concentration of brittle, ductile or combined brittle and ductile deformation. Deformation zones at Forsmark are denoted ZFM followed by two to eight letters or digits. An indication of the orientation of the zone is included in the identification code.
- **Fracture zone:** Fracture zone is a term 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.

- **Fault zone:** Fault zone is a term used for a fracture zone that shows a shear sense of movement along it.
- **Fracture domain***:* A fracture domain is a rock volume outside deformation zones in which rock units show similar fracture frequency characteristics. Fracture domains at Forsmark are denoted FFMxx.

There are also two additional terms that are used in the description of the bedrock characteristics:

- **Discrete fracture network** (geological DFN). The fracturing in the bedrock is described on the basis of a standardized statistical procedure, which provides geometries, directions and spatial distributions for the fractures within defined fracture domains. Both open and sealed fractures are used to establish the DFN /Stephens et al. 2007, p 28/.
- **Sealed fracture network** is used to denote a high frequency and complex network of sealed fractures associated with deformation zones.

Table 1-2 presents the terminology for brittle structures based on trace length and thickness that is used to describe the Forsmark bedrock geology /Stephens et al. 2007/.

1.7 Report structure

This report is organized into 9 chapters. Chapter 1 contains an overview of the design strategy for the layout and design of the underground openings for design stage D2. Chapter 2 presents a synthesis of the SDM-Site Forsmark as it pertains to the ground descriptions needed for the underground design. Chapter 3 summarises the relevant construction experience from the Forsmark nuclear power plant and the SFR Facility. Chapter 4 provides the designer with the relevant parameters required for the underground design. Chapters 5, 6 and 7 describe the conditions that are likely to be encountered in the Access, Central and Deposition functional areas, respectively. Chapter 8 provides a summary of the factors that influenced the selection of the repository depth. Chapter 9 provides a summary of major issues that should be considered in the layout in design stage D2.

Table 1-2. Terminology and general descriptions of the geological structures used to describe the bedrock in /Stephens et al. 2007/. The equivalent engineering term is also provided.

Terminology	Length	Width	Engineering description
Regional deformation zone	>10 km	>100 m	Regional shear zone or fault
Local major deformation zone	1 km–10 km	5 m–100 m	Major shear zone or fault
Local minor deformation zone	10 m–1 km	0.1–5 m	Shear zone or fault
Fracture (open/sealed)	<10 m	<0.1 m	Discontinuity or joint

2 General site conditions and rock properties

The candidate area is approximately 6 km long and the north-western part of the candidate area has been selected as the target volume (Figure 2-1 and Figure 2-2) for hosting a repository for spent nuclear fuel. The lens is approximately 25 km long and it extends along the Uppland coast from north-west of the Forsmark nuclear power plant south-eastwards to Öregrund /Stephens et al. 2007/. In this report the focus is on the target volume.

The target volume is located within the tectonic lens that developed more than 1,850 million years ago, when the rock units were situated at mid-crustal depths and were affected by penetrative but variable degrees of ductile deformation under amphibolite-facies metamorphic conditions. The bedrock inside the lens at the depths of the repository is relatively homogeneous whereas the lithology and deformation is more variable outside the lens.

2.1 Rock types and properties of intact rock

Confidence in both the existence and geometry of rock domains within, or immediately around, the target volume is high down to a depth of 1,000 m, whereas significant uncertainties still remain concerning the character and geometry of rock domains outside the candidate area, e.g. in the sea area towards the northeast and inland towards the southwest.

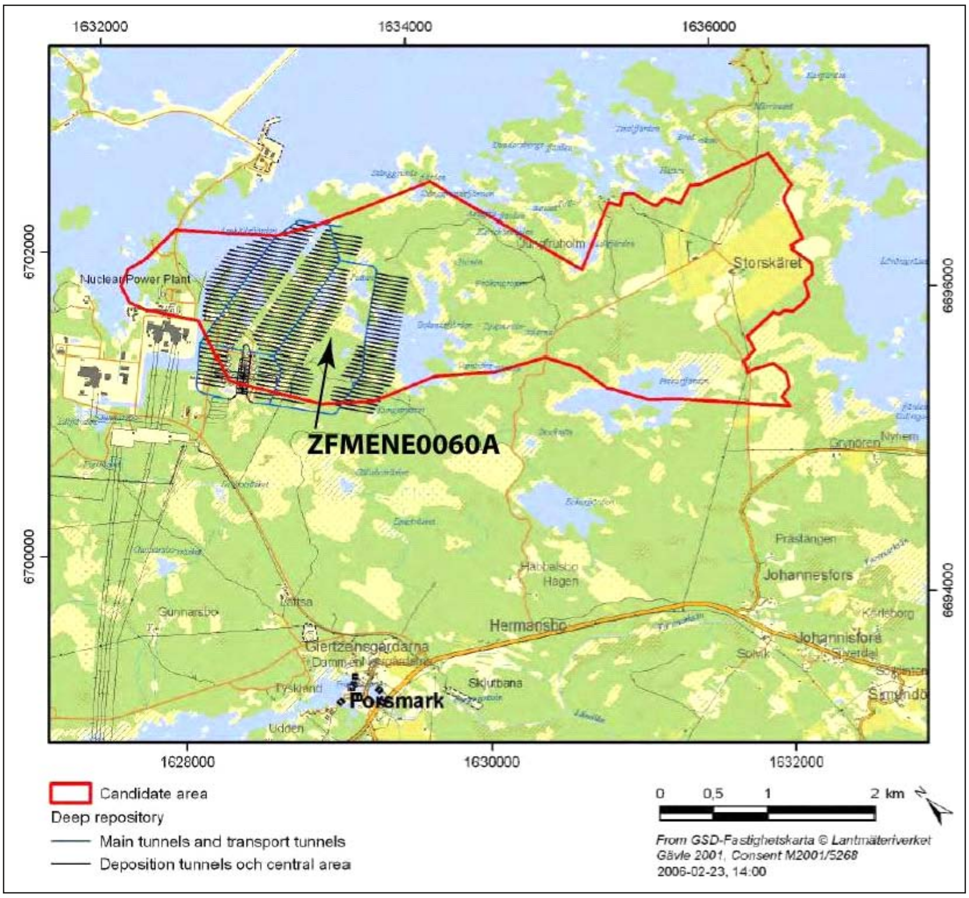


Figure 2-1. *Geographical setting of the Forsmark site and location of the deep repository from design stage D1 (based on Figure 5-2 in SKB R-06-34).*

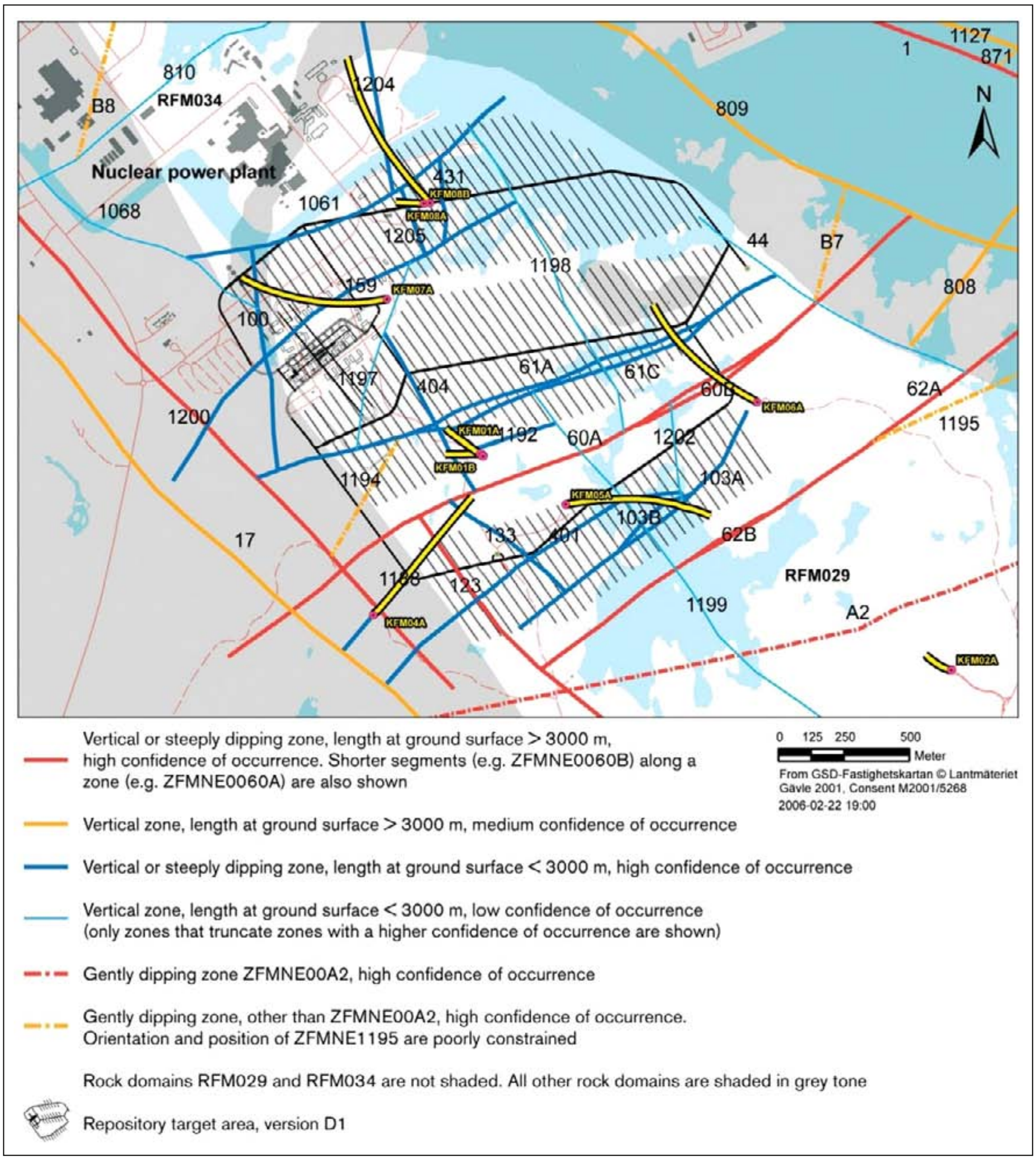


Figure 2-2. *Repository layout at the end of design stage D1 and the location of the boreholes used in design stage D1 from the site investigation.*

2.1.1 Rock domains and rock types

Rock domain RFM029 dominates the tectonic lens at Forsmark and is the volumetrically most significant domain inside the target volume (Figure 2-3 and Figure 2-4). The dominant rock type in RFM029 is metamorphosed, medium-grained granite to granodiorite (c. 74% of the domain volume). Subordinate rock types are fine- to medium-grained metagranodiorite or metatonalite (5%), amphibolite (4%), pegmatitic granite or pegmatite (13%), fine- to medium-grained granite (2%), and metamorphic aplitic granite (1%) (Table 2-1). The dominant rock type and the subordinate rock types, except for amphibolite, have high quartz content, c. 20 to 50%. A foliation within the metagranite is folded and both fold axis and mineral stretching lineation plunge towards the south-southeast. The amphibolites follow the orientation of the ductile grain-shape fabrics /Stephens et al. 2007/.

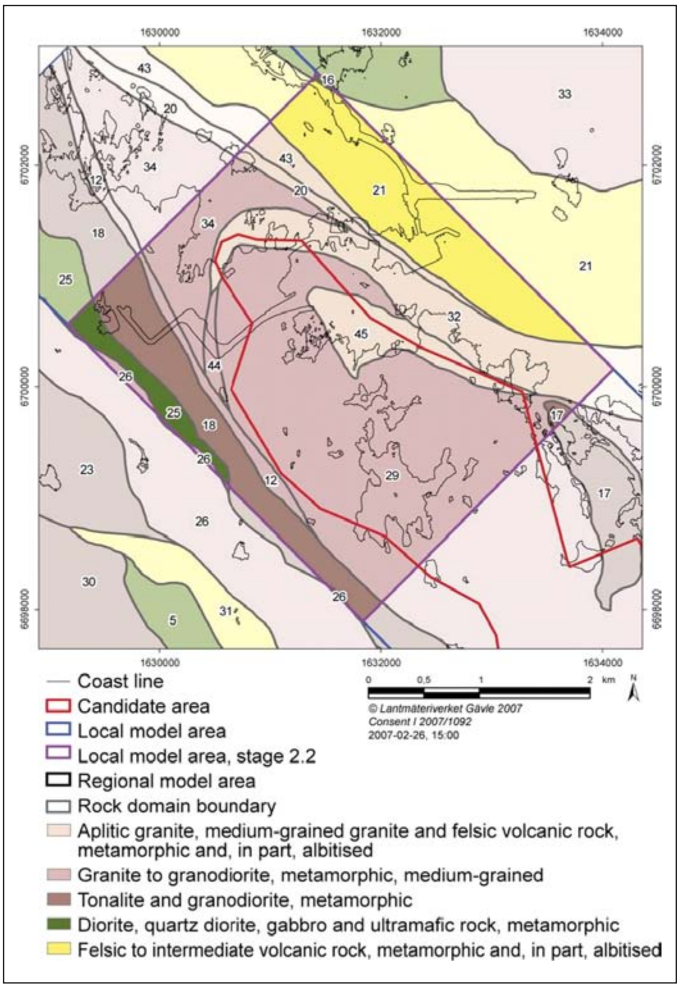


Figure 2-3. *Plan view at the surface of rock domains inside the local model area /Figure 5-24b in SKB 2008/.*

Table 2-1. Proportions of different rock types in Rock Domains RFM029 and RFM045 /Stephens et al. 2007/.

Rock name/code	Proportion in domain RFM029 [%]	Proportion in domain RFM045, [%]
Granite to granodiorite (metamorphic), 101057	74	18
Granite, aplitic (metamorphic), 101058	1	49
Granite, granodiorite and tonalite (metamorphic), 101051	5	9
Felsic to intermediate metavolcanic rock, 103076	<1	1
Pegmatite, pegmatitic granite (metamorphic), 101061	13	14
Granite (metamorphic), 111058	2	1
Amphibolite, 102017	4	6
Diorite, quartz diorite and gabbro (metamorphic), 101033	<1	<1

Rock domain RFM045 is located north-east of rock domain RFM029 and has a constricted rod-shaped geometry that plunges moderately to steeply to the southeast (Figure 2-3 and Figure 2-4. The dominant rock types in this domain are aplitic metagranite and medium-grained metagranite, which represents approximately 49% and 18%, respectively, of the rock domain. Both these rock types are commonly affected by Na-K alteration (albitization) /Stephens et al. 2007/. Modal analyses indicate that Na-K alteration gives rise to an increase in the quartz content and a significant decrease in the content of K-feldspar, relative to unaltered rocks /Stephens et al. 2007/. Subordinate rock types in rock domain RFM045 are essentially the same as in domain RFM029 and include pegmatite and pegmatitic granite (14%), fine to medium-grained metagranitoid and tonalite (9%), and amphibolite (6%) (Table 2-1**)**.

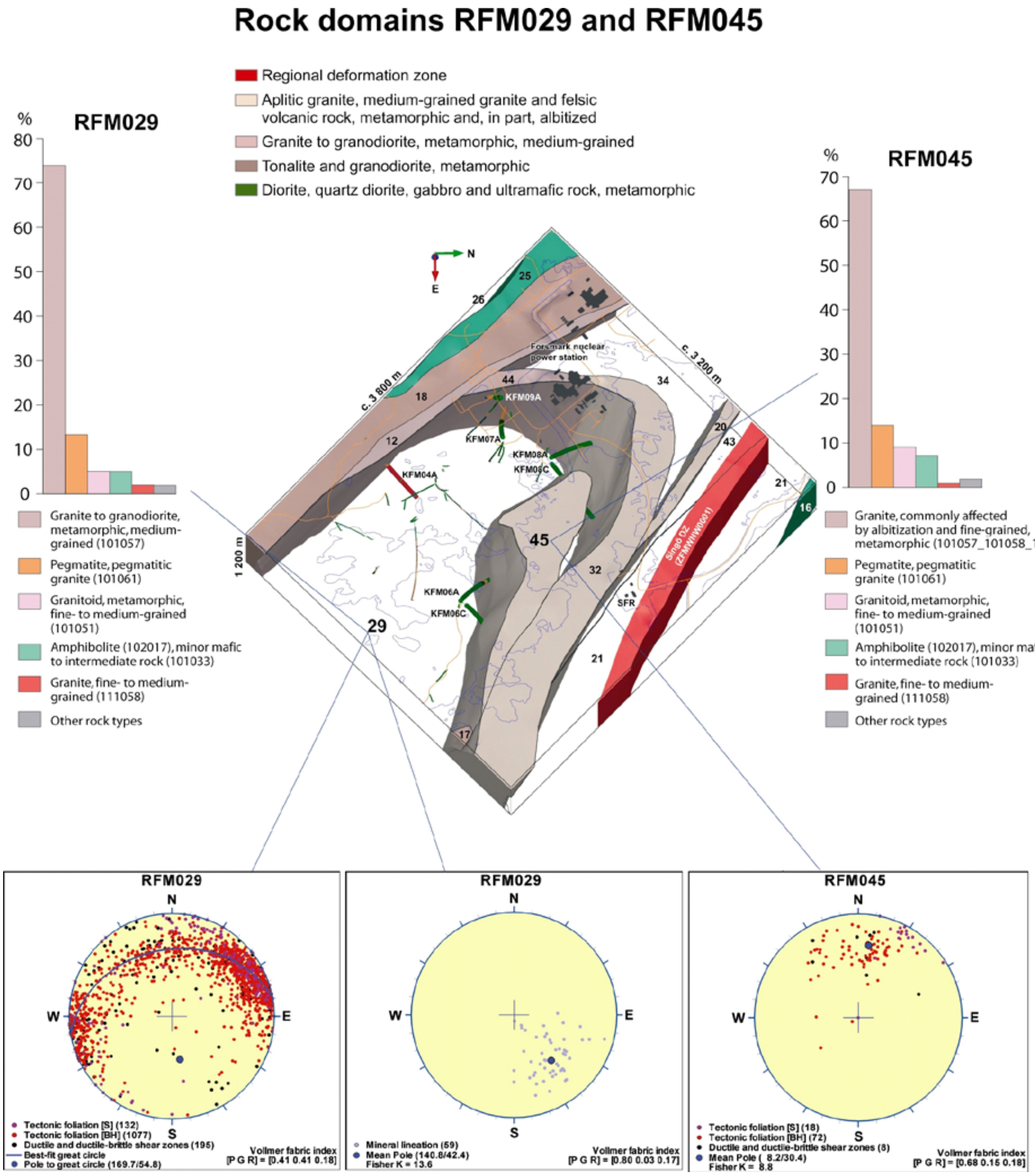


Figure 2-4. *Isometric view of the rock domain model. The colours indicate the dominant rock type in each domain. Quantitative estimates of the proportions of different rock types in rock domains RFM029 and RFM045 are shown in the histograms and the orientation of ductile structures inside these two rock domains are shown in the stereographic projections (equal-area, lower hemisphere). /Figure 5-25 in SKB 2008/.*

The subordinate rock amphibolite is clearly affected by ductile deformation and is, by definition, metamorphic in character. This rock is inferred to have intruded originally as dykes. Amphibolite occurs as narrow, dyke-like tabular bodies and irregular inclusions that are elongated in the direction of the mineral stretching lineation /Stephens et al. 2007/. Due to the low content or absence of quartz in this rock type, it requires special treatment in the thermal modelling work (see Appendix A).

The tectonic lens is surrounded by various rock domains that strike north-west, dip steeply to the south-west and are dominated by SL-tectonites, i.e. contain both planar and linear ductile mineral fabrics. In general, the rocks in these domains show a considerably higher degree of ductile deformation relative to that observed inside the tectonic lens. As the margins of the tectonic lens are approached, the tectonic foliation in the metagranite increases gradually in intensity.

The bedrock outside the tectonic lens is heterogeneous and composed of various types of felsic to intermediate metavolcanic rocks, metagranitoids and major mafic to intermediate intrusions with low quartz content. In the rock domain model, this is described as rock domains with strongly deformed, and also in part, banded and inhomogeneous rocks that occur along the south-western (e.g. RFM012, RFM018) and the north-eastern (e.g. RFM021, RFM032) margins of the lens.

The distribution of rock types at the site reveals important aspects of the homogeneity of the tectonic lens. Furthermore, it directly affects the ore potential as well as thermal and rock mechanics properties of the intact rock. The bedrock is described in the context of rock domains which are based on composition, grain size of the dominant rock type, degree of bedrock homogeneity, and inferred degree of ductile deformation. The rock domains RFM029 (dominant) and RFM045 (subordinate) comprise the target volume (Figure 2-3 and Figure 2-4).

2.1.2 Thermal properties

The thermal properties, i.e. thermal conductivity and heat capacity, of the rock are closely related to the rock types, since these properties depend on the mineral composition, particularly the quartz content. The thermal conductivity of the rock has been assessed from direct measurements and by calculations based on mineral composition from modal analyses. These two methods give consistent results and mean values for RFM029 and RFM045 are summarized in Table 2-2 (see also Appendix A).

There is generally a high confidence in the modelled distribution of the thermal properties, due to their strong correlation with rock types and the low spatial variability of the data. Investigations both in the laboratory and in situ measurements indicate anisotropy in thermal conductivity in the rock mass related to foliation, i.e. a higher conductivity is measured parallel to the foliation. Field measurements, including a large-scale experiment that measured larger volumes of rock, showed that the thermal conductivity is approximately 1.15 greater parallel to the foliation /Sundberg et al. 2007/. Given that most of the rock mass in the target volume displays less intense foliation than that at drill site 7 where the measurements were made, lower anisotropy factors would be expected for the greater part of the target volume /Section 6.2.3 in SKB 2008/.

The in situ temperatures have been measured in various boreholes to depths of 1,000 m. The mean rock mass temperatures at the depth(s) for the repository are provided in Table 2-3.

Table 2-2. Thermal conductivity (W/(m·K)) for domain RFM029 and RFM045 based on simulations at the 1 m scale and up-scaled to 5 m /Table 6-16 in SKB 2008/.

Statistical parameter	RFM029 5 m scale	RFM045 5 m scale
Mean	3.57	3.56
Standard deviation	0.13	0.28
0.1-percentile	2.87	2.37
1-percentile	3.12	2.56
2.5-percentile	3.23	2.73

Table 2-3. Mean temperature at different vertical depths from the ground surface /Section 6.5.3, SKB 2008/.

	400 m	500 m	600 m
Mean temperature (ºC)	10.5	11.6	12.8

2.1.3 Strength and mechanical properties of intact rock

Rock type also affects the strength and deformation properties of the intact rock. The evaluated deformation and strength properties for intact rock in fracture domains FFM01 and FFM06, as well as for deformation zones, are summarized in Table 2-4. Minimum and maximum truncation values are based on the observed min and max for the tested population. The uncertainty of the mean is quantified for a 95% confidence interval. The intact rock strength and deformation properties correspond to stiff and strong rock. It should be noticed that the albitization of the granite metamorphic (SKB code 101057) which is observed in FFM06 results in a consistent improvement of the rock strength properties, compared to the unaltered intact rock observed in FFM01 (see Section 2.3 for the definition of fracture domains). The results for samples inside or in the vicinity of deformation zones are in the same range as the results for samples taken in the host rock outside deformation zones (Table 2-4).

Young's modulus, the uniaxial compressive strength and the indirect tensile strength of the dominant rock type 101057 all display a slight decrease (Young's modulus 2–4%, compressive strength 5–10% and tensile strength 10–15%) in the values with depth /SKB 2008/. The decrease in these values with depth is likely related to an increasing volume of micro-cracks in the samples.

Table 2-4. Laboratory strength and deformation properties for intact rock in fracture domains FFM01 and FFM06 and deformation zones composed mainly of sealed fractures /Table 7-3 in SKB 2008/.

Parameter	FFM01		FFM06		Deformation Zones[1]		PDZ[2]
	101057 **Mean/stdev** **Min–Max** ***Uncertainty***	**101061** **Mean/stdev** **Min–Max** ***Uncertainty***	**101057** **Mean/stdev** **Min–Max** ***Uncertainty***	**101058** **Mean/stdev** **Min–Max** ***Uncertainty***	**101056[3]** **Mean/stdev** **Min–Max** ***Uncertainty***	**101057[4]** **Mean/stdev** **Min–Max** ***Uncertainty***	**101057** **Mean/stdev** **Min–Max** ***Uncertainty***
Number of tests	47	13	10	5	4	5	4
Young's modulus (GPa)	76/3 69–83 *±1%*	74/4 69–80 *±3%*	80/1 78–82 *±1%*	83/3 80–86 *±4%*	77/3 73–81 *±4%*	71/1 69–72 *±1%*	78/1 77–79 *±1%*
Poisson's ratio	0.23/0.04 0.14–0.30 ±4%	0.30/0.03 0.26–0.35 ±5%	0.29/0.02 0.26–0.31 ±4%	0.27/0.03 0.25–0.31 ±8%	0.23/0.03 0.19–0.25 ±11%	0.25/0.01 0.24–0.27 ±4%	0.22/0.02 0.20–0.24 ±8%
Uniaxial Compressive strength (MPa)	226/29 157–289 ±4%	214/32.8 158–266 ±8%	373/20 338–391 ±3%	310/58 229–371 ±16%	236/12 222–249 ±5%	220/17 191–233 ±7%	205/33 166–242 ±16%
Crack initiation stress (MPa)	116/23 60–187 ±7%	114/18 85–140 ±15%	196/20 180–250 ±6%	169/29 125–200 ±15%	–	112/18 85–130 ±14%	105/22 85–134 ±20%
Cohesion M-C (MPa)	28	33	–	–	–	–	24
Friction angle M-C (MPa)	60	56	–	–	–	–	62
Constant m_i H-B	28	18	–	–	–	–	37
Number of tests	82	12	10	–	11	–	
Indirect tensile strength (MPa)	13/2 10–18 ±2%	12/3 8–16 ±9%	15/1 13–17 ±5%	–	18/1 17–20 ±3%	–	13/2 12–17 ±9%

Note: The uncertainty of the mean is quantified for a 95% confidence interval. Minimum and maximum truncation values are based on the observed min' and max' for the tested population. The cohesion and friction angle are determined for a confinement stress between 0 and 15 MPa.
101056 – Granodiorite, metamorphic.
101057 – Granite to granodiorite, metamorphic, medium grained (albitized in FFM06).
101058 – Granite, metamorphic, aplitic (albitized).
101061 – Pegmatite, pegmatitic granite.
[1)] DZ – Deformation zones modelled deterministically.
[2)] PDZ – Possible deformation zones.
[3)] Intact samples from NW1200.
[4)] Samples from ENE0060A composed of sealed fracture network.

2.1.4 Deformation properties of massive rock

It is well known that the deformation properties of a rock mass are a function of scale. The deformation properties of the intact rock measured in laboratory samples was given in Table 2-4. It must be remembered that these small-scale laboratory values are representative of the relatively homogeneous rock free of any micro or macro flaws. These values are not used when modelling tunnel scale or repository scale problems. Scaling of the laboratory values to the tunnel scale or repository scale is problematic and there are no guidelines established for such scaling procedures. /Hoek and Diederichs 2006/ established a correlation between the Geological Strength Index (GSI) and rock mass modulus. While this method is a significant improvement over the RMR and Q empirical correlations, there is still an issue when the GSI values are greater than 80. This issue arises because as the GSI value approaches 100, the rock mass modulus approaches the modulus of the intact laboratory value. /Jackson and Lau 1990/ carried out a series of uniaxial compressive tests on Lac du Bonnet granite to investigate the effect of scale on the tangent Young's modulus determined at about 50% of the peak uniaxial strength. They showed using samples that varied in diameter from 38 mm to 300 mm that the laboratory Young's modulus of Lac du Bonnet granite decreased by approximately 12% as the scale of the laboratory samples increased from 50 mm diameter samples to 200 mm in diameter. Considering the effect of sealed fractures and sparse open fractures, this reduction by 12% may not be sufficient to account for these more compliant features in the massive rock at repository level.

2.2 Deformation zones

Deformation zones and the frequency and the properties of the fractures in the bedrock outside the deformation zones affect the layout and location of the repository, the mechanical stability and the groundwater flow. These can affect both the construction (rock stability and water inflow) and operation (water inflow) of the facility, and the safety assessment for the site (respect distances to deformation zones with a trace length at ground surface greater than 3,000 m). It is therefore essential to have a clearly defined geometry and description of these features. Figure 2-5 defines a "generic" deformation zone using the generally accepted division of zones into undeformed host rock, transition or damage zone, and fault core, e.g. /Caine et al. 1996, Gudmundsson et al. 2001, Munier et al. 2003/.

2.2.1 Description

At Forsmark, the bedrock between the fracture zones and inside rock domains RFM029 and RFM045, shows a low frequency of fractures and little or no pervasive alteration refered as oxidation. The transition or damage part of the zones, which can range in thickness from a few metres up to several tens of metres, contains a higher frequency of fractures and a more conspicuous hydrothermal alteration. The alteration is defined by red staining (fine-grained hematite dissemination formed by oxidation of magnetite) of the minerals along and the wall rock adjacent to fractures. Both sealed and open fractures usually increase in abundance inside the zones. However, the transition zone can also contain segments of bedrock that resemble the unaffected host rock outside the fracture zone (Figure 2-5). The properties of the deformation zones whitin the rock domains RFM029 and RFM045, inside the local model volume are presented in Appendix B.

In the cases where a fault core has been recognised along a deformation zone, it is composed of a high frequency of sealed fractures, commonly in the form of a complex sealed fracture network, in combination with more intense rock alteration. Cohesive breccia or cataclasite are also conspicuous along some fault cores at Forsmark which may vary in thickness from a few centimetres up to a few metres (Appnedix B). Fault gouge has not been recognised along the fracture zones at Forsmark.

Figure 2-5 shows the deformation zone definitions used in the site descriptive modelling and the terms modelled thickness and respect distance. The respect distance is the 100 m perpendicular offset applied to the modelled thickness of deformations zones that have a trace length at the ground surface longer than 3,000 m. As illustrated in the Figure 2-5, the confidence in the modelled thickness depends entirely on the number of borehole intersections and their spatial distribution.

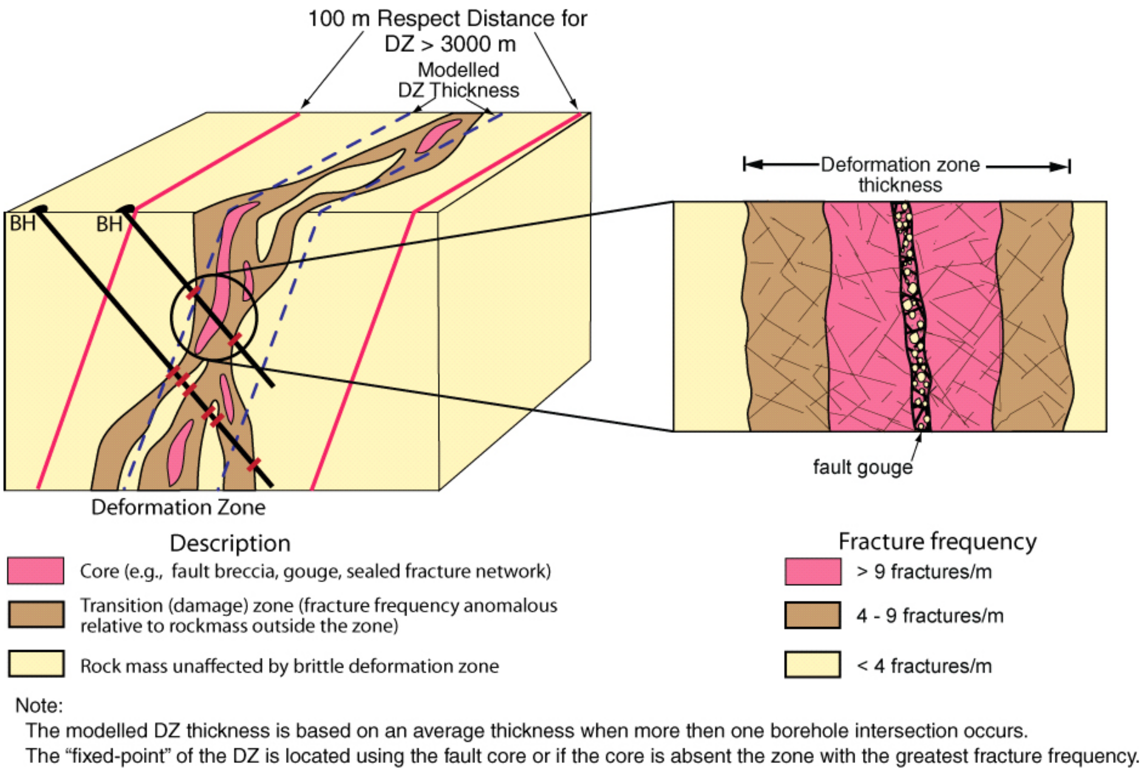


Figure 2-5. *Definition of deformation zone, modelled deformation zone thickness and deformation zone respect distance. Within the target volume at Forsmark fault gouge is not found and the fault core is primarily composed of a sealed fracture network. Modified from /Stephens et al. 2007, Munier et al. 2003/.*

The deformation zones at Forsmark contain sealed and open fractures with the orientation of each fracture recorded during the geological core logging. When the frequency of the sealed fracture is such that describing individual fractures is not practical, a sealed fracture network term is used. Figure 2-6 shows an example of a sealed fracture network observed in borehole KFM06A. While this term is useful for geological core logging, and identifying deformation zones, it may not have any significant impact on engineering behaviour of the rock mass. Mechanically and hydrogeologically, there is little difference between the properties of the sealed fracture network and the host rock, e.g. see rock properties for samples taken from deformation zones in Table 2-4.

Figure 2-6. *Example of a sealed fracture network from borehole KFM06A. This term "sealed fracture network" is used to describe a high frequency of sealed fractures that is commonly encountered in deformation zones at Forsmark. The core diameter is 51 mm.*

Figure 2-7 illustrates the identification of a 40 m long deformation zone in a single borehole. Note that the zone consists mainly of sealed fractures and altered rock. While there are a few open fractures, only the open fractures near the top and bottom of the zone are hydraulically transmissive. Obviously there is a significant difference between the characteristics of this deformation zone and the idealised zone in Figure 2-5. The characteristics of all deterministically modelled deformation zones within rock domains RFM029 and RFM045 are summarised in Appendix B.

Four major sets of deformation zones with trace length at ground surface grater than 1,000 m has been deterministically modelled within the target volume. These zones are predominantly vertical or steeply dipping, with WNW, NW, ENE (NE) and NNE sub-sets, or gently dipping with dips to the south and SE. A few deformation zones that are vertical or steeply dipping and oriented NNW or E-W are also present (Figure 2-8).

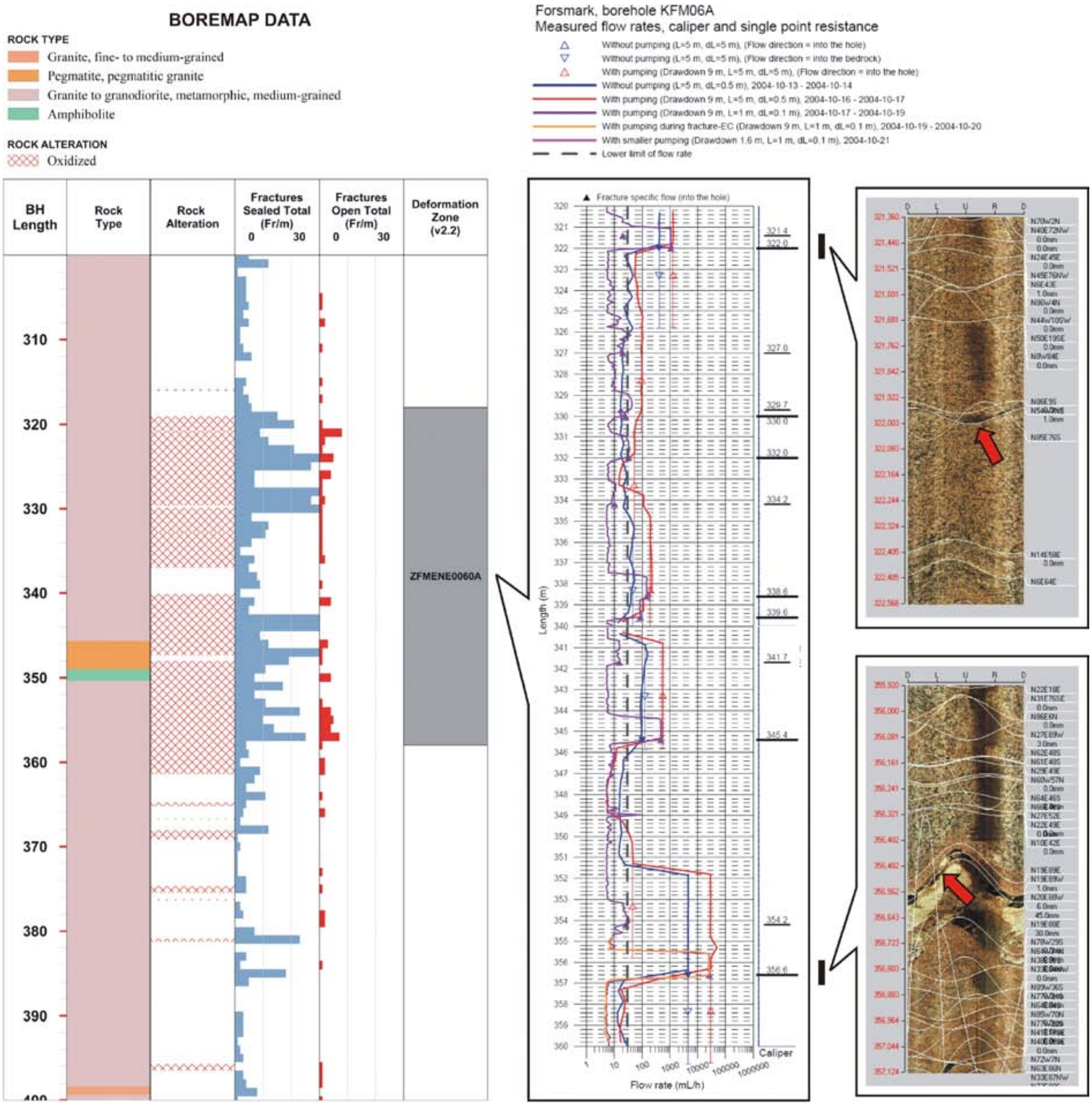


Figure 2-7. Example of the single hole interpretation used to identify deformation zone NE60A in borehole KFM06A. Note that the deformation zone identified in the borehole is approximately 40 m in borehole length, yet only fractures near the top and bottom of the zone are hydraulically transmissive.

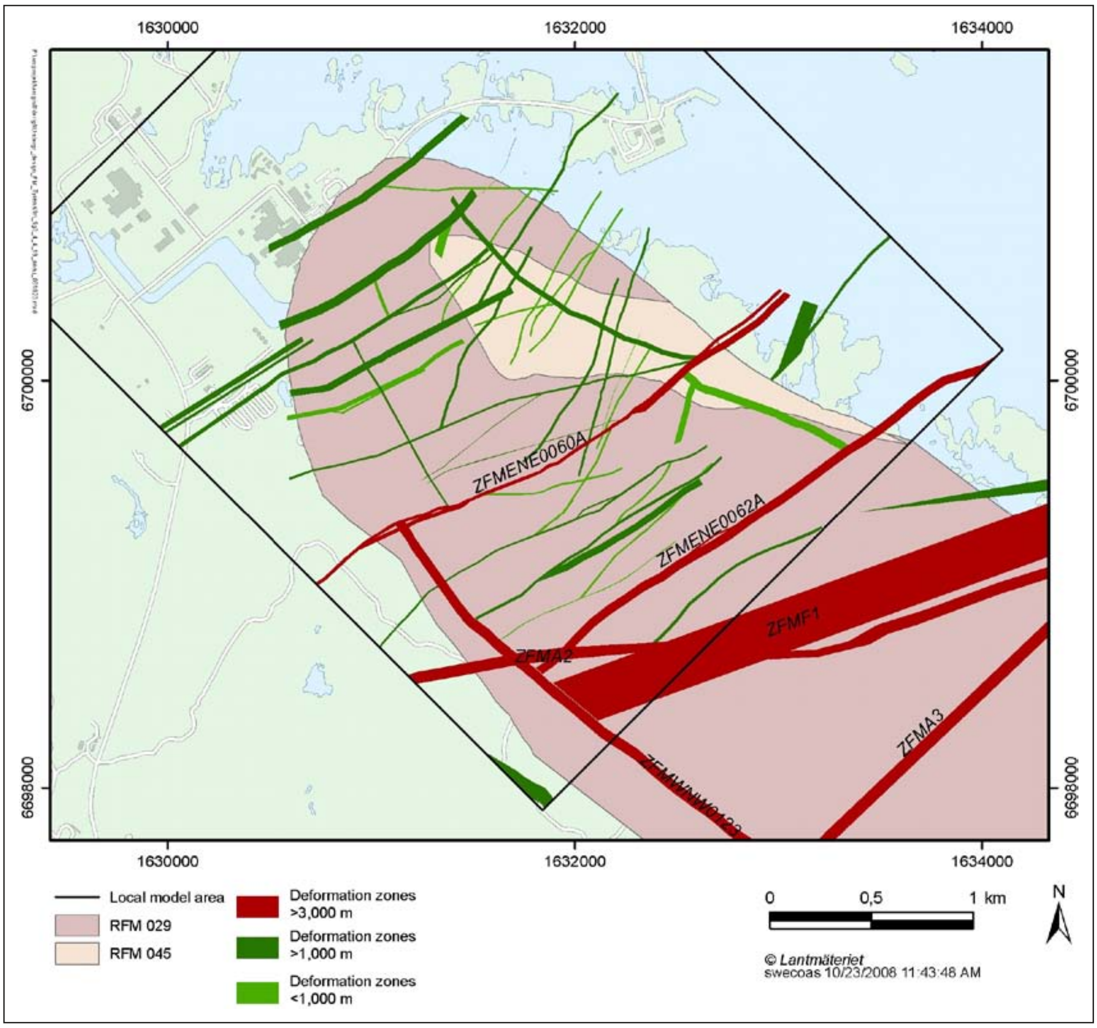


Figure 2-8. Deformation zones at the depth of 470 m (RHB 70).

Both deformation zones and minor deformation zones are identified in boreholes by a population of fractures distinct from the background fractures in fracture domains and by the significant occurrence of hydrothermal alteration. All fractures belonging to deterministically modelled deformation zones are excluded from the statistical modelling of fractures and minor deformation zones in the geological discrete fracture network model (DFN). However, some minor deformation zones, with a trace length less than 1,000 m, have also been modelled deterministically. These zones are vertical or steeply dipping and belong predominantly to the ENE to NNE set. However also some minor zones that are oriented NNW, WNW and E-W are present (Figure 2-8). Such zones have been treated two times in both the DFN and the deterministic modelling work.

(1) **WNW to NW (Vertical or steeply dipping) Deformation Zones:** Only two zones in the WNW-NW set (WNW0123 and WNW2225), with a trace length at the ground surface greater than 1,000 m are present inside the target volume between 400–600 m depth. Both these zones are present in the marginal parts of this volume and one of these zones (WNW0123), along the south-western margin, is longer than 5,000 m. The estimated thicknesses of these two zones are 52 m (WNW0123) and 25 m (WNW2225). By contrast, several zones in the WNW to NW set are present along the high-strain belts that surround the Forsmark tectonic lens. These include the regionally important Singö zone with associated splays, Forsmark zone and Eckarfjärden zone (WNW0001, WNW0004 and NW0003, respectively), all of which are situated a considerable distance (>1 km) from the targeted part of the local model volume. These three regional deformation zones extend for several tens of kilometres at the ground surface in the northern part of Uppland and range in thickness between c. 50 and 170 m.

The deformation zones are dominated by sealed fractures and sealed fracture networks. However, an increased frequency of open fractures and non-cohesive crush rock is also present at different intervals inside several of these zones. Both ductile and brittle fault rocks, including protomylonites and mylonites, cataclastic rocks and cohesive breccias, are present. Several fault core intervals, which are up to several tens of metres thick, are present within the regionally important Singö and Forsmark zones. Although non cohesive crush rock and fractures filled with clay minerals have been recorded along fault core intervals in tunnels that intersect the Singö zone /Glamheden et al. 2007a/, no fault gouge has been documented along any of the zones (see Figure 2-9).

(2) NNW (Vertical or steeply dipping zones in) Deformation Zones: The vertical or steeply dipping deformation zones in the NNW set have only been intersected in five cored boreholes in the local model volume. Only one zone (NNW0404) with a trace length at the ground surface of c 1,000 m is conspicuous at 400 to 600 m depth inside the targeted part of the local model volume. A second zone (NNW0101) occurs to the south-east of zone ENE0062A, against which it terminates. The surface trace length of the three zones included in the local model varies between c. 1,000 and 2,000 m. The estimated measured thicknesses are 10 and 41 m.

Vertical or steeply dipping fractures that strike NNW dominate in the NNW zones. However, vertical or steeply dipping fractures that strike ENE to NNE and gently dipping to sub-horizontal fractures are also conspicuous. The dominance of sealed fractures, the character of wall-rock alteration, the character of the fault core (if present), and the fracture mineralogy all resemble the corresponding features in the vertical or steeply dipping zones in the ENE to NNE set.

***Figure 2-9.** Character of regional deformation zones in the vertical or steeply dipping, WNW to NW set. Crush zones, laumontite-sealed cataclasites and networks, and wall-rock alteration defined by dissemination of hematite and red staining, along part of a fault core interval in the Singö deformation zone (WNW0001) in borehole KFM11A (borehole interval c. 597 to 608 m). Modified from Figure 5-33 in /SKB 2008/.*

(3) ENE, NE and NNE (vertical and steeply-dipping) Deformation Zones: These brittle deformation zones transect the candidate volume (Figure 2-8). The surface trace length of these zones included in the local model varies from approximately 1,000 m to 3,500 m, and most are less than 2,000 m. Only two zones with a surface trace length longer than 3,000 m intersect the target volume (zones ENE0060A and ENE0062A with their attached branches, see Figure 2-10). The thickness of the zones in the ENE to NNE set (21 measurements) varies considerably, with a range between 2 and 45 m, a mean value of 18 m and a standard deviation of 13 m. The measured thickness includes the transition and, if present, the fault core parts of a zone (Figure 2-5 and Appendix B). 24 zones, which either show a trace length at the ground surface of 1,000 m or longer or form minor splays or attached branches to such zones, are present at 400 to 600 m depth inside the potential repository volume.

The zones in the ENE, NE and NNE set have a distinct expression at the surface in the form of lineaments classified as magnetic minima. They are characterised by a high frequency of especially sealed fractures and conspicuous alteration in the form of red staining. The alteration is related to a fine-grained dissemination of hematite, in both the wall rock to the fractures in the zone as well as in certain minerals (e.g. laumontite, adularia,) that fill or coat these fractures. Alteration referred to as quartz dissolution that gave rise to a vuggy rock is also locally present. Fault core intervals consist of a highly elevated fracture frequency, commonly with sealed fracture networks (Appendix B). Locally, cohesive breccia and cataclasite are also present. Fault gouge has not been documented along any of these zones.

Figure 2-10. Character of deformation zones in the vertical or steeply dipping, ENE to NNE set. The photo shows the core from deformation zone ENE0060A in the interval c. 237–248 m in KFM01C showing the dominance of sealed fractures and sealed fracture networks. A fault core interval has been recognised at c. 238 m. The darker portion of the core is amphibolite. Modified from Figure 5-31 in /SKB 2008/.

(4) **Gently dipping Deformation Zones**: These brittle deformation zones occur more frequently in the south-eastern part of the candidate volume and dip gently towards the southeast. Similar features were observed in the construction of the Forsmark nuclear power plant discharge tunnels and the SFR Facility /Carlsson and Christiansson 2007/. Only three gently dipping zones A2, A8 and B7 enter the target volume between 400 to 600 m depth, north-west of zone ENE0062A. As indicated above, two of these zones, A2 and A8, belong to a family of gently dipping structures that occur along or close to the roof of the rock volume that has been identified as potentially suitable for the excavation of a waste repository. The thickness of the zones that are present inside the local model volume (10 borehole intersections) varies considerably, with a range between 6 and 44 m, a mean value of 21 m and a standard deviation of 13 m (see also Appendix B).

Relative to all the other deformation zones, the gently dipping zones contain a higher frequency of open fractures and non-cohesive crush rock. Many of these open fractures are hydraulically connected (see Section 2.5). In a similar manner as the steeply dipping sets, most of the gently dipping zones show bedrock alteration in the form of red staining related to hematite dissemination (see Figure 2-11).

Altered vuggy rock with quartz dissolution is also present along some of the gently dipping zones (e.g. zone A3). If present, fault core intervals consist of a highly elevated fracture frequency, occasionally with sealed fracture networks or non-cohesive crush rock, cohesive breccia and cataclasite. Fault gouge has not been documented along these zones.

Deformation zones with trace length at the ground surface longer than 3 km require a respect distance due to the risk of seismicity caused by post-glacial rebound /Munier and Hökmark 2004/. The relevant structures affecting the target volume are visualized in Figure 2-12. Their dimensions are summarized in Table 2-5. Also listed in that table are splays to larger deformation zones that might be of concern for the layout work. Figure 2-14 gives a schematic illustration of available rock volumes for layout work in design stage D2 when the respect distance rules are applied. Detailed information on geometries and coordinates for the deformation zones and respect distances are given in RVS models, maintained by SKB.

Table 2-5. Basis for interpretation, confidence of existence (C), orientation (S/D), length (L), thickness (T), calculated thickness(Tcalc) and estimated range in thickness(Tspan) of the deformation zones included in the local model volume according to /Stephens et al. 2007/. Bold ID code represents a DZ that has assigned respect distance due to its trace length >3 km.

ID code	C	S/D (°)	L (m)	T (m)/*T calc. (m)*	T span (m)
Vertical and steeply dipping deformation zones with sub-sets that show WNW and NW trends					
WNW0123	High	117/82	5,086	52	10–64
Vertical and steeply dipping fracture zones with ENE (and NE) trends					
ENE0060A	High	239/85	3,120	17	10–64
ENE0060B	High	234/78	1,070	33	3–45
ENE0060C	High	241/75	1,161	20	3–45
ENE0062A	High	058/85	3,543	44	10–64
ENE0062B	Medium	057/82	616	*10*	2–43
ENE0062C	Medium	064/80	346	*5*	2–30
Gently S-, SE- and W-dipping fracture zones					
1203	High	180/10	881	10	6–16
A2	High	080/24	3,987	35	23–48
A8	High	080/35	1,852	32	6–37
F1	High	070/10	Not at surface	44	23–48

C = Confidence of existence.
S/D (°) = Strike and dip in degrees using right-hand-rule method.
L (m) = Trace length at the ground surface in metres.
T (m) = Thickness in metres.
T calc. (m) = Calculated thickness in metres, based on the length-thickness correlation diagram.
T span (m) = Estimated range of thickness in metres, based on the length-thickness correlation diagram.

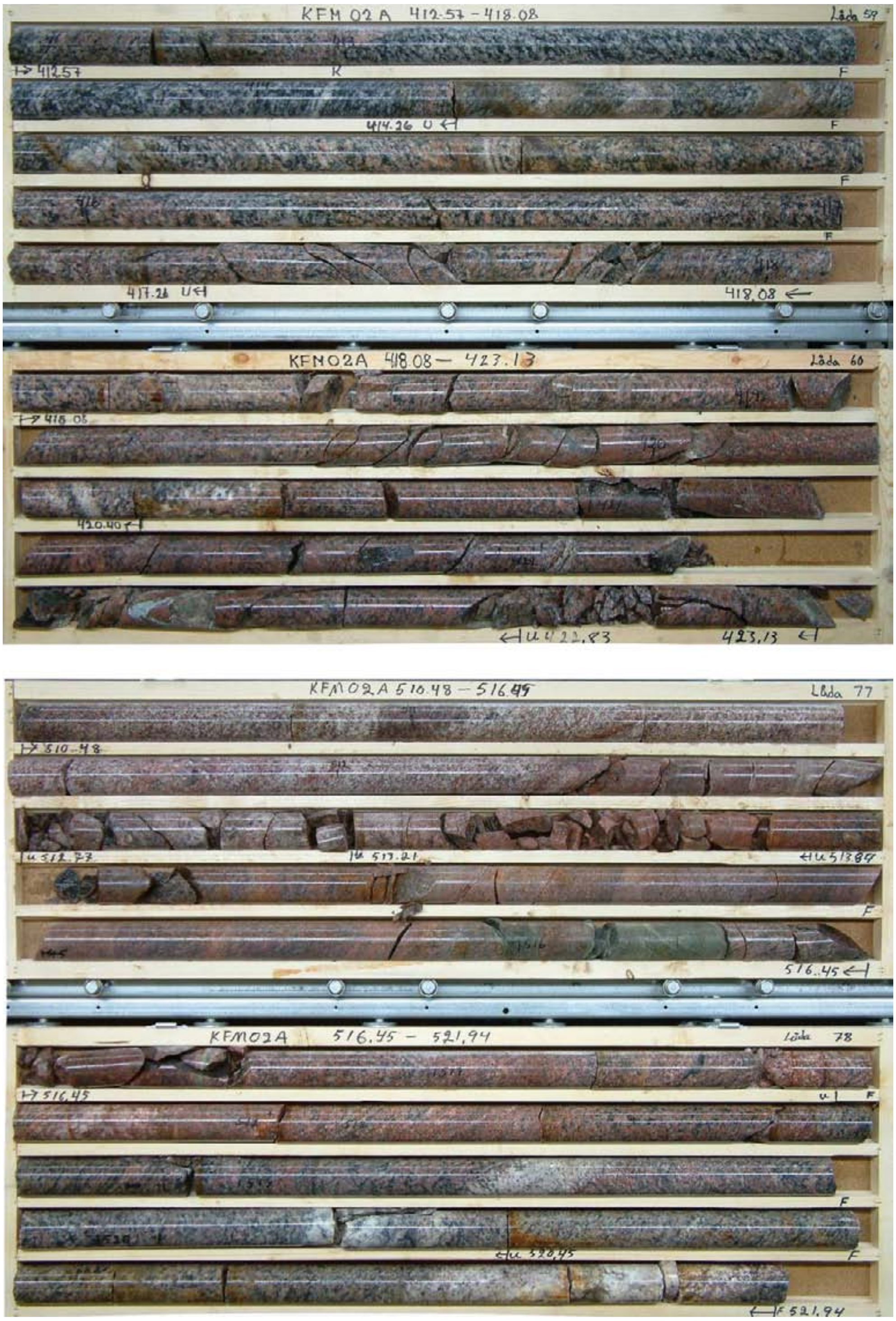
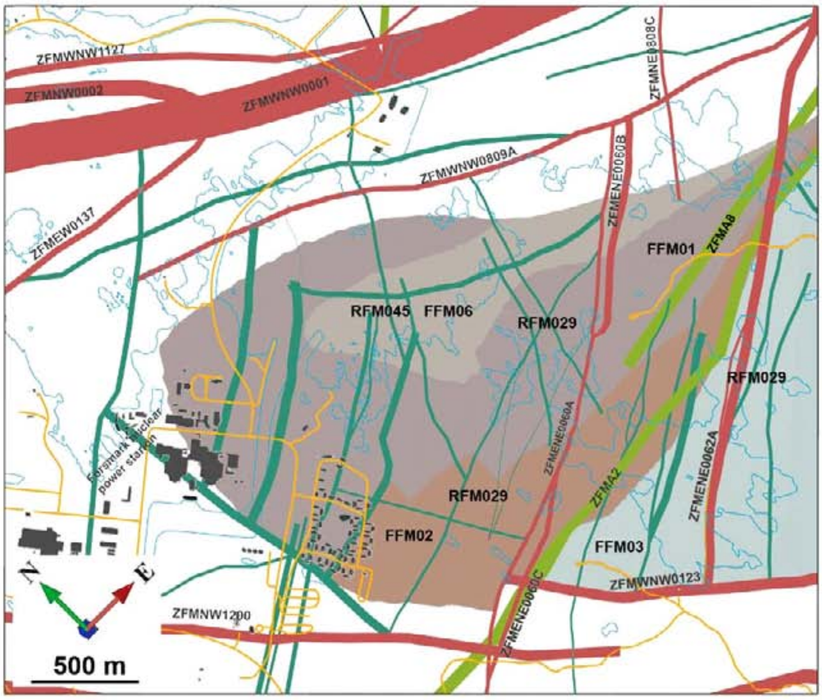


Figure 2-11. Character of deformation zones in the gently dipping set. a*) Open and sealed fractures, crush zone and alteration defined by hematite dissemination and red staining along the borehole interval c. 413 to 423 m in KFM02A. This interval marks the transition from the bedrock above zone A2, predominantly in the upper drill core box, into the bedrock affected by zone A2 predominantly in the lower* drill core box. b*) Similar features along the borehole interval c. 510 to 522 m in KFM02A. This view shows the transition from the bedrock inside zone F1, predominantly in the upper drill core box and approximately half of the lower drill core box, into the bedrock beneath zone F1, in the remainder of the lower drill core box.*

Elevation –150 m (RHB 70)



Elevation –500 m (RHB 70)

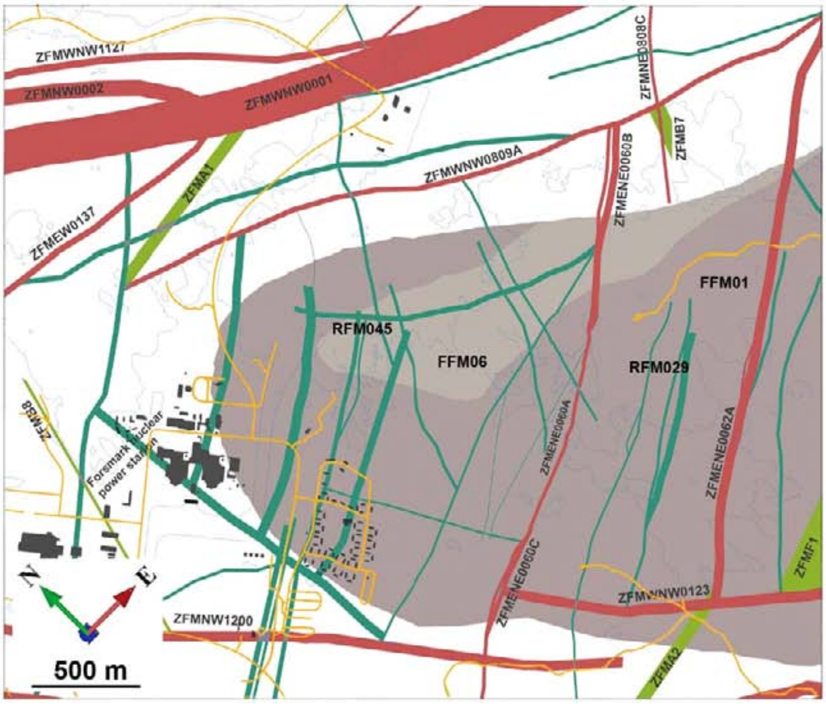


Figure 2-12. Plan view of the rock domains, deformation zones and fracture domains at the Forsmark site at elevations, –150 m and –500 m, inside the target volume. In each figure, deformation zones marked in red are steeply dipping or vertical and have a trace length at the surface longer than 3,000 m. Zones marked in blue-green are steeply dipping or vertical and are less than 3,000 m in length. Zones marked in green are gently dipping. Other features are labelled directly on the figures /SKB 2008/.

The majority of gently dipping deformation zones are situated outside or in the south-eastern, peripheral part of the local model volume (Figure 2-13a). Within the target volume only zone A2 has been provided with a respect distance. Zones A8, B4, B7, F1 and 1203 either lie above the proposed repository level or do not fulfil the size requirement for respect distance. However, it should be noted that zones A8, A2, F1 and A3 appear to splay off from each other in an integrated mesh from north to south in the south-eastern part of, and outside the local model volume (Figure 2-13b).

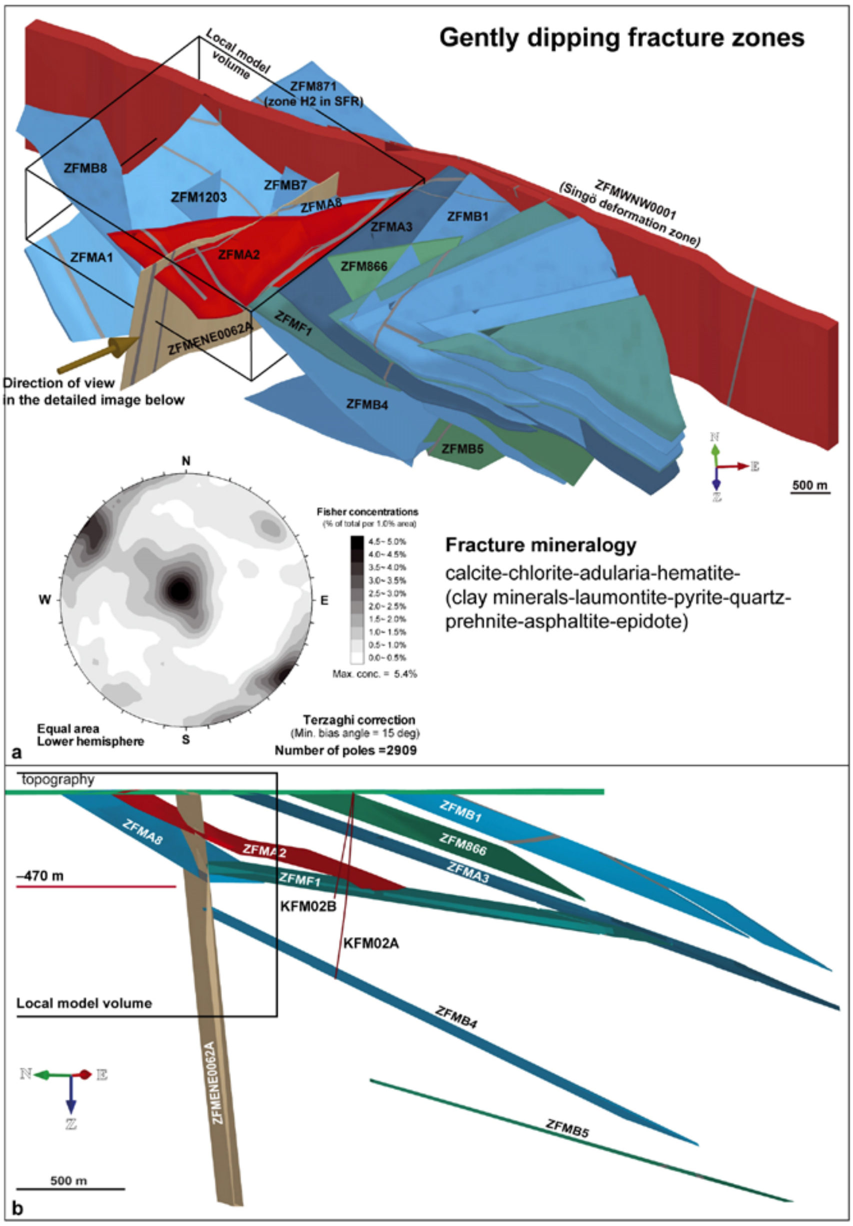


Figure 2-13. *Gently dipping deformation zones on both sides of the Singö zone (WNW0001). The orientation of fractures inside the gently dipping deformation zones are plotted as poles to planes in a stereographic projection (equal-area, lower hemisphere) and contoured. The fracture mineralogy in the gently dipping zones is also shown and the order of mineral presentation reflects the order of abundance (see also Appendix B). b) Apparent splay-like pattern between zones A2, A8, F1 and A3 in the south-eastern part of and outside the local model volume. Boreholes KFM02A and KFM02B and three of the boundaries to the local model volume are also shown. The boundary of the local model volume to the north lies outside the view of the figure. The repository level, –470 m (RHB 70) is marked with a red line /SKB 2008/.*

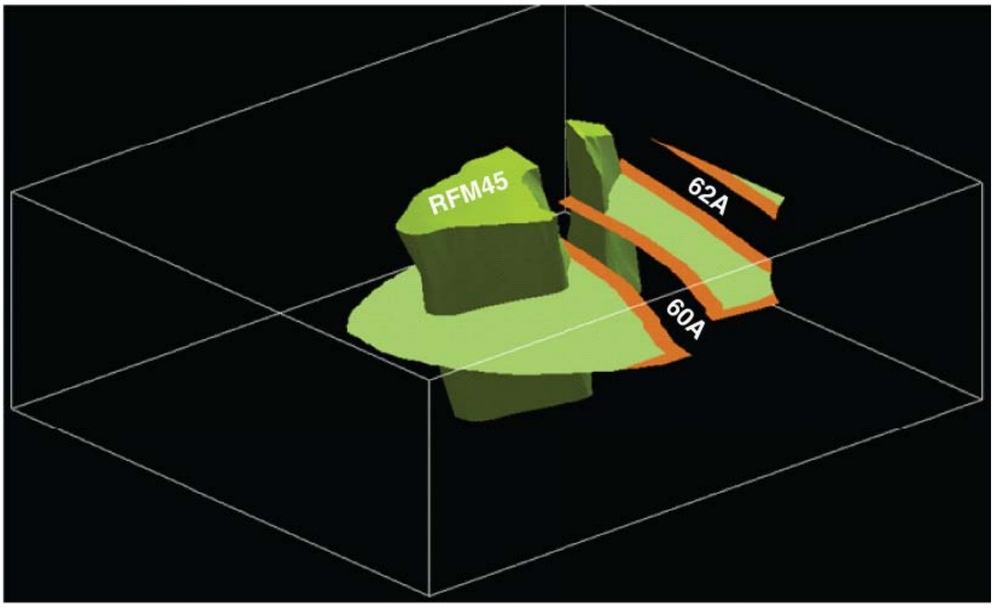


Figure 2-14. Schematic illustration of the available surface within the tectonic lens at a depth of 470 m north of deformation zone A2. Elevated darker green volume is RFM045. Deformation zones ENE0060A and ENE0062A and their respect distances cut across the target volume. Orange colour is a 100 m zone outside respect distances where a slightly higher loss of deposition positions can be expected (cf. Section 7.6).

2.2.2 Mechanical properties of deformation zones

The location and extent of the major deformation zones at Forsmark within the target volume are known with reasonable confidence for preliminary design purposes. From the construction experience at the Forsmark nuclear power plant and the SFR Facility, and the general construction experience in Sweden, the strength, i.e. plastic yielding or squeezing, of these deformation zones does not significantly inhibit the construction of tunnels through these features. What can impact the construction is water inflows and ravelling of blocks. Typically such zones have several fracture sets with an increase in fracture frequency; as such localized blocky ground may be encountered. /Carlsson and Christiansson 2007/ documents the tunnelling conditions encountered when passing the Singö deformation zone during the construction of the discharge tunnels for the Forsmark nuclear power plant and the SFR Facility and /Glamheden et al. 2007a/ documents the back calculated mechanical properties of this zone.

Provisional geomechanical properties of major deformation zones, based on the results reported by /Glamheden et al. 2007a/, are provided in Table 2-6. A deformation zone may have three distinct sections: (1) central core, (2) a transition zone and (3) adjacent host rock as described in Figure 2-5. The parameters in Table 2-6 are provided for each section but should be treated cautiously. The experience in Sweden and elsewhere is that these deformation zones have large undulations and may vary significantly in thickness and properties. Should the design identify that these deformation zones could have a significant impact on the facility a parametric study may be required.

Table 2-6. Summary of geomechanical parameters for deterministic deformation zones using the definitions in Figure 2-5. Note that none of the deformation zones within the target volume at repository level are expected to have a core. Data from /Glamheden et al. 2007a/

Property	Host Rock	Transition Zone	Core
Deformation Modulus (GPa)	45	32	2.7
Poisson's ratio	0.36	0.43	0.43
Tensile strength (MPa)	0.3	0.1	0.1
Cohesion (MPa)	5	4	2
Friction angle (°)	65	51	37

2.3 Fractures and fracture domains

Deformation zones with a trace length at ground surface less than 1,000 m and fractures in the rock mass between deformation zones are not covered by the deterministic deformation zone model. They are handled in a statistical way through discrete fracture network (DFN) models. The DFN models are based on fracture observations in the boreholes, mapped fractures at outcrops, size modelling and from interpretation of lineaments. The DFN model captures both open and sealed fractures.

The upper part of the bedrock inside the tectonic lens at Forsmark contains an increased frequency of sub-horizontal and gently dipping fractures with apertures, referred as open and partly open fractures. A systematic assessment of the variation in the frequency of particularly open and partly open fractures with depth along investigation boreholes, led to the division of the bedrock between deformation zones into fracture domains. On the basis of these borehole data, a 3D geometric model for four of the six fracture domains (FFM01, FFM02, FFM03 and FFM06), inside the target volume, was constructed. The rock domains RFM029 and RFM045 inside the local model volume consequently have been divided into separate fracture domains (FFM01, FFM02, FFM03 and FFM06) (Figure 2-15) /SKB 2008/.

Fracture domain FFM01 is situated within rock domain RFM029 inside the target volume. It lies north-west of the steeply dipping deformation zone NE0065, beneath the gently dipping or sub-horizontal zones A2, A3 and F1, and beneath a depth (RHB 70) that varies from approximately 40 m (large distance from zone A2) to approximately 200 m (close to zone A2).

Vertical or steeply dipping fractures that strike ENE to NNE and NNW, as well as gently dipping to sub-horizontal fractures are conspicuous in this domain. The experience at the SFR Facility, while outside this domain, suggests sub-horizontal fractures may appear as localised occurrences of limited areal extent. Hence at the repository horizon, detailed analyses of the core logs may be required to determine if these sub-horizontal fractures are present. This issue can only be addressed during the Detailed Characterisation Phase.

Fracture domain FFM02: High frequency of gently dipping to sub-horizontal fractures and vertical to steeply dipping fractures that strike ENE or NNW are most conspicuous in this domain and occur to approximately 200 m depth. As in domain FFM01, calcite, chlorite, laumontite, adularia, hematite and quartz are present along the different sets of fractures. However, clay minerals, pyrite, asphaltite and goethite, which all belong to the younger generations of minerals, are more conspicuous in fracture domain FFM02 relative to all the other domains. Furthermore, fractures without any mineral coating or filling ("no mineral") are also prominent in FFM02. This fracture domain contains the open and hydraulically connected fractures and stress-relief fractures. The vertical extension of FFM02 appears to increase towards SE and has its maximum depth (ca 200 m) at the location of boreholes KFM01A and KFM05A.

Fracture domain FFM03: FFM03 is situated within rock domains RFM029 and RFM017, south-east of and outside the target volume. In particular, it is inferred to be present above zone A2 in borehole KFM02A and along the whole length of the boreholes KFM03A and KFM03B to the south-east of the local model volume. The rock domains in this volume are characterized by a high frequency of gently dipping fracture zones containing both open and sealed fractures. High frequency of gently dipping minor fracture zones that are open and show hydraulic connections over a large area.

Fracture domain FFM06 is situated within rock domain RFM045, inside the target volume. It resembles fracture domain FFM01 in the sense that it lies beneath both deformation zone A2 and fracture domain FFM02 (Figure 2-15). It is distinguished from domain FFM01 by the widespread occurrence of fine-grained, altered (albitized) granitic rock, with slightly higher contents of quartz compared to unaltered granitic rock, i.e. on the basis of rock type.

Two sets of vertical or steeply dipping fractures that strike NE to NS and NW to WNW, as well as gently dipping to sub-horizontal fractures are conspicuous in this domain (Figure 2-15). Fracture minerals are dominated by chlorite, calcite, adularia, hematite, laumontite and quartz. Epidote is relatively uncommon along the fractures in this domain. The more common mineral laumontite is

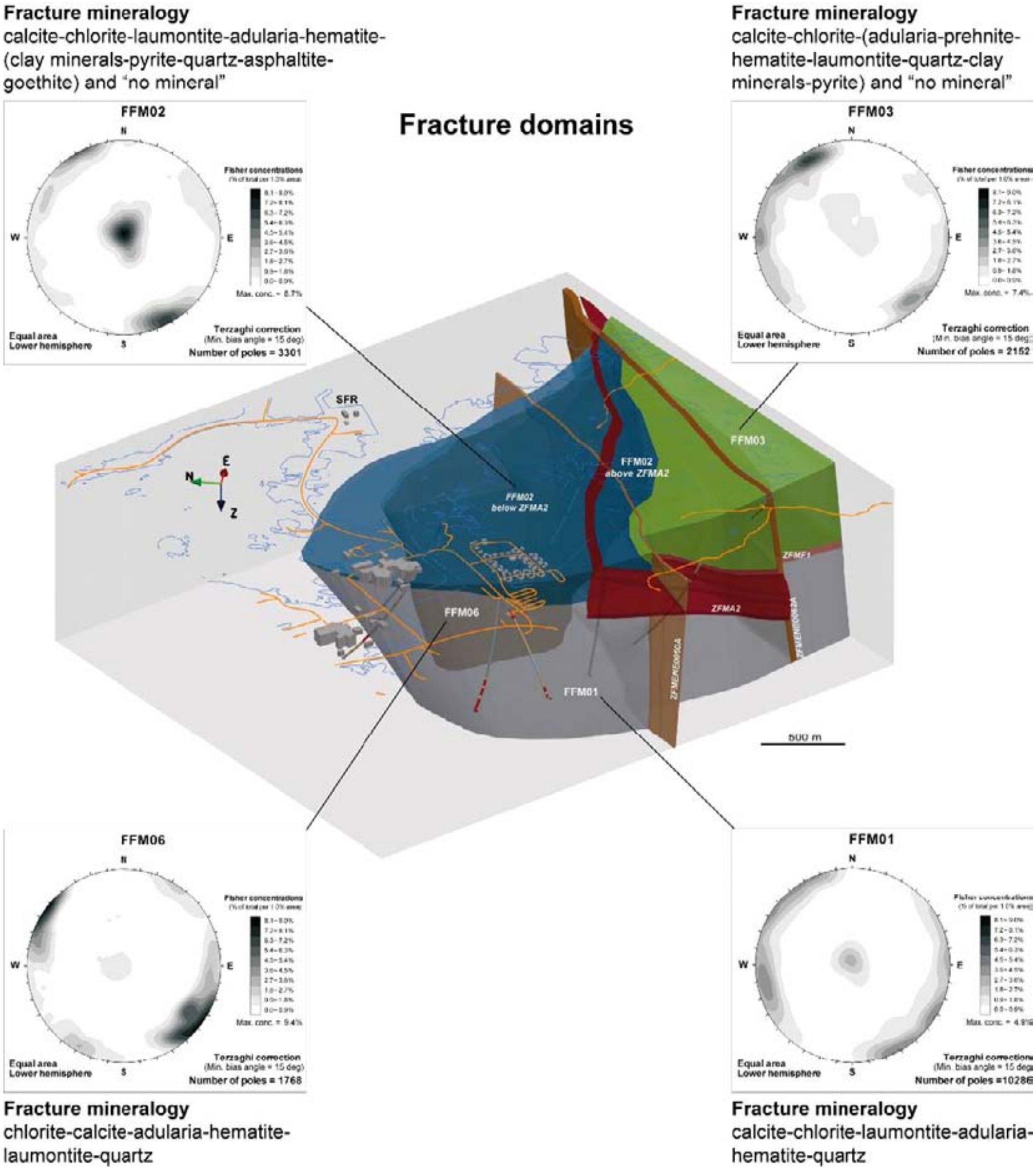


Figure 2-15. *Three-dimensional model for fracture domains FFM01, FFM02, FFM03 and FFM06 in the north-western part of the Forsmark tectonic lens, viewed towards the ENE. The gently dipping and sub-horizontal zones A2 and F1 as well as the steeply dipping deformation zones ENE0060A and ENE0062A are also shown /after Olofsson et al. 2007/. The orientation of fractures inside the different fracture domains are plotted as poles to planes in stereographic projections (equal-area, lower hemisphere) and contoured /SKB 2008/.*

predominantly found along the steeply dipping NE to N-S fractures. However, some occurrences are also present along the fractures with other orientations. Clay minerals, in the youngest generation of minerals, are present in both the steeply and gently dipping fractures. These features are very similar to those observed in the NNE sub-set of deformation zones that is also prevalent in this part of the target volume.

The contrasting character of the fracture domain FFM01 and FFM02 can be seen in Figure 2-16. The figure shows typical fracture frequency observed in FFM02 and the hematite staining often found in this domain. Figure 2-16b shows the typical fracture spacing observed in FFM01.

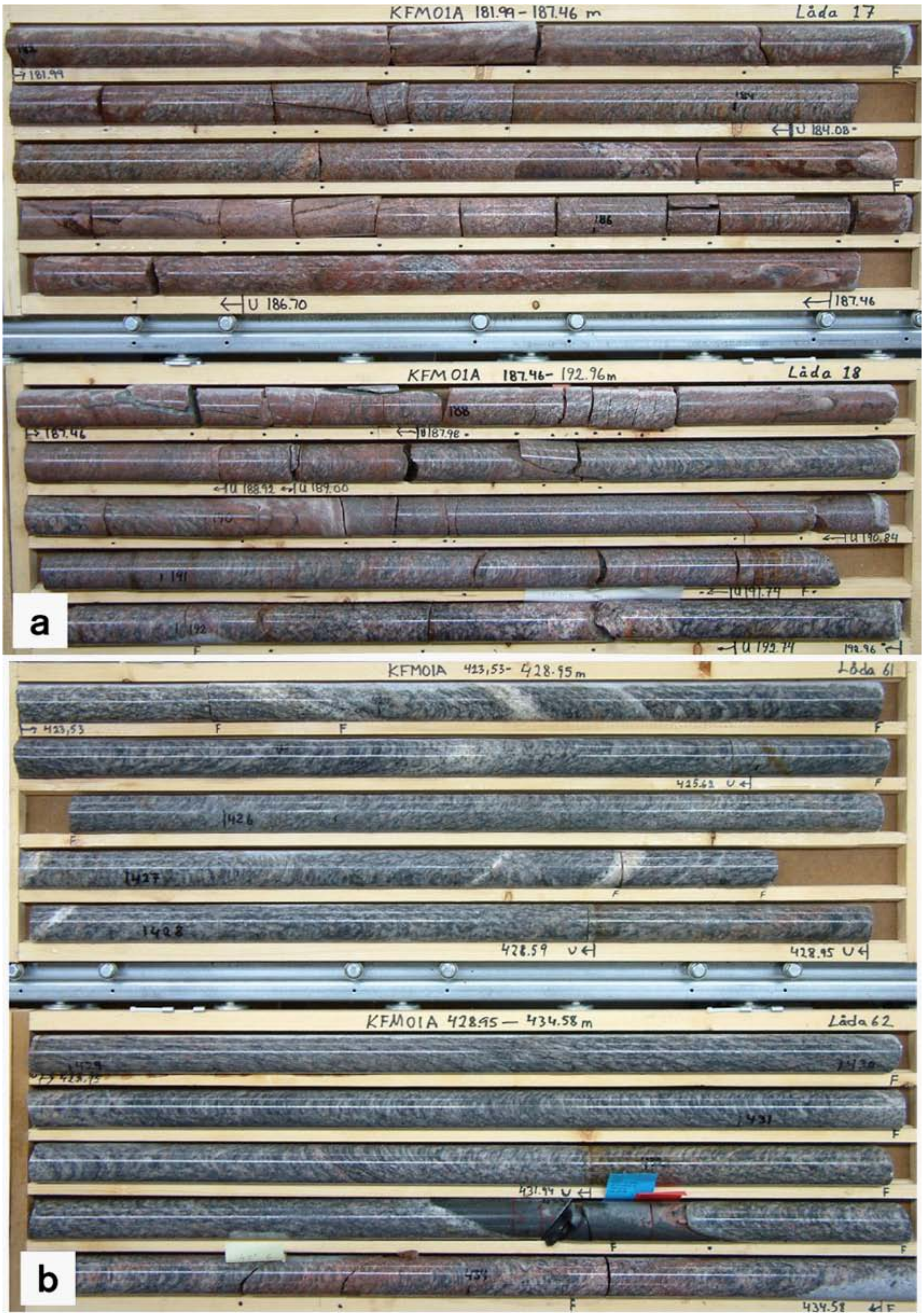


Figure 2-16. a) Fracture domain FFM02 in borehole KFM01A, borehole interval 182–193 m. Note the hematite staining and the high frequency of open fractures. b) Fracture domain FFM01 in borehole KFM01A, borehole interval 423–435 m. Note the lack of open fractures in FFM01.

2.3.1 Mechanical properties of fractures

The discrete fractures (commonly referred to as joints or discontinuities in underground engineering) within the fracture domains are classed as open and sealed. An extensive laboratory testing program has been carried out to characterise the mechanical behaviour of the discrete open fractures. These fractures were selected from core samples and were tested using direct shear tests. A summary of the test results on open fractures in fracture domain FFM01 and three deformation zones intersecting the target volume (NW1200, ENE1192, ENE1061) is given in Table 2-7. These values from the direct shear tests are based on direct measurements with a normal stress magnitude comparable to that expected at the tentative repository depth in the Forsmark target volume.

Samples from the adjacent fracture domains (FFM02, FFM03, FFM04 and FFM05) on the whole show similar results as samples from FFM01. This is also the case for the samples examined from the deformation zones.

2.3.2 Mechanical properties of fractured rock

The strength and deformation of the fractured rock mass has been evaluated using empirical approaches such as Q, RMR and GSI. A comparison of the Q and RMR values for fracture domains FFM01 and FFM06 and deformation zones in the target volume are provided in Table 2-8. Inspection of Table 2-8 reveals that mean Q values for fracture domains FFM01 and FFM06 class the rock mass as “Exceptionally Good (400–1,000)” and “Extremely Good (100–400)”, and the deformation zones as “Very Good (40–100)” /Barton 2002/. Similarly the mean RMR values class the fracture domains FFM01 and FFM06, and the deformation zones as “Very Good (81–100)” /Bienawski 1989/. These comparisons highlight the excellent quality of the rock mass at the target depth and that properties of the deformations zones are slightly lower to that of the fractured rock outside the deformation zones (fracture domains).

These *Q* and RMR values were converted to strength and deformation properties using traditional empirical approaches such as GSI. In addition, an independent assessment of the fractured rock strength and deformation properties was carried out using a numerical approach based on the DFN model. Table 2-9 provides estimated values for the strength and deformation characteristics of the fractured rock mass.

Table 2-7. Results from direct shear tests on open fractures in fracture domain FFM01 and deformation zones intersecting the target volume. The tests include 29 samples from FFM01 and 10 samples from three DZ /Table 7-4 in SKB 2008/.

Parameter	FFM01 Mean/stdev *Uncertainty*	 Min–Max	DZ Mean/stdev *Uncertainty*	 Min–Max
Normal stiffness (MPa/mm)	656/396 *±22%*	159–1,833	662/729 *±68%*	167–2,445
Shear stiffness, $K_{S20,}$ (MPa/mm)	34/10 *±11%*	18–52	31/8 *±16%*	19–44
Peak friction angle (°)	37/3 *±3%*	29.–42	35/2 *±4%*	32–38
Peak cohesion (MPa)	0.8/0.3 *±14%*	0.2–1.3	0.8/0.5 *±39%*	0.0–1.7
Residual friction angle (°)	34.9/3.4 *±4%*	28–42	35/2 *±4%*	30–37
Residual cohesion (MPa)	0.3/0.2 *±24%*	0.1–0.8	0.3/0.2 *±41%*	0.0–0.6

Note: The uncertainty of the mean is quantified for a 95% confidence interval. Minimum and maximum truncation values are based on the observed min’ and max’ for the tested population.

Table 2-8. Q and RMR values for fracture domains FFM01 and FFM06 and deformation zones in the target volume /Table 7-1 in SKB 2008/.

	Q-value				RMR-value			
	Length (m)	Min	Mean [mode]	Max	Length (m)	Min	Mean [mode]	Max
Fracture domain								
FFM01	2,565	6	477 [150]	2,133	2,565	74	89 [90]	98
FFM06	525	20	287 [150]	800	525	74	87 [88]	94
Deformation zones								
Major DZ	750	2	66 [29]	1,067	150	64	81 [80]	94
Minor DZ	350	4	55 [33]	400	350	70	82 [81]	94
Possible DZ	255	10	99 [60]	1,067	255	75	82 [81]	91

Table 2-9 Suggested rock mechanics properties of the rock mass in FFM01 and FFM06 after harmonization /Table 7-6 in SKB 2008/.

Properties of the fractured rock mass	Rock domain Mean/std. dev. Min–max *Uncertainty of mean* FFM01	FFM06
Deformation Modulus, (GPa)	70/8 39–79 *±2%*	69/12 40–81 *±3%*
Poisson's ratio	0.24/0.03 0.12–0.33 *±5%*	0.27/0.04 0.12–0.37 *±4%*
Friction angle, Mohr-Coulomb, (°)	51/2 32–56 *±2%*	51/2 43–57 *±2%*
Cohesion Mohr-Coulomb, (MPa)	24/5 6–42 *±13%*	23/5 1–40 *±15%*
Tensile strength, (MPa)	2.4/1.0 0.6–5.0 *±3%*	2.3/1.0 0.6–4.0 *±8%*

Note: The uncertainty of the mean is quantified for a 95% confidence interval. Minimum and maximum truncation values are based on the observed minimum and maximum for the tested population.

2.4 In situ stress

Two stress models were developed for Forsmark. The model by /Ask et al. 2007/ used the results from hydraulic fracturing and hydraulic testing of pre-existing fractures while the model by /Martin 2007/ relied primarily on overcoring data and indirect observations (Table 2-10). The stress magnitudes from the stress model proposed by /Martin 2007/ are judged to be the "most likely" values in Table 2-10. The rationale for excluding the hydraulic fracturing data are discussed in /Martin 2007, Glamheden et al. 2007b/.

The "most likely" stress model for the target volume has been divided into three depth ranges and the stress magnitudes and orientations for those depth ranges are given in Table 2-10. The depth ranges 0–150 m considered representative of the fractured rock mass that is affected by the sub-horizontal and vertical fractures, and reflects the stress release that occurs in the upper portion of a rock mass. The depth range 400–600 m is considered representative of the relatively massive homogenous portion of the tectonic lens. While the anticipated variability have been provided in the 3 depth ranges, the uncertainty in both magnitude and orientation is greater for the 0–150 depth range. The uncertainty decrease slightly with depth reflecting the notion that the rock mass is more uniform with depth.

At the depth of the repository the stress magnitudes and orientations are expected to be relatively consistent spatially in FFM01. However, the stress magnitudes and orientations may deviate from those given in Table 2-10 in the vicinity of deformation zones. It is anticipated that additional stress measurements will be carried out during the construction of the access ramp, tunnels and shafts, and deposition tunnels to confirm the in situ stress design values. The most likely stress magnitudes and orientation in Table 2-10 shall be used for the design stage D2.

To evaluate the possibility of elevated stress magnitudes at the repository level a maximum stress model is proposed in Table 2-11. These magnitudes shall only be used in assessing the risks associated with spalling for the depth range given in Table 2-11. When combining the stress magnitudes in Table 2-11 for probability analyses, the ratio of maximum to minimum horizontal stress shall be constrained between 1.4 and 2.0.

2.5 Hydraulic properties

2.5.1 Near surface – down to 150 m

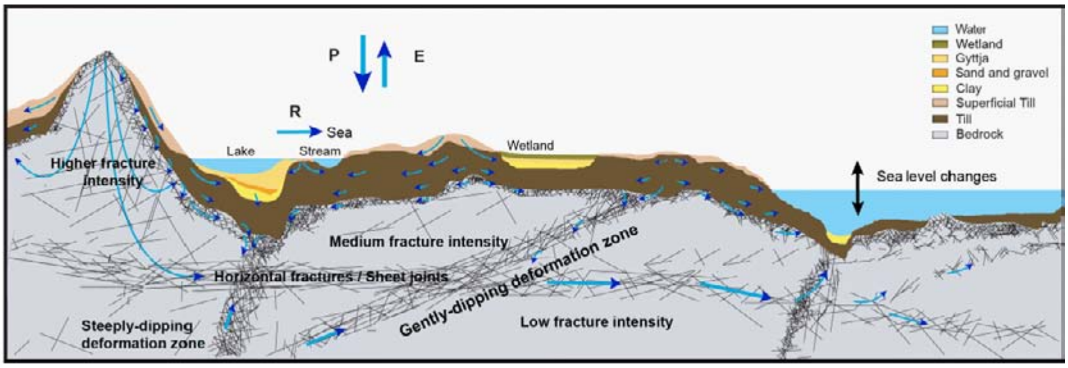
/Follin et al. 2007a/ observed that in the near-surface bedrock in the north-western part of the tectonic lens, down to about 100 to 150 m depth, the bedrock is heterogeneously intersected by sub-horizontal sheet joints besides the ordinary occurrence of fractures and fracture zones. The combination of extensive near-surface sheet joints and outcropping deformation zones, both gently-dipping and steeply-dipping, is believed to form a well-connected lattice of potential flow paths, which may short-circuit the groundwater flow field from above as well as from below, depending on the transmissivities of the discrete features involved. Figure 2-17 shows an illustration of the concept. It is based on several strands of hydrogeological evidence.

Table 2-10 Stress magnitudes and stress orientations for the target volume. From Table 7-2 in /SKB 2008/ and Table 7-2 in /Martin 2007/.

Depth Range (m)	Maximum horizontal stress – σ_H (MPa)	Trend (°)	Minimum horizontal stress – σ_h (MPa)	Trend (°)	Vertical stress σ_{vert} (MPa)
Most likely /Martin 2007/					
0–150	19+0.008z, ±20%	145 ±20	11+0.006z, ±25%	055	0.0265z±0.0005
150–400	9.1+0.074z, ±15%	145 ±15	6.8+0.034z, ±25%	055	0.0265z±0.0005
400–600	29.5+0.023z, ±15%	145 ±15	9.2+0.028z, ±20%	055	0.0265z±0.0005
400 mvd	38.7 ±5.8	145 ±15	20.4 ±4.0	055	10.6 ±0.2
500 mvd	41.0 ±6.2	145 ±15	23.2 ±4.6	055	13.2 ±0.3
/Ask et al. 2007/					
400 mvd	19.2 ±0.7	124 ±6	9.3 ±1.1	034	10.4
500 mvd	22.7 ±1.1	124 ±6	10.2 ±1.6	034	13.0

Table 2-11 Proposed Maximum Stress Model for the repository elevation –450 to –475 m.

Depth Range (m)	Maximum horizontal stress – σ_H (MPa)	Trend (°)	Minimum horizontal stress – σ_h (MPa)	Trend (°)	Vertical stress σ_{vert} (MPa)
450–475	56 ±6	145 ±15	35 ±8	055	0.0265z±0.0005

a) 

b) 

Figure 2-17. (a) Cross-section illustrating the "hydraulic cage phenomenon" caused by the highly transmissive fractures in the uppermost part of the bedrock within the target area. P=precipitation, E=evapotranspiration, R=runoff. From Figure 8-23 in /SKB 2008/. (b) Sub-horizontal fractures/sheet joints encountered along 13-m deep intake channel constructed for the Forsmark nuclear power plant. From Figure 8-22 in /SKB 2008/.

The cored boreholes in Forsmark are generally percussion-drilled and cased with a steel casing down to c. 100 m depth. This means that there are not many cores collected nor fractures tested in detail with the PFL-f method in the depth interval 0 to 100 m. However, the many percussion-drilled boreholes provide valuable information regarding the transmissivities of the structures intersected, but the geological interpretations of the structures intersected by the percussion-drilled boreholes are much less certain due to lack of geological control. Hence, it is unclear if the hydrogeological data (heads) and the hydraulic test responses (transmissivities) observed represent sheet joints, outcropping deformation zones or both. Most likely the situation varies in space from one borehole to the next for one or several reasons. For instance, both the sheet joints and the fracturing found in the outcropping deformation zones are known to be hydraulically heterogeneous depending on if they are filled with glaciofluvial sediments or not. A compilation of the inferred HTHB impeller flow logging transmissivities divided into intervals of 50 m for the uppermost 200 m of bedrock, Figure 2-18, shows a complex pattern of high and low transmissivities for 50-m sections, ranging from 10^{-6} to 10^{-3} m^2/s, in the uppermost parts of the bedrock. This confirms the notion of a lattice of discrete features, some of which may be very transmissive.

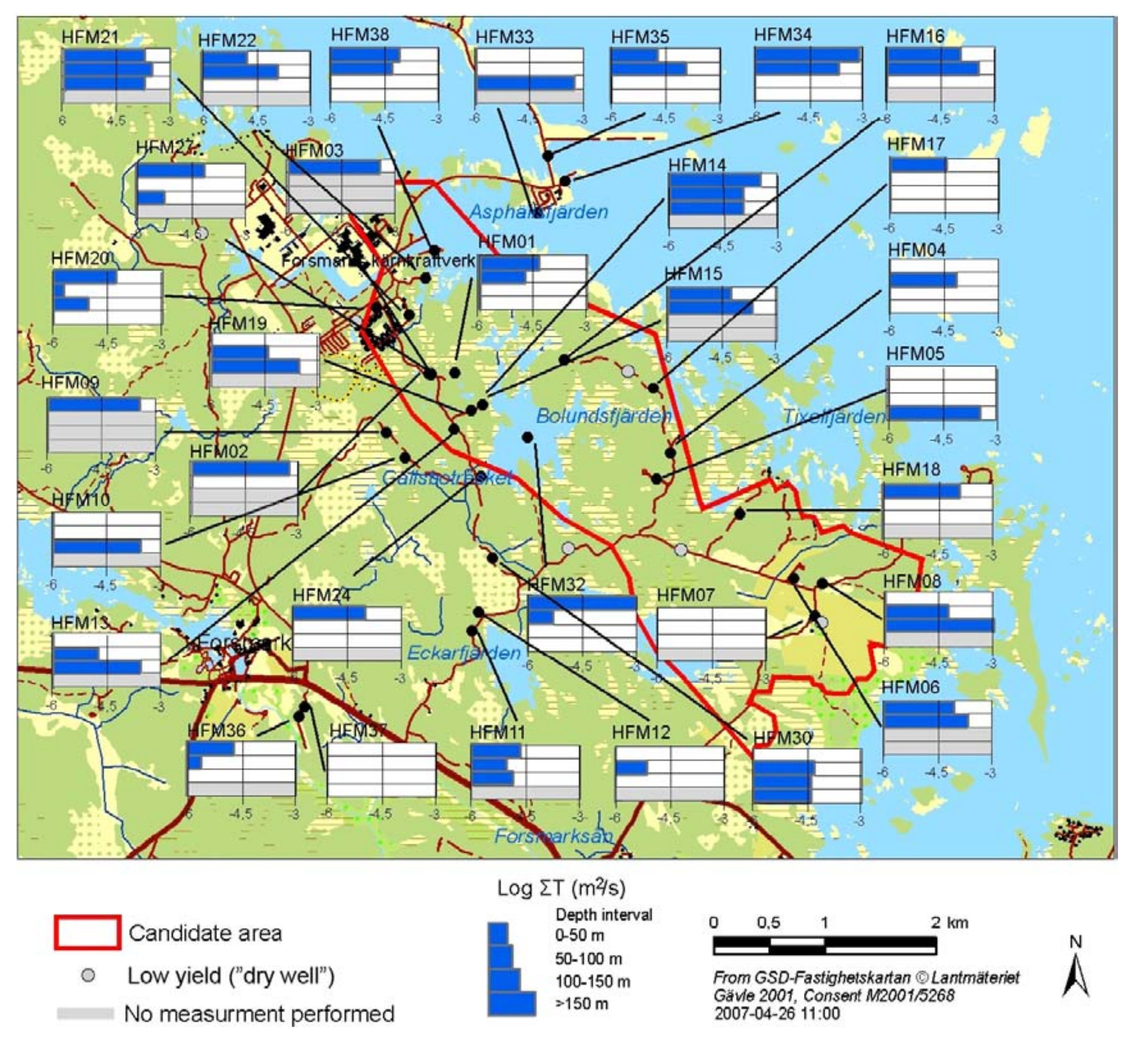


Figure 2-18. *HTHB transmissivities lumped into intervals of 50 m for the uppermost 200 m of bedrock /Figure 4-30 in Follin et al. 2007a/. The logarithmic transmissivity scale ranges from 10^{-6} to 10^{-3} m^2/s and confirms the notion of a lattice of discrete features, some of which may be very transmissive.*

2.5.2 Rock mass below 150 m

The site descriptive model provides hydraulic properties for the deterministic deformation zones as well as to the different fracture domains (Table 2-12). Furthermore, the hydraulic properties vary with depth inside fracture domains FFM01 and FFM06.

In fracture domain FFM02, and especially near the surface, analyses of hydraulic data from the boreholes in the candidate area have shown that there are highly transmissive, generally gently dipping fractures forming a connected network over long distances (e.g. up to 2 km). The linear frequency of flowing fractures is about 0.3 m^{-1} in this domain, see Table 2-12 and an indication of its "average conductivity" could be estimated by the ratio ΣT/ΣBH equal to $4.3 \cdot 10^{-8}$ m/s, see Table 2-12. The highly transmissive character of the superficial rock mass in the candidate area is also reflected by comparing the yield of percussion drilled wells within the candidate area with that in the surrounding area. Within the candidate area the median well yield is 12,300 L/h, while in the immediate surrounding area the median well yield is 700 litre per hour (Figure 2-44 in /SKB 2006a/).

Table 2-12. Summary of flowing fracture transmissivity statistics for the different fracture domains. $P10_{,PFL}$ denotes the linear fracture frequency [m^{-1}], T denotes transmissivity [m^2/s] of individual fractures. Compiled from the Tables 10-17 to 10-24 in /Follin et al. 2007a/.

Fracture Domain	Σ BH Length (m)	No. of flowing fractures PFL–f	Flowing fracture frequency ($P_{10,PFL}$ 1/m)	ΣT/L (m/s)	Max T of an individual fracture (m²/s)	Min T of an individual fracture (m²/s)	Mean log(T) of individual fractures	Std of log(T) of individual fractures
FFM01								
100–200	474.4	52	0.152	1.4E–07	4.68E–05	2.48E–10	–7.84	1.28
200–400	1,387.5	39	0.042	5.2E–10	1.83E–07	2.67E–10	–8.51	0.88
<–400	3,279.7	12*	0.005	6.3E–11	8.89E–08	6.16E–10	–8.19	0.66
FFM02	366.4	81	0.326	4.3E–08	7.31E–06	2.45E–10	–8.02	1.00
FFM03	1,334	49	0.072	1.6E–09	6.77E–07	1.09E–09		
FFM04	154.9	15	0.152	7.4E–09	2.80E–07	4.59E–09		
FFM05	122.0	2	0.027	3.2E–09	2.00E–07	2.00E–07		
FFM06	210.4	0	0.000	–	–	.		

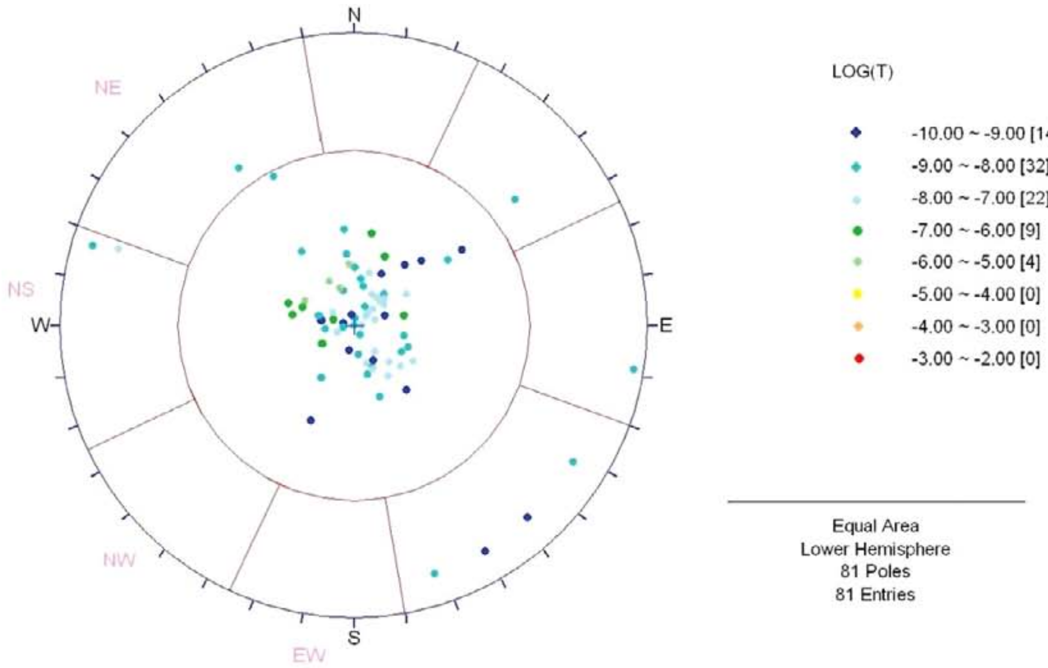
* 10 of the 12 PFL-f anomalies occur between A2 and F1 in borehole KFM02A.

In contrast, the rock mass at depth beneath deformation zone A2, i.e. in fracture domain FFM01, is of very low permeability as it has a low frequency of flowing fractures. Between levels 200–400 m the linear frequency of flowing fractures is about 0.05 m^{-1} in FFM01 and the rock mass has an "average conductivity" in the order of $5.2 \cdot 10^{-10}$ m/s. Below approximately 400 m depth, the frequency is even lower. Boreholes exploring FFM01 suggest that there are very few measurable water flows outside the deterministically modelled deformation zones in the target volume below approximately 360 m depth. The observed frequency of flowing features below 400 m is 0.005 m^{-1} and the rock mass "average conductivity" in the order of $6.3 \cdot 10^{-11}$ m/s, Table 2-12. This suggests that the rock mass between the deformation zones in FFM01 approaches the permeability of intact rock. This observation is supported by the double-packer injection tests conducted in the KFM01A–07A boreholes. The few boreholes penetrating fracture domain FFM06 have not recorded any flowing features. This suggests that it is at least as low permeable as fracture domain FFM01. This is also the assumption made in SDM-Site Forsmark. However, the occurrence of low transmissive fractures in this domain cannot be excluded.

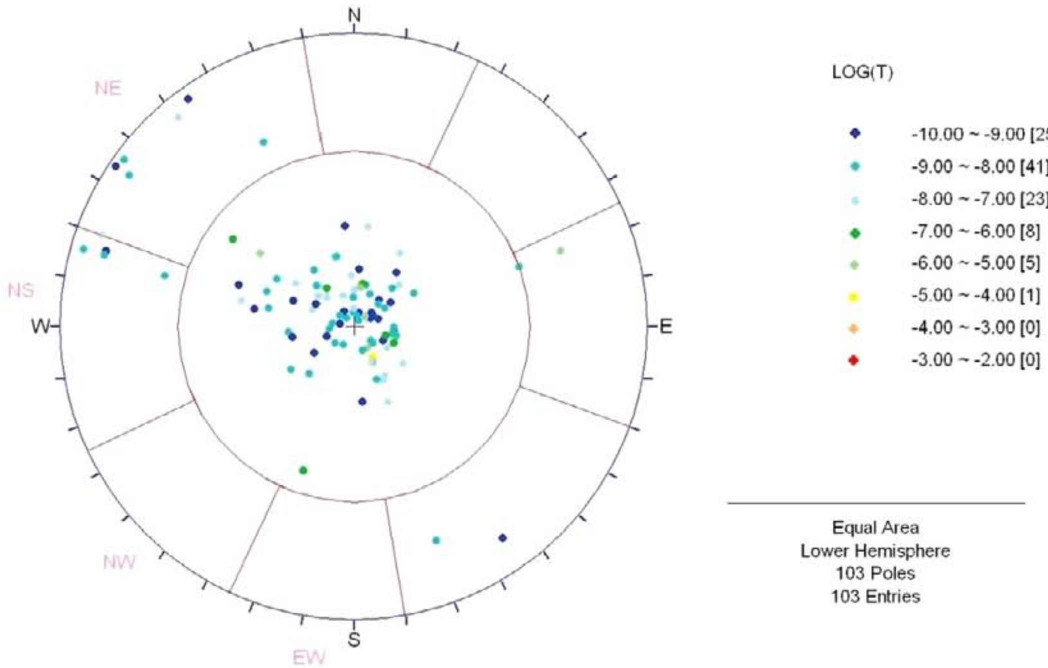
It should also be noted that the flowing fracture frequency could be used to estimate the number of flowing features along a certain tunnel distance. At least approximately this number follows a Poisson distribution with mean $Dist \cdot P_{10PFL}$.

The majority (75–80%) of all features measured with the PFL-f logging are associated with gently dipping fractures regardless of fracture domain, see Figure 2-19. Note that the remaining 20 to 25% of the flowing fractures are steeply dipping and strike ENE and NE striking.

Using this basic data, hydrogeological discrete fracture network (DFN) model was developed /Follin et al. 2007a/. These models are primarily developed for use in safety assessment, but are also essential for estimating the inflow distribution to deposition holes – and thus for estimating loss of canister positions. In addition to the discrete fracture network model, an equivalent continuous porous medium model (ECPM) was also developed. Figure 2-20 shows a typical (single) realisation from ECPM model, which clearly indicates very low hydraulic conductivity values at 450 m depth within the target volume. Realization of water-bearing fractures described by the hydrogeological DFN model has been carried out in accordance with methodology described in /Stigsson 2009/. Sampling of transmissivities along 20 m long horizontal scan lines in the main orientation of deposition tunnels (145°) and 8 m vertical scanlines has been carried out and are presented in Table 2-13 and Table 2-14, respectively. Results are given both for the DFN-model assuming complete correlation between fracture size and transmissivity (Corr) and for the DFN-model assuming only a statistical correlation between fracture size and transmissivity (Semi). While the semicorrelated model may be more realistic for assessing groundwater flow and transport, the correlated model is likely to give a more adequate description of the effective transmissivity of fractures intersecting deposition tunnels or deposition holes.



a) FFM02



b) FFM01

***Figure 2-19.** Orientation of flowing fractures in fracture domains a) FFM02 and b) FFM01. Almost all flowing fractures are gently dipping, but there are also a few ENE and NE striking flowing fractures. (Based on Figures 10-17 and 10-18 in /Follin et al. 2007a/).*

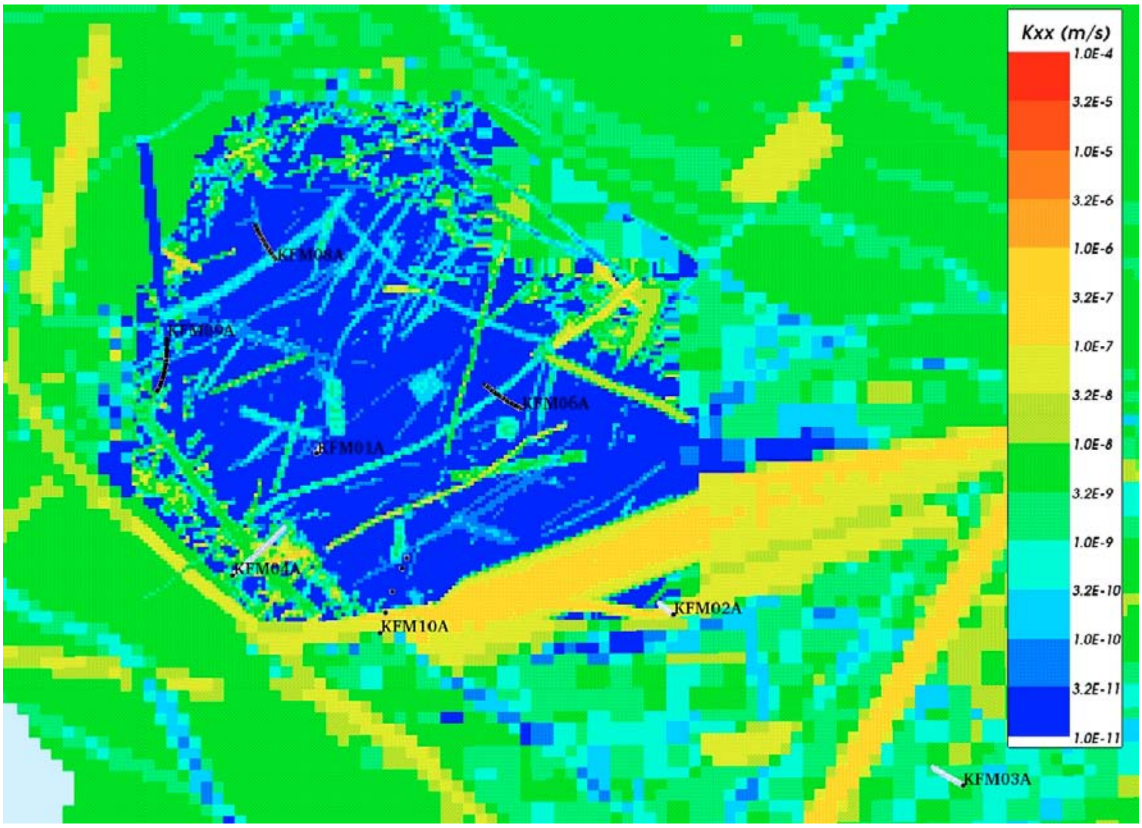


Figure 2-20. An example of the distribution of hydraulic conductivity for a realisation of the Equivalent Continuum Porous Medium model. A horizontal slice is shown at –450 m RHB 70. The hydraulic conductivity tensor is potentially anisotropic, but only the E-W diagonal component is shown here. Note the very low hydraulic conductivity values within the target area. /Figure 3-42 in Follin et al. 2007b/.

Table 2-13. Total transmissivity in the given intervals, 20 m horizontal sections.

Model	$<4\cdot10^{-9}$	$4\cdot10^{-9}$–$3\cdot10^{-8}$	$3\cdot10^{-8}$–$2\cdot10^{-7}$	$2\cdot10^{-7}$–$5\cdot10^{-7}$	$5\cdot10^{-7}$–$1\cdot10^{-6}$	$>1\cdot10^{-6}$
Corr	0.9128	0.0648	0.0224	0	0	0
Semi	0.9742	0.0208	0.0042	0.0004	0.0002	0.0002

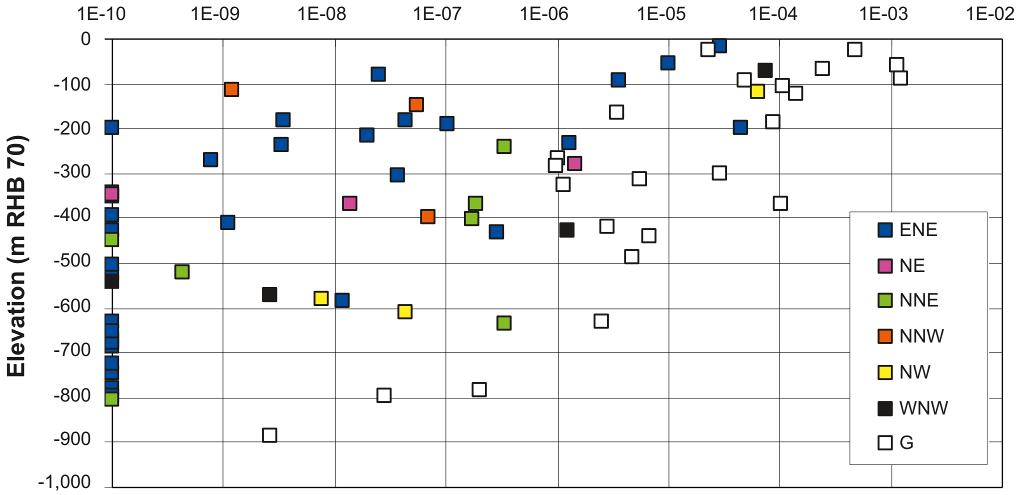
Table 2-14. Total transmissivity in the given intervals, 8 m vertical sections.

Model	$<4\cdot10^{-9}$	$4\cdot10^{-9}$–$3\cdot10^{-8}$	$3\cdot10^{-8}$–$2\cdot10^{-7}$	$2\cdot10^{-7}$–$5\cdot10^{-7}$	$5\cdot10^{-7}$–$1\cdot10^{-6}$	$>1\cdot10^{-6}$
Corr	0.94008	0.04088	0.01904	0	0	0
Semi	0.98456	0.01264	0.00232	0.00024	0	0.00024

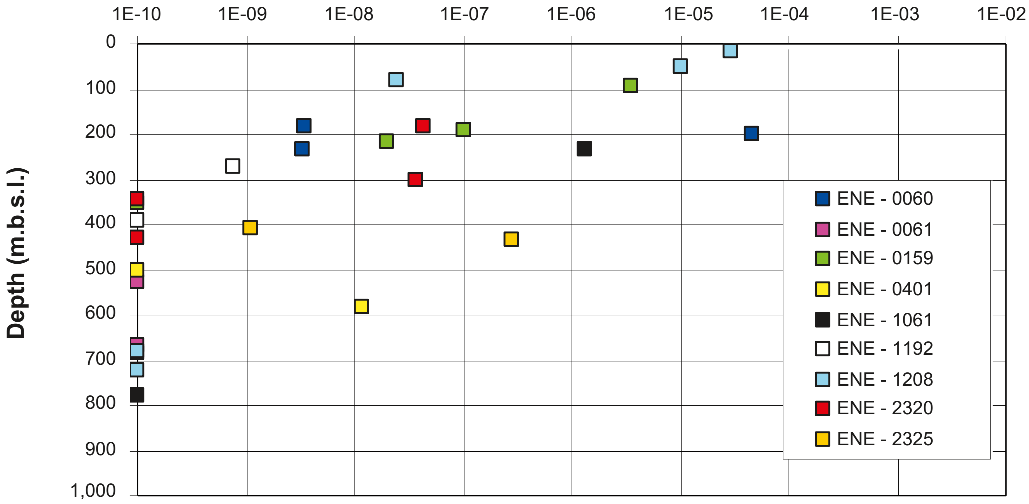
2.5.3 Deterministic deformation zones

Figure 2-21 presents measured deformation zone transmissivities. The gently dipping zones are much more transmissive than the steeply dipping zones, show a clear decrease of transmissivity with depth and show strong spatial variability. The depth trends are less obvious in the steeply dipping zones.

It need also be noted that the studied boreholes KFM01A–8A, -10A, -08C and -01D contain all together 21 borehole intervals interpreted as deformation zone intercepts but not modelled deterministically; that is, possible deformation zones. Possible deformation zones with little or no flow can occur at any depth. The flowing possible-deformation zones tend to be very discrete; with 1 or 2 flowing fractures. However, an exception occurs close to the ground surface where an approximately



a) All deformation zones



b) ENE striking steeply-dipping deformation zones

Figure 2-21. *Transmissivity values (x-axis, m²/s) versus depth for the deterministically modelled deformation zones. The transmissivities are coloured with regard to the orientations of the deformation zones, where G means gently dipping. The deformation zones with little or no flow are assigned an arbitrary low transmissivity value of $1 \cdot 10^{-10}$ m²/s in order to make them visible on the log scale. The gently (G) dipping zones (mainly zone A2) are much more transmissive than the steeply dipping zones, and show a clear decrease of transmissivity with depth. The depth trends are less obvious in the steeply dipping zones. /Figures 8-14 and 8-15 in SKB 2008/.*

15-m-thick possible deformation zone has 17 flowing fractures. According to /Follin et al. 2007a/ these “possible-deformation zones” are not a well defined feature, at least not from a hydrogeological or geological point of view.

Only four (4) transmissive possible deformation zones were encountered at repository depth in the target volume. They show up as single fractures and not as fracture networks in contrast to most of the possible deformation zones encountered in the uppermost part of the bedrock. Clearly, it is important to take the four possible deformation zones at repository depth in the target volume into account since there are practically no other flowing fractures nearby, but their lateral extent is unknown. This is achieved by incorporating these features in the Hydro-DFN model, but with the addition of a conditioning approach, which honours the position, orientation and transmissivity of each of the four possible deformation zones /Chapter 7 in Follin et al. 2007a/. However, there could be additional zones, not intersected by the current boreholes. In practice this means that the layout and design work could not beforehand adapt tunnel layouts to avoid these features.

2.6 Groundwater composition

Explorative analyses of measured groundwater chemistry data and hydrogeochemical modelling have been used to evaluate the hydrogeochemical conditions at the site in terms of the origin of the groundwater and the processes that control the water composition.

Data on groundwater composition show an increase in salinity down to a depth of about 200 m, Figure 2-22. Very high saline contents have been measured in boreholes KFM07A, KFM09A and KFM03A.

2.7 Summary

In this section a summary of the rock mass descriptions and properties have been provided based on the SDM-Site Forsmark and related documents. In all cases, the source of the data used to produce parameter values associated with that description has been provided. In Chapter 4, these data provide the basic input that was used to establish the ground engineering description.

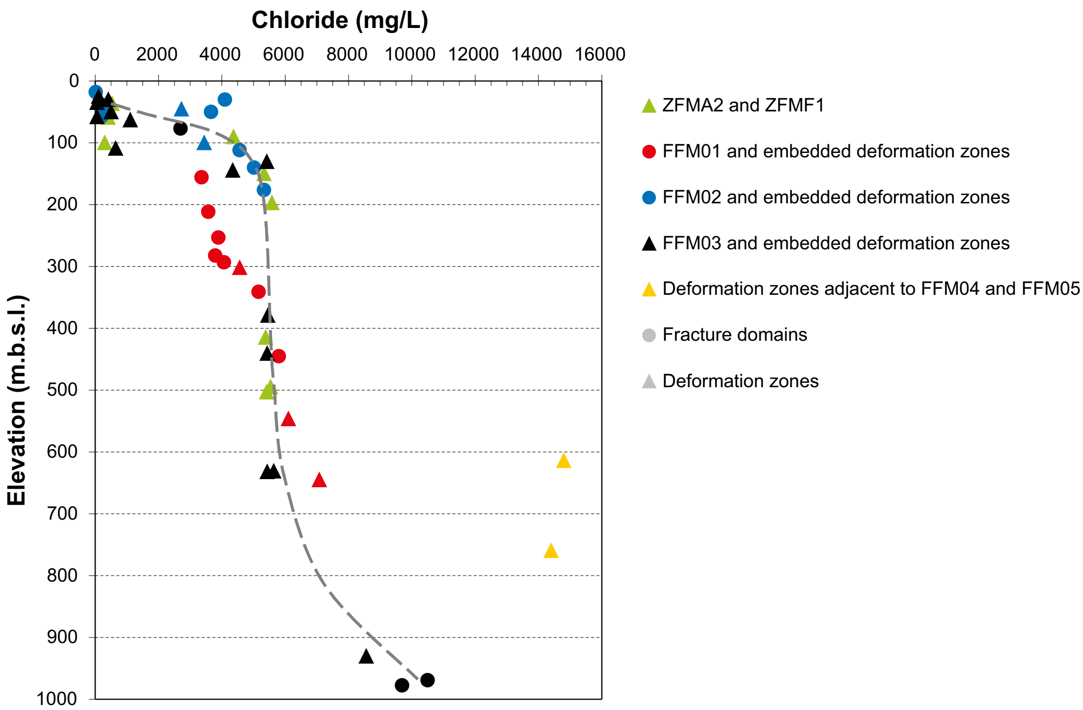


__Figure 2-22.__ Chloride concentration versus vertical depth. Data from different fracture domains are indicated by a colour code. Data representing conditions above and adjacent to the deformation zone A2 as well as from the southeast part of the candidate area are joined by a dashed grey line. (Figure 7-11 of SKB R-07-15).

3 Overview of Forsmark tunnelling experience

The construction experience from the Forsmark nuclear power plant and the SFR facility are summarized in /Carlsson and Christiansson 2007/. While the construction experience is restricted to depths between 0 and 140 m and took place outside the target volume, it is indicative of the construction conditions that could be encountered when excavating portions of the repository access tunnels, particularly those portions located in FFM02. At the depth of the repository and in FFM01, the rock mass conditions are expected to improve significantly as described in Chapter 2.

A brief summary of the major issues that arose during the construction of the SFR facility and the Forsmark Nuclear Power Plants are summarized below. Detailed information can be found in /Carlsson and Christiansson 2007/

3.1 Highly transmissive and gently dipping fracture zones

The occurrence of gentle dipping fractures in the superficial rock mass has been described by /Carlsson 1979/. This fracturing is to a large extent stress release fracturing closest to the surface. Some of these fractures are filled with sediments of glacial origin.

In addition, significantly transmissive gently dipping deformation zones were met in the discharge tunnel from units 1 and 2, as well as in the lower construction tunnel of the SFR. These structures were intersected at a depth (below sea level) of 65 m in unit 1 and 140 m in unit 2. In addition, the site investigations for the SFR drilled through a similar structure at approximately 40 m depth. The geological structure (fracture zone) at the bottom of the SFR has been described by /Carlsson and Christiansson 1987/. The horizontal fractures dip 10–15° and occur locally with very high frequency as a 'swarm or cluster'. Locally, vertical fractures also increase in frequency where these sub-horizontal "clusters" are intersected. The fracturing was locally rather high, displaying lenses with more or less crushed rock approximately 0.3–0.5 m thick and some meters in length. These lenses of crushed rock occurred step-wise (cf. Figure 3-1), being the irregular core of a deformation zone dipping approximately 25° towards SE. The nature of this kind of gently dipping deformation zone indicates an origin not related to the sub-horizontal stress release fracturing commonly found in the superficial rock mass at the Forsmark area. The extension of these gentle dipping deformation zones with depth is uncertain. Exploration drilling during construction of the SFR could not define the location of the lower deformation zone, maybe due to the possible heterogeneity of the structure, or simply because its extension with depth was limited.

The tunnelling through the gentle dipping fracture zones in the first discharge tunnel and in the SFR required a significant grouting program. At the SFR approximately 9,000 kg of cement was required for grouting approximately 40 m length of tunnel. This area is the part of the SFR facility that has the highest seepage even today. This is due to several reasons:

- There was no requirement to completely seal this part of the construction area, which is located below all operational areas.
- The significant difficulty associated with sealing a gently dipping fracture zone by pre-grouting from the tunnel.
- The complex layout at this lower part of the SFR with auxiliary tunnels for the drainage under the silo, a cavern for the deepest pump station and vertical shaft for the discharge of drained water and other installations.

The rock mass encountered, outside the major deformation zones, was blocky with vertical joint sets trending NW-SE and NE-SW, and a sub-horizontal set, Figure 3-2. In addition, a minor set dipping some 40–50° towards S-SE was observed occasionally. The fracture frequency was found to be relatively low in the tunnels, but in places not evenly distributed. The fractures within the dominant three sets often occur in clusters, forming minor deformation zones. Because of the extensive mineral precipitation in most of the fractures, these minor structures were not considered

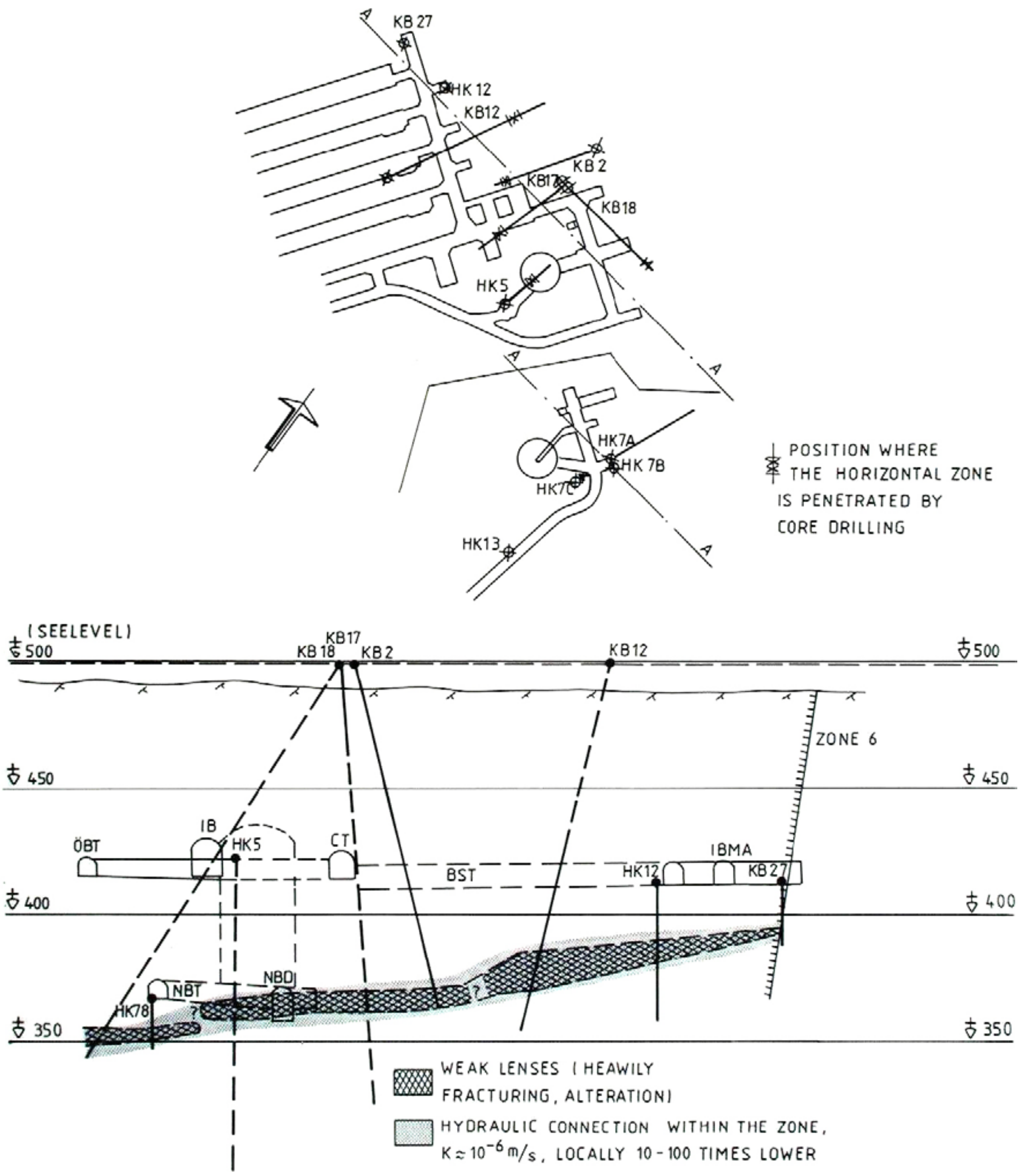


Figure 3-1. *Example of the deformation zone encountered during the construction of the SFR facility /Carlsson and Christiansson 1987/.*

significant for the construction of stable tunnels. There are two situations that generally required systematic bolting:

1. The occurrence of sub-horizontal fractures in the roof normally required systematic bolting. Overbreak in the crown and towards the abutments was commonly observed in this situation. The extension of the more pronounced cluster of sub-horizontal fractures was observed for example in the access tunnels to the SFR to have a length of >30–40 m.

2. Tunnel walls aligned parallel to the NE trending joint set also displayed overbreaks up to the abutment. This occurs also if there is a 5–20° difference in the trend of the tunnel wall and the fracturing, indicating that the resistance of the strength of the fracture is low to the stresses caused by the tunnelling. This joint set often displays calcite and laumontite infillings. Dripping water occurred only occasionally. The extension of these NE trending minor deformation zones could be followed for up to some 100 m in the deposition area of the SFR.

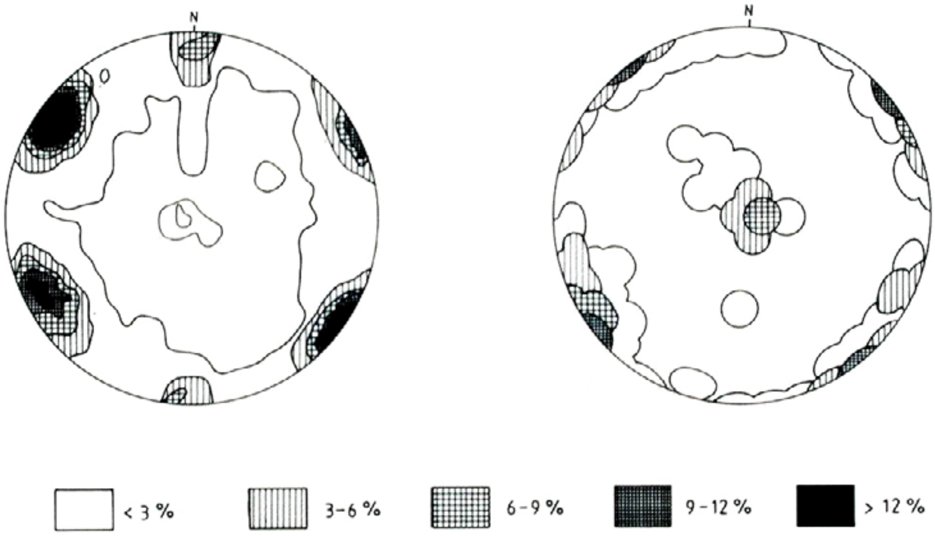


Figure 3-2. Lower hemisphere equal angle stereonets for fractures mapped in the foundation of Forsmark Unit 3 (left stereonet) and for fractures compiled from tunnel mapping in two 100-m-long orthogonal tunnels from the SFR facility at a depth between 50 and 70 m (right stereonet). (from Carlsson and Christiansson 1987).

3.2 Distribution of water bearing fractures

Outside the major deformation zones, the tunnel construction at the Forsmark site encountered rather dry, even at shallow depth, tunnelling conditions. In the upper 30–40 m of the superficial rock mass, the gentle dipping stress release fracturing contributed significantly to the seepage encountered. At larger depth all dominant fractures contributing to the seepage, especially when they form "clusters", could be defined as "minor deformation zones.

The distribution of all seeping fractures in the deposition and operational area of the SFR was evaluated /Figure 4-3 in Carlsson and Christiansson 1988/. The data included roughly 10,000 observed fractures in roofs and walls. Of the total population 6% was seeping water, the smallest observation was defined as "a spot of moisture, some dm^2 in area". In Figure 3-3 the largest seepage (2.5 l/min) originates from the minor deformation zone that cross-cuts all rock caverns and the operational

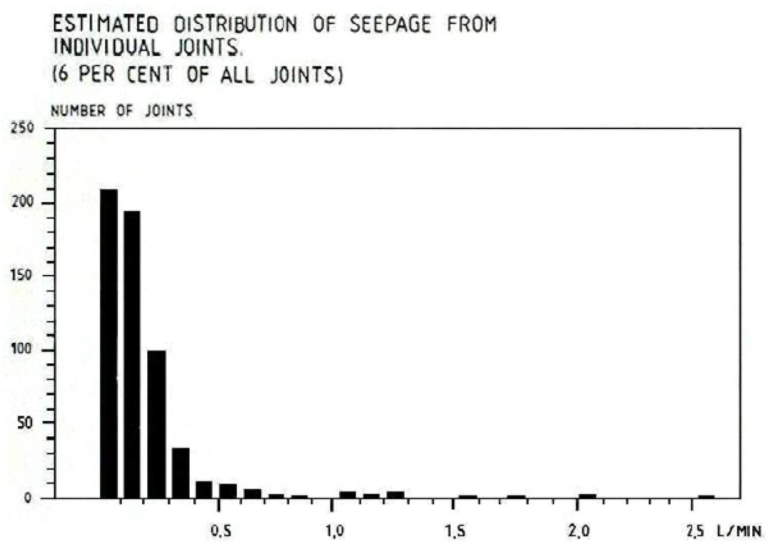


Figure 3-3. Distribution of the seepage from individual joints in the repository area measured during construction of the SFR facility. From /Carlsson and Christiansson 1988/.

tunnel, but not the construction tunnel. Selective grouting on that structure was done in one of the caverns. This was the only grouting carried out in the whole deposition and operational area of SFR. This measure probably had very little influence on overall distribution of seepage into the deposition and operational area of the SFR.

The measured inflows into the silo illustrate the low permeability of the rock mass even at this relatively shallow depth. This cavern has a diameter of 30 m and a height of 69 m with an excavated volume of 45,000 m^3. After excavation was completed, a total inflow of 1.4 l/min was measured at a temporary weir where the water coming into the silo discharged in to the lower construction tunnel. In addition, by measuring the humidity in the ventilation air going into and out of the silo it was estimated that the ventilation evacuated approximately 0.6 l/min, giving a total inflow of approximately 2 l/min.

The water seeping into the SFR outside the major deformation zones occurred primarily as spots of moisture and locally dripping water. The most predominant structures for seepage were:

- Areas where cluster of NE trending vertical fractures occur. This may be defined as minor deformation zones. The longest such structure was observed in the access tunnel to the silo roof, along the roof of the silo and further into the cavern for handling of the waste packages. The total observed length was 100 m, even though the fracture frequency was irregular over the observed distance. Spots of moisture and dripping water occurred.
- Areas where cluster of NW trending fractures occur. These cross most of the tunnels and caverns at high angles, so the length is difficult to estimate. But because these structures seldom could be traced from one rock cavern to another they are probably limited in length. The water occurred mainly as spots of moisture.
- Amphibolitic dykes that were schistose and had been strongly deformed. These dykes occur more or less as minor deformation zones. These dykes were limited to 1–2 dm in width and seldom exceeded 100 m in length. Water occurred as moisture/dripping along large stretches of the areas where the structure was intersected. These structures are sub-vertical and trend N-S to NW-SE in the SFR.

The improvement of air quality during the operation of the SFR facility has included measures to decrease the humidity underground. This may be one of the reasons for decreased total seepage into the facility, Figure 3-4.

Examination of the wet spots and seepage locations in the SFR today shows the type of structures that contributed to most of the seepage during construction. In other words the seepage locations at the end of construction are still visible today even though the total inflow is decreasing.

3.3 Stress conditions

The experiences of high stresses in underground works are limited from the Forsmark area. /Carlsson and Olsson 1982/ reported stress induced spalling in the roof of the discharge tunnel from unit 3 at shallow depths. This is related to a very limited rock cover over the tunnel, indicating significant stress concentrations, caused by the high horizontal stresses.

Significant construction problems due to high stresses were never experienced at the SFR. Only in the upper part of the lower construction tunnel when the tunnels was driven in a direction close to the orientation of the major horizontal stress was loosening up of the tunnel face experienced for some rounds. The tunnelling went through a body of pegmatite in that area.

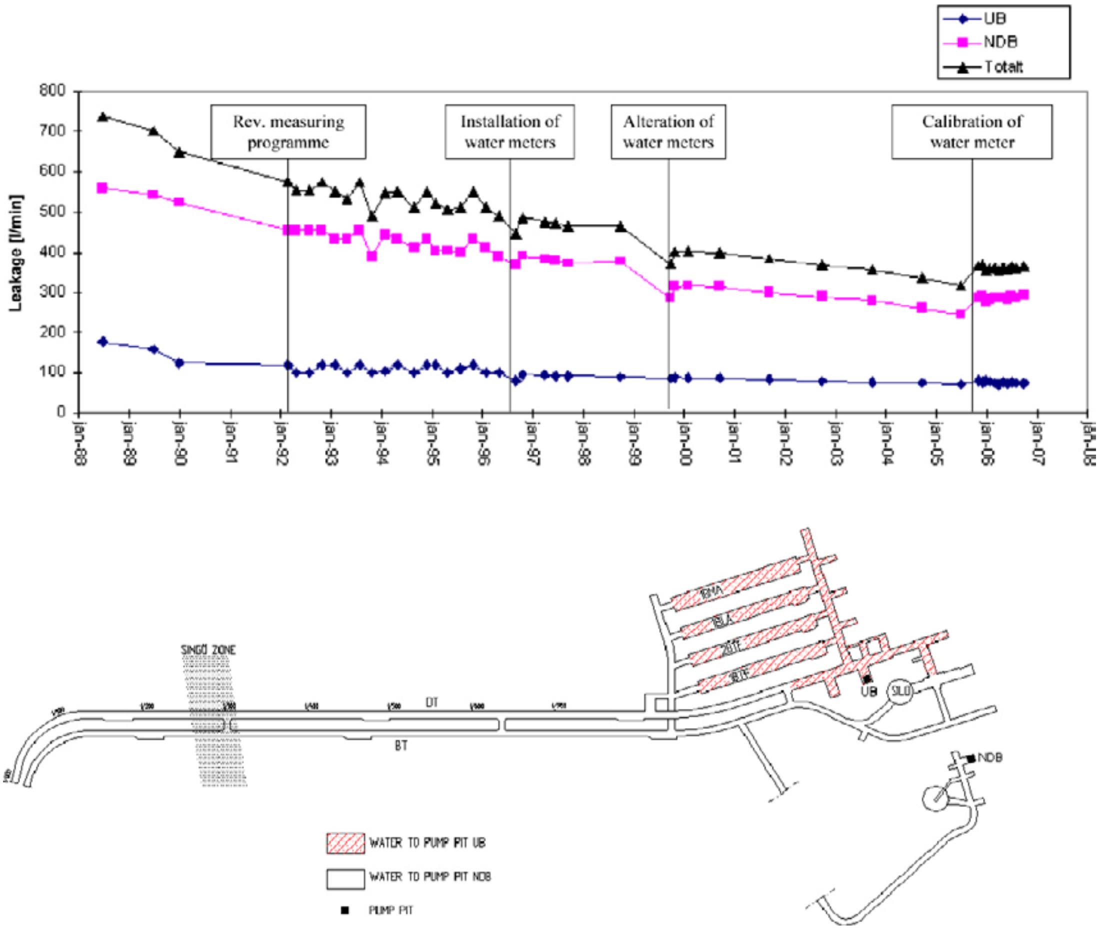


Figure 3-4. *A summary of the water inflow rates recorded at SFR.*

4 Ground types and behaviour, rock support and grouting

To apply the design methodology described by /Palmström and Stille 2006/ and outlined in Figure 1-4, the ground types (GT) and anticipated ground behaviour (GB) must be defined in design stage D2. In addition to the ground types and behaviour, design stage D2 will also require an estimate of ground support and grouting quantities.

To facilitate estimates for the ground support, support types (ST) are defined. These support types are based on the extensive underground construction experience in the Forsmark area, documented in the Construction experience report /Carlsson and Christiansson 2007/ and modern day construction experience in the Scandinavian shield. Likewise, grouting types (GRT) are also defined based on the construction experience at Forsmark and elsewhere. Because grouting technology has advanced significantly since the construction of the Forsmark facilities, the grouting types have been modified to incorporate those changes. The descriptions in this section shall be used by the designer for this design step.

4.1 Variability and uncertainty in key parameters

To assess the system behaviour, values must be assigned to key parameters that will be used in this assessment. There is no doubt that uncertainty and spatial variability exists in these values. The values assigned to each parameter are based on the data provided in SDM-Site Forsmark /SKB 2008/ as well as in the engineering judgement of the authors of this report. To establish the system behaviour, the designer is provided with what is judged to be the most likely value and a deterministic design based on this value may be adequate in most cases. However, in keeping with the philosophy of the Observational Method, a range of values that represent conceivable best and worst case conditions may also be provided. The range in values is provided when it is judged that a change in this value, may significantly impact the design. For example, the in situ stress magnitudes are difficult to estimate and can significantly impact the ground behaviour. Hence minimum and maximum stress values are provided in addition to the most likely value so that the impact in the range of values can be fully assessed. For such situations a probability based approach may be required to explore the likely outcome. Probability functions are usually not known for many of the design parameters and for such cases a triangular distribution may be assumed, truncated by a minimum and maximum value.

4.2 Ground types

The division of the rock mass into ground types starts with a description of the basic geology and proceeds by defining key geotechnical parameters for each ground type. The key parameters values and distributions are based on the data provided in Chapter 2, the SDM-Site Forsmark /SKB 2008/ and the authors engineering judgment. Table 4-1 provides a description of the four ground types (GT) that have been defined for design stage D2 and the properties for these ground types are given in the forms that follow Table 4-1. Table 4-2 provides an estimate of the expected distribution of ground types to be encountered in the deformation zones and the fracture domains.

GT1 represents the good quality rock mass suitable for the placement of deposition holes. The parameters used to describe the rock mass properties were compiled from SDM-Site Forsmark /SKB 2008/ using the values provided for competent rock. While joints are widely spaced in this ground type, joint properties are also provided. These properties were taken from laboratory tests but were scaled to the tunnel dimensions. As a result the properties, particularly the stiffness values have been reduced from those values provided in Table 2-7.

Table 4-1. Summary of the four ground types for design stage D2.

Ground type	Description
GT1a	Massive to sparsely fractured rock mass in RFM029 (FFM01).
GT1b	Massive to sparsely fractured rock mass in RFM045 (FFM06).
GT2	Blocky rock mass. Moderately fractured rock contains fractures and hairline cracks, but the blocks between joints are intimately interlocked. (FFM02).
GT3	Deformation zone containing sealed fracture network, fault breccias and cataclasite.
GT4	Regional deformation zone, containing fault breccias, crushed rock, sealed networks and cataclasite.

Table 4-2. Summary of expected distribution of ground types in the target volume.

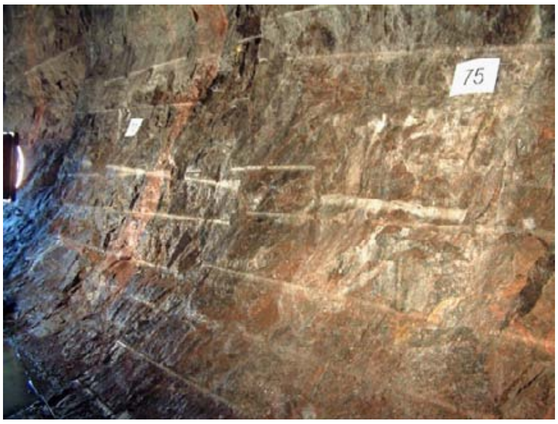
	Distribution of ground type (%)		
Description	**GT1**	**GT2**	**GT3**
Deformation zones			
ENE0060A	20	40	40
ENE0060A (respect distance)	80	20	
Gently dipping	–	100	–
Steeply dipping (<3 km)	20	40	40
Fracture domains (Deformation zones excluded)			
FFM02	85	15	
FFM01*	95	5	
FFM06*	95	5	

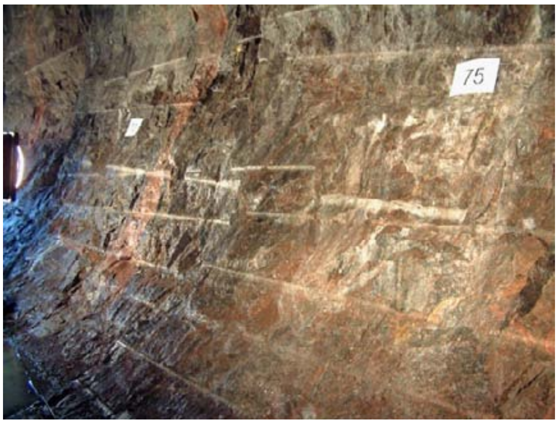
*This apply also for the boundaries of the Tectonic Lens at the repository level.

GT2 represents the blocky rock conditions that are likely to be encountered in FFM02. The mechanical and strength properties for this ground type are slightly reduced from those in GT1. Additionally, GT2 is also used to denote minor deformation zones, regardless of the fracture domain.

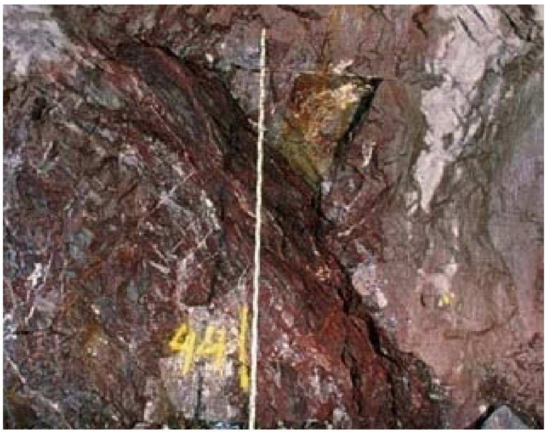
GT3 represents the sealed fracture network generally associated with the local major and minor deformation zones. Limited laboratory test results on sealed fracture networks indicate almost similar deformation and strength properties as intact rock found in GT1. However, it is likely that at the tunnel scale, the alteration commonly associated with sealed fracture networks and the increased frequency of sealed fractures will result in decreased stiffness and strength. Engineering judgement has been used to assign properties.

GT4 represents the regional deformation zones. The mechanical and strength properties of this ground type have been taken from /Glamheden et al. 2007a/. It is very difficult to determine mechanical and strength properties from borehole data for such large scale highly heterogeneous features. The values taken from /Glamheden et al. 2007a/ were back calculated from measured deformations and hence represent a tunnel scale best estimate.

<table>
<tr><td colspan="6">Ground type: GT1a – Massive to sparsely fractured rock mass</td></tr>
<tr><td>Description</td><td colspan="5">Lithology: RFM029
Dominant rock type: medium-grained granite to granodiorite (c. 75% domain volume).
Subordinate rock types: fine- to medium-grained metagranodiorite or metatonalite, amphibolite, pegmatitic granite or pegmatite, and fine- to medium-grained granite.</td></tr>
<tr><td rowspan="4">Indicators</td><td>Fracture/anisotropy:</td><td colspan="4">Sparsely fractured to massive / isotropic</td></tr>
<tr><td>Block Size:</td><td colspan="4">>1.5 m</td></tr>
<tr><td>Joint persistence:</td><td colspan="4">Low</td></tr>
<tr><td>Large scale hydraulic conductivity</td><td colspan="4">Approaches that of intact rock
1 10^{-12} to 1 10^{-10} m/s</td></tr>
<tr><td>Intact Rock – Lab</td><td>UCS =230 MPa,
Crack Initation =120 MPa</td><td>Tensile Strength
14 MPa</td><td colspan="2">Young's Modulus
75 GPa</td><td>Poisson's ratio
0.23</td></tr>
<tr><td rowspan="3">Joints</td><td colspan="3">Cohesion = 0.5 MPa</td><td colspan="2">Friction angle = 34°, dilation angle= 10°</td></tr>
<tr><td colspan="3">Normal Stiffness = 500 MPa/mm</td><td colspan="2">Shear stiffness = 100 MPa/mm</td></tr>
<tr><td colspan="5">Infilling: Low temperature precipitation minerals such as calcite and chlorite occurs commonly</td></tr>
<tr><td>Thermal</td><td colspan="5">See Table 2-2 for thermal properties</td></tr>
<tr><td rowspan="3">Unsupported behaviour indicators</td><td colspan="5">Stress: Far-field maximum stress <0.15 UCS, Gravity controlled block failure may occur locally
Maximum tangential stress on boundary of opening >120 MPa, Local spalling should be expected.</td></tr>
<tr><td colspan="5">Structure: Joints can cluster to form minor deformation zones of limited extent</td></tr>
<tr><td colspan="5">Water: Inflows can occur as minor seepage along individual joints. $T<10^{-8}$ m^2/s</td></tr>
<tr><td rowspan="3">Tunnel scale properties (Empirical systems)</td><td>GSI = 85–95</td><td>RMR = 85–95</td><td colspan="2">Q = >100</td><td>Em = 60 GPa, ν = 0.23</td></tr>
<tr><td colspan="5">Hoek-Brown: UCS=230 MPa, mi = 27, mb = 18.5, s = 0.317, D=0</td></tr>
<tr><td colspan="5">Mohr-Coulomb: Cohesion = 15 MPa, Friction angle = 60°, Tensile strength = 3.8 MPa</td></tr>
<tr><td colspan="6">Photo or sketch</td></tr>
<tr><td colspan="3"></td><td colspan="3">Example of good wall quality in a 5-m-diameter tunnel excavated by drill and-blast in massive to sparsely fracture rock mass. Note the half-barrels on the perimeter profile.</td></tr>
<tr><td>Uncertainties</td><td colspan="5">Secondary horizontal jointing, frequency dependent on depth.</td></tr>
</table>

<table>
<tr><td colspan="6">Ground type: GT1b – Massive to sparsely fractured rock mass</td></tr>
<tr><td>Description</td><td colspan="5">Lithology: RFM045
Dominant rock type: fine grained Granite, metamorphic, aplitic (49%). Subordinate rock type(s): Granite to granodiorite, metamorphic (18%), Pegmatite, pegmatitic granite (14%), Granitoid, metamorphic, fine- to medium-grained (9%), Amphibolite (6%), Granite, fine- to medium-grained (1%), Felsic to intermediate metavolcanic rock (1%).</td></tr>
<tr><td rowspan="4">Indicators</td><td>Fracture/anisotropy:</td><td colspan="4">Sparsely fractured to massive / isotropic</td></tr>
<tr><td>Block Size:</td><td colspan="4">>1.5 m</td></tr>
<tr><td>Joint persistence:</td><td colspan="4">Low</td></tr>
<tr><td>Large scale hydraulic conductivity</td><td colspan="4">Approaches that of intact rock
1 10^{-12} to 1 10^{-10} m/s</td></tr>
<tr><td>Intact Rock – Lab</td><td>UCS =310 MPa,
Crack Initiation =169 MPa</td><td colspan="2">Tensile Strength
18 MPa</td><td>Young's Modulus
82 GPa</td><td>Poisson's ratio
0.27</td></tr>
<tr><td rowspan="3">Joints</td><td colspan="3">Cohesion = 0.5 MPa</td><td colspan="2">Friction angle = 34°, dilation angle= 10°</td></tr>
<tr><td colspan="3">Normal Stiffness = 500 MPa/mm</td><td colspan="2">Shear stiffness = 100 MPa/mm</td></tr>
<tr><td colspan="5">Infilling: Low temperature precipitation minerals such as calcite and chlorite occurs commonly</td></tr>
<tr><td>Thermal</td><td colspan="5">See Table 2-2 for thermal properties</td></tr>
<tr><td rowspan="3">Unsupported behaviour indicators</td><td colspan="5">Stress: Far-field maximum stress <0.15 UCS, Gravity controlled block failure may occur locally.
Maximum tangential stress on boundary of opening >170 MPa, Local spalling should be expected.</td></tr>
<tr><td colspan="5">Structure: Joints can cluster to form minor deformation zones of limited extent.</td></tr>
<tr><td colspan="5">Water: Inflows can occur as minor seepage along individual joints. $T<10^{-8}$ m^2/s.</td></tr>
<tr><td rowspan="3">Tunnel scale properties (Empirical systems)</td><td>GSI = >90</td><td>RMR = >90</td><td>Q = >100</td><td colspan="2">Em = 70 GPa, ν = 0.23</td></tr>
<tr><td colspan="5">Hoek-Brown: UCS=310 MPa, mi = 27, mb = 18.5, s = 0.317, D=0</td></tr>
<tr><td colspan="5">Mohr-Coulomb: Cohesion = 15 MPa, Friction angle = 60°, Tensile strength = 3.8 MPa</td></tr>
<tr><td colspan="6">Photo or sketch</td></tr>
<tr><td colspan="2"></td><td colspan="4">Example of good wall quality in a 5-m-diameter tunnel excavated by drill and-blast in massive to sparsely fracture rock mass. Note the half-barrels on the perimeter profile.</td></tr>
<tr><td>Uncertainties</td><td colspan="5">Secondary horizontal jointing, frequency dependent on depth</td></tr>
</table>

<table>
<tr><td colspan="5">Ground type: GT2 – Blocky rock mass</td></tr>
<tr><td>Description</td><td colspan="4">Lithology: RFM029</td></tr>
<tr><td rowspan="4">Indicators</td><td>Fracture/anisotropy:</td><td colspan="3">Blocky rock mass, 2 to 3 joint sets and 1 random set</td></tr>
<tr><td>Block Size:</td><td colspan="3">0.5< between >1.5 m</td></tr>
<tr><td>Joint persistence:</td><td colspan="3">Low to moderate</td></tr>
<tr><td>Large scale hydraulic conductivity</td><td colspan="3">Blocky rock: $1\ 10^{-10}$ to $1\ 10^{-9}$ m/s
Minor deformation zones: $1\ 10^{-8}$ to $1\ 10^{-5}$ m/s</td></tr>
<tr><td>Intact Rock – Lab</td><td>UCS =230 MPa,
Crack Initiation=120 MPa</td><td>Tensile Strength
14 MPa</td><td>Young's Modulus
75 GPa</td><td>Poisson's ratio
0.23</td></tr>
<tr><td rowspan="3">Joints</td><td colspan="2">Cohesion = 0.5 MPa</td><td colspan="2">Friction angle = 34°, dilation angle= 10°</td></tr>
<tr><td colspan="2">Normal Stiffness = 500 MPa/mm</td><td colspan="2">Shear stiffness = 100 MPa/mm</td></tr>
<tr><td colspan="4">Infilling: Low temperature precipitation minerals such as calcite, chlorite and laumontite occurs commonly. Open fractures may occur</td></tr>
<tr><td rowspan="3">Unsupported behaviour indicators</td><td colspan="4">Stress: Far-field maximum stress <0.15 UCS, Gravity controlled block failure may occur locally
Maximum tangential stress on boundary of opening >120 MPa, Local spalling should be expected.</td></tr>
<tr><td colspan="4">Structure: Joints can cluster to form minor sub-horizontal deformation zones of limited extent</td></tr>
<tr><td colspan="4">Water: Inflows can occur as minor seepage along individual joints. $T<10^{-8}$ m²/s
Along steeply dipping minor deformation zones inflow occurs occasionally $T<10^{-7}$ m²/s
Along minor sub-horizontal deformation zones inflows can be significant
$T\leq10^{-5}$ m²/s</td></tr>
<tr><td rowspan="3">Tunnel scale properties (Empirical systems)</td><td>GSI = 80–90</td><td>RMR = 80–90</td><td>Q = 40–100</td><td>Em = 50 GPa, ν = 0.3</td></tr>
<tr><td colspan="4">Hoek-Brown: UCS=230 MPa, mi = 30, mb = 17.6, s = 0.189, D=0</td></tr>
<tr><td colspan="4">Mohr-Coulomb: Cohesion = 15 MPa, Friction angle = 55°, Tensile strength = 2 MPa</td></tr>
<tr><td colspan="5">Photo or sketch</td></tr>
<tr><td colspan="2"></td><td colspan="3">Example of the sidewall quality observed in a drill-and-blast tunnel in a blocky rock mass.</td></tr>
<tr><td>Uncertainties</td><td colspan="4">Frequency of sub-horizontal and sub-vertical minor deformation zones at the depth of the repository</td></tr>
</table>

<table>
<tr><td colspan="6">Ground type: GT3 – Sealed Fracture network(Deformation zones <3 km))</td></tr>
<tr><td>Description</td><td colspan="5">Lithology:
RFM029 or RFM045</td></tr>
<tr><td rowspan="4">Indicators</td><td>Fracture/anisotropy:</td><td colspan="4">Sealed fracture network, blocky rock mass if fractures open</td></tr>
<tr><td>Block Size:</td><td colspan="4">0.5< between>1.5 m</td></tr>
<tr><td>Joint persistence:</td><td colspan="4">Low to moderate</td></tr>
<tr><td>Large scale hydraulic conductivity</td><td colspan="4">HRD: 1 10^{-10} to 1 10^{-9} m/s</td></tr>
<tr><td>Intact Rock (Estimated)</td><td>UCS =150 MPa,
Crack Initiation =80 MPa</td><td>Tensile Strength
5 MPa</td><td>Young's Modulus
50 GPa</td><td colspan="2">Poisson's ratio
0.23</td></tr>
<tr><td rowspan="3">Joints</td><td colspan="2">Cohesion = 0.5 MPa</td><td colspan="3">Friction angle = 34°, dilation angle= 10°</td></tr>
<tr><td colspan="2">Normal Stiffness = 100 MPa/mm</td><td colspan="3">Shear stiffness = 30 MPa/mm</td></tr>
<tr><td colspan="5">Infilling: Adularia, laumontite</td></tr>
<tr><td rowspan="3">Unsupported behaviour indicators</td><td colspan="5">Stress: Far-field maximum stress <0.15 UCS, Gravity controlled block failure may occur locally
Maximum tangential stress on boundary of opening >80 MPa, Spalling/crushing should be expected.</td></tr>
<tr><td colspan="5">Structure: System of sealed fractures that may be susceptible to blast induced damage. This is particularly noticeable when tunnels are excavated parallel to the deformation zone. These zones typically show significant red alteration</td></tr>
<tr><td colspan="5">Water: Inflows can occur as minor seepage along individual joints. T<10^{-7} m^2/s
Along steeply dipping minor deformation zones inflow occurs occasionally with T<10^{-7} m^2/s</td></tr>
<tr><td rowspan="3">Tunnel scale properties (Empirical systems)</td><td>GSI = 75–85</td><td>RMR = 75–85</td><td>Q = 10–40</td><td colspan="2">Em = 35 GPa, v = 0.3</td></tr>
<tr><td colspan="5">Hoek-Brown: UCS=150 MPa, mi = 25, mb = 12.2, s = 0.108, D=0</td></tr>
<tr><td colspan="5">Mohr-Coulomb: Cohesion = 10 MPa, Friction angle = 45°, Tensile strength = 1.3 MPa</td></tr>
<tr><td colspan="6">Photo or sketch</td></tr>
<tr><td colspan="3"></td><td colspan="3">Appearance of a sealed fracture network in a drill core (photo above) and in the sidewall of the Forsmark tunnels (left photo).
</td></tr>
<tr><td>Uncertainties</td><td colspan="5">Intense fracturing may lead to zones which are relatively weak with few open fractures.</td></tr>
</table>

<table>
<tr><td colspan="5">Ground type: GT4 – Major deformation zones (>3 km)</td></tr>
<tr><td>Description</td><td colspan="4">All rock types</td></tr>
<tr><td rowspan="4">Indicators</td><td>Fracture/anisotropy:</td><td colspan="3">Regional Deformation Zone – Heterogeneous fracturing with both opened and sealed fractures, including sealed fracture network, fault breccias and crushed rock</td></tr>
<tr><td>Block Size:</td><td colspan="3">dm< between >1 m</td></tr>
<tr><td>Joint persistence:</td><td colspan="3">Continuous</td></tr>
<tr><td>Large scale hydraulic conductivity</td><td colspan="3">1 10^{-8} to 1 10^{-5} m/s</td></tr>
<tr><td>Intact Rock (Estimated)</td><td>UCS =150 MPa,
Crack Initiation =80 MPa</td><td>Tensile Strength
1 MPa</td><td>Young's Modulus
40 GPa</td><td>Poisson's ratio
0.23</td></tr>
<tr><td rowspan="3">Joints</td><td colspan="2">Cohesion = 0.5 MPa</td><td colspan="2">Friction angle = 34°, dilation angle= 10°</td></tr>
<tr><td colspan="2">Normal Stiffness = 100 MPa/mm</td><td colspan="2">Shear stiffness = 25 MPa/mm</td></tr>
<tr><td colspan="4">Infilling: Joints likely to have clay coating</td></tr>
<tr><td rowspan="3">Unsupported behaviour indicators</td><td colspan="4">Stress: Far-field maximum stress <0.15 UCS, Gravity controlled block failure may occur locally
Maximum tangential stress on boundary of opening >80 MPa, Spalling/crushing should be expected.</td></tr>
<tr><td colspan="4">Structure: System of sealed and open fractures that may be susceptible to blast induced damage</td></tr>
<tr><td colspan="4">Water: Inflows can be large if open fracture encountered. T ≤10^{-4} m^2/s</td></tr>
<tr><td rowspan="3">Tunnel scale properties (Empirical systems)</td><td>GSI = 70–80</td><td>RMR = 70–80</td><td>Q = 4–20</td><td>Em = 35 GPa, ν = 0.3</td></tr>
<tr><td colspan="4">Hoek-Brown: UCS=150 MPa, mi = 25, mb = 12.2, s = 0.108, D=0</td></tr>
<tr><td colspan="4">Mohr-Coulomb: Cohesion = 4 MPa, Friction angle = 45°, Tensile strength = 1. MPa</td></tr>
<tr><td colspan="5">Photo or sketch</td></tr>
<tr><td colspan="5">
Typical deformation zone observed in the core from borehole KFM06A in Forsmark</td></tr>
<tr><td>Uncertainties</td><td colspan="4">Fault gouge has not been noted in the regional deformation zones in the Forsmark target volume.</td></tr>
</table>

4.3 Ground behaviour

/Palmström and Stille 2006/ provide three general categories of ground behaviour commonly observed in hard rocks Table 4-3 and /Martin 2005/ provides a detailed description of the hard rock behaviour referred to as stress-induced spalling. The categories of ground behaviour given in Table 4-3 should be used to assess the system behaviour.

4.4 Support types

The support types are based on modern construction practice in the Scandinavian shield. For this design stage D2, 5 tunnel support types (ST1 through ST5) and 1 cavern support type (STC) are provided (Table 4-4). The bolt type, spacing and length, and shotcrete thickness are not provided as part of the support types. That decision remains with the designer when all the functional requirements and influence factors are considered.

Table 4-3. General categories for ground behaviour (GB). Modified from /Palmström and Stille 2006/.

GB1	Gravity driven, mostly discontinuity controlled failures (block falls), where pre-existing fragments or blocks in the roof and sidewalls become free to move once the excavation is made.	
GB2	Stress induced, gravity assisted failures caused by overstressing, i.e. the stresses developed in the ground reaching the local strength of the material. These failures may occur in two main forms, namely:	
	GB2A	as spalling, buckling or rock burst in materials with brittle properties, i.e. massive brittle rocks;
	GB2B	as plastic deformation, creep, or squeezing in materials having ductile or deformable properties, i.e. massive, soft/ductile rocks or particulate materials (soils and heavy jointed rocks).
GB3	Water pressure; an important load to consider in design especially in heterogeneous rock conditions.	
	GB3A	Groundwater initiated failures may cause flowing ground in particulate materials exposed to large quantities of water, and trigger unstable conditions (e.g. swelling, slaking, etc.) in some rocks containing special minerals. Water may also dissolve minerals like calcite in limestone.
	GB3B	Water may also influence block falls, as it may lower the shear strength of unfavourable joint surfaces, especially those with a soft filling or coating.

Table 4-4. Summary of support types to be used in design stage D2.

Support type:	Description
ST1	Spot bolts, Example: ground type 1, ground behaviour 1
ST2	Systematic bolting, ground types 1 and 2 Example: ground behaviour 1 and ground behaviour 2A
ST3	Systematic bolting plus wire mesh Example: ground types 1 and 2 Example: ground behaviour 1
ST4	Systematic bolting plus fibre-reinforced shotcrete Example: ground types 1, 2 and 3 Example: ground behaviour 1 and 2B
ST5	Concrete lining Example: ground type 4 Example: ground behaviour 3
Caverns STC	Systematic bolting plus fibre-reinforced shotcrete All ground types suitable for central area caverns Example: ground behaviour 1 and 2

4.5 Grouting

The need for construction grouting at Forsmark will vary significantly as the hydraulic properties of the rock mass varies from large volumes of intact rock to that of discrete open fractures connected to a constant head (Baltic Sea). These were also the conditions encountered during the construction of the underground excavation associated with the Forsmark nuclear power plants and SFR Facility /Carlsson and Christiansson 2007/.

For the current design stage D2, 3 grouting types (GRT1 through GRT3) are provided and this number is considered sufficient to meet the design requirements (Table 4-5). The parameters that define each grouting type, e.g. number of holes, spacing, number of stages, and the type of grouting material are not provided. Those parameters must be chosen by the designer to meet the grouting criteria specified in Table 5-1, 6-1 and 7-1 for each of the functional areas. The grouting requirements at Forsmark will vary depending on the fracture domain being traversed by the underground excavations and the functional requirements. For example in Fracture Domain FFM01, no systematic grouting is anticipated but sub-vertical minor deformation zones may be encountered which will require grouting. However, excavations in fracture domain FFM02 are expected to encounter a wide range of hydrogeological conditions and hence extensive grouting may be required locally to meet the seepage requirements.

The hydrogeological conditions expected in each of the functional areas are described in Table 4-6. It should also be noted that the flowing fracture frequency could be used to estimate the number of flowing features along a certain tunnel distance (Dist). At least approximately this number follows a Poisson distribution with mean Dist·P10PFL. This means that in FFM02 there is an average of about 30 flowing fractures per 100 m tunnel and in FFM01 there are about 15 flowing fractures between 100–200 m depth per100 m tunnel, about 4.5 between 200–400 m depth per 100 m tunnel and about 0.6 flowing fractures below 400 m depth per 100 m tunnel. Whereas the transmissivity distribution of individual fractures, based on the PFL-data, is essentially the same in all domains and depths, the frequency of flowing fractures drops dramatically with depth. Based on this information the designer must evaluate if the predicted inflows exceeds the seepage requirements. If grouting must be carried out, the designer must specify the parameters for the grout type that will achieve the required seepage. The seepage limits are specified in the Design Premises Document for D2. The methodology that shall be used to estimate the grout quantities required to meet the seepage limits is given by /Emmelin et al. 2007/.

The grout-hole lengths, number of holes, spacing, pressures, and grouting material are not provided as part of the grouting types. That decision remains with the designer when all the functional requirements and influence factors are considered. It is anticipated that the execution of grouting works will be carried out using the Observational Design Method.

Table 4-5. Summary of grouting types to be used in design stage D2.

Grouting type	Description
GRT1	Discrete fracture grouting
GRT2	Systematic tunnel grouting
GRT3	Control of large inflows and high pressure

Table 4-6. Transmissivity of individual fractures and their distribution with depth determined from PFL-f measurements (based on the tables and text provided in Section 2.5).

Depth (m)	Transmissivity (m^2/s) of individual water bearing fractures (in log scale) min, mean, max, StDev.	Water bearing Fracture frequency fractures/m
0–100 m FFM02	min=–6 mean= –4.5 max=–3 StDev = 3	0.306/m
100–200 m FFM02	min=–9.61 mean= –8.02 max=–5.14 StDev = 1.0	0.306/m
100–200 m FFM01	min=–9.61 mean= –7.84 max=–4.33 StDev = 1.28	0.152/m
200–400 m FFM01	min=–9.57 mean=–8.51 max=–6.74 StDev =0.88	0.042/m
Below 400 m FFM01	min=–9.21 mean= –8.19 max=–7.05 StDev = 0.66	0.005/m
FFM06	same as FFM01	same as FFM01

4.6 Monitoring and documenting the performance of underground excavations

In Section 1.4 it was noted that the Observational Method shall be used as a key component in the design of the underground excavations. As listed in Section 1.4, one of the steps in the Observational Method is to develop a monitoring plan which can be used to assess whether the actual ground system behaviour lies within the acceptable limits of the predicted behaviour. By monitoring the key elements of the system, the observed system behaviour during construction can be compared with the predicted system behaviour. In order to make this assessment a monitoring and documentation plan will be required. The basic elements of that monitoring/documenting plan are described below and are focused on providing the designers with sufficient information to make the assessment. For design stage D2, the Designer shall propose a monitoring plan for each functional area. These plans should address the uncertainty in the design assumptions, particularly where the consequences of this uncertainty may significantly impact the design and/or performance of the project /SKB 2007/.

Prior to the start of any excavation an assessment will be made of the adequacy of available geological and geotechnical information to predict the underground system behaviour. It is anticipated that cored probe-hole drilling will be required for all excavations and that this information will form the bases for the predicted system behaviour following the general flow chart logic given in Figure 1-4. Once the excavation commences the following steps shall be carried out and will form the bases for assessing the underground system behaviour during construction.

1. **Determine the ground type encountered**
   Geological documentation during construction must record sufficient information that the ground types can be readily established. The three-dimensional spatial description of the excavated profile, lithology, open fractures and inflows shall be documented.
2. **Determine the actual ground type Behaviour**
   The types of anticipated ground behaviour are listed in Table 3-2. The observations during excavation, must document the ground behaviours encountered and their spatial location.

3. **Determine the adequacy of the support type**
   Prior to the start of construction, support classes will be determined and specified in the baseline construction plan. Documentation during construction must adequately record the support types used in the support classes and their spatial locations. The adequacy of the support types must be assessed in a formal manner. For example convergence monitoring should be carried out and used to aid in assessing the adequacy of the support type. Even if no support type is specified convergence monitoring shall be carried out to show that support is not required, i.e. the ground behaviour is elastic.
4. **Determine the adequacy of the grouting type**
   Grouting classes will be determined and specified in the baseline construction plan. Documentation during construction must adequately record the grout types used and their spatial locations. Monitoring of tunnel inflows must be carried out to demonstrate that the grout type is effective in meeting the specified seepage requirements. Monitoring of tunnel inflows will also be required in areas where no grouting is specified to ensure that the specified seepage limits are met.

In addition to monitoring the seepage, the chemistry of the inflows shall also be monitored. This will be used to aid in evaluating the support types for long-term performance.

5. **Verification of system behaviour**
   When differences between the observed and predicted system behaviour occur, the parameters and criteria used have to be reviewed. When the displacements, support utilization or grout takes are higher than predicted, a detailed investigation into the reasons for the different system behaviour has to be carried out, and if required the design may be modified or the basis for support and/or grouting classes must be changed. In case the system behaviour is better than expected, the reasons for this difference must also be analyzed, and the findings used to update future predictions.

The frequency of a formal evaluation of the system behaviour will depend on the complexity of the geological environment. At Forsmark it is anticipated that the formal evaluation of the system behaviour will be carried out for each of the functional areas and for each of the ground types in these functional areas. In addition the intersection of minor and major deformation zones will also require a formal evaluation.

It should be noted that in addition to the monitoring elements described above there may be additional monitoring required as part of the detailed site characterisation program and as part of the contractor's method statements and QA/QC related to the construction works. Those monitoring requirements are not considered part of the Observational Method for underground design. For example, the in situ stress is an essential parameter needed for the evaluation of the system behaviour. In situ stress will be one of the parameters measured as part of the detailed site characterisation program prior to and during construction and is therefore not considered a parameter for construction monitoring.

5 Repository access

5.1 Location

Surface location will be specified by SKB. The access to the repository will be arranged via vertical shafts and an inclined ramp. Based on the layout defined by SKB, the main access areas will be in the area between KFM01A and KFM07A, i.e. in fracture domain FFM02 within RFM029. Cross sections through the target volume that shows the rock and fracture domains are shown in Figure 5-1 and Figure 5-2.

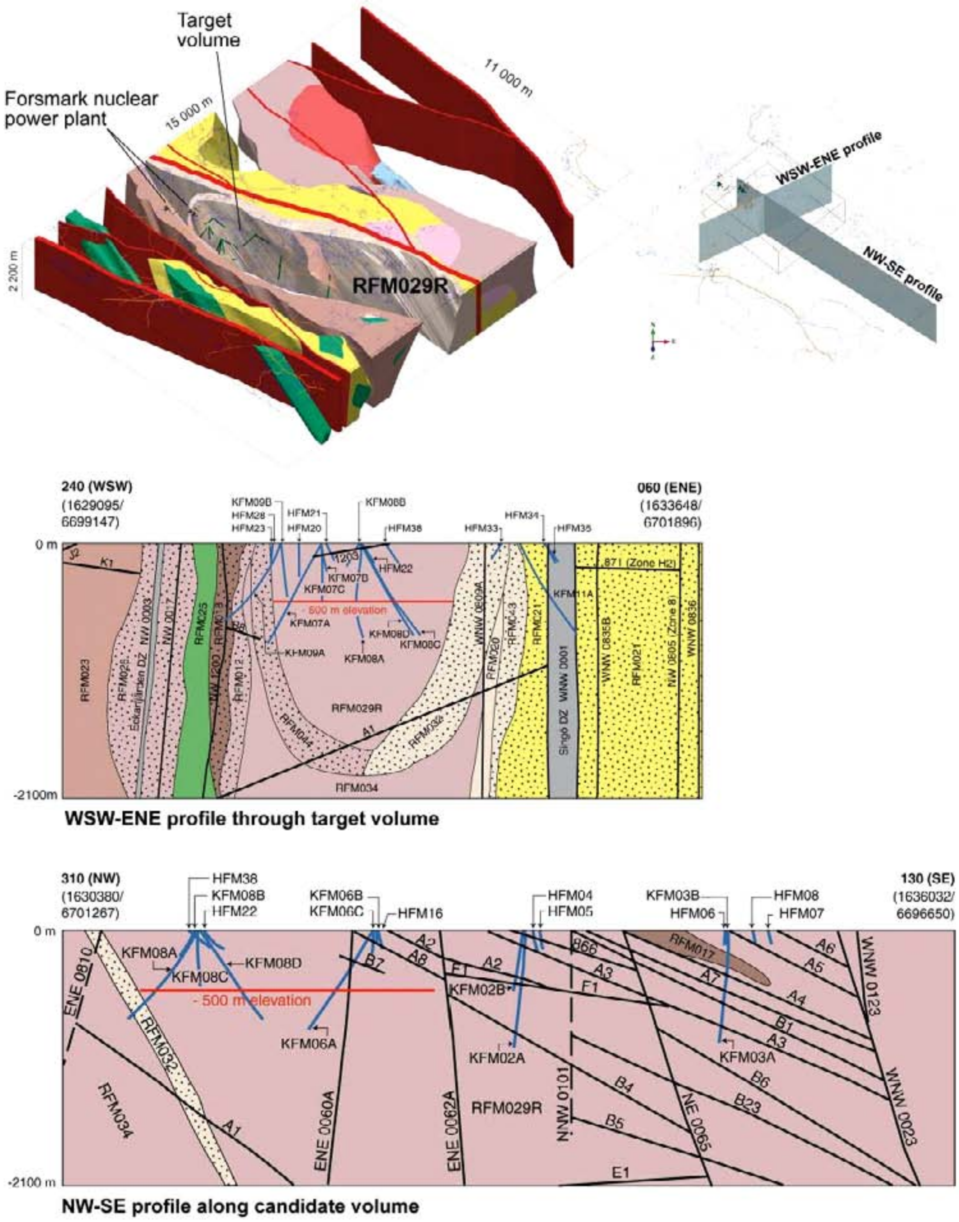


Figure 5-1. Integrated geological model for rock domains and deformation zones at the Forsmark site in a regional model scale perspective. The colours represent the dominant rock type in each rock domain. Regional deformation zones are marked in dark red (3D image) or grey (profiles). Other deformation zones in the profiles are marked as black lines. Dotted ornament in the profiles indicates bedrock with high ductile strain. The profile planes are shown in the small inset. /Figure 5-41 in SKB 2008/.

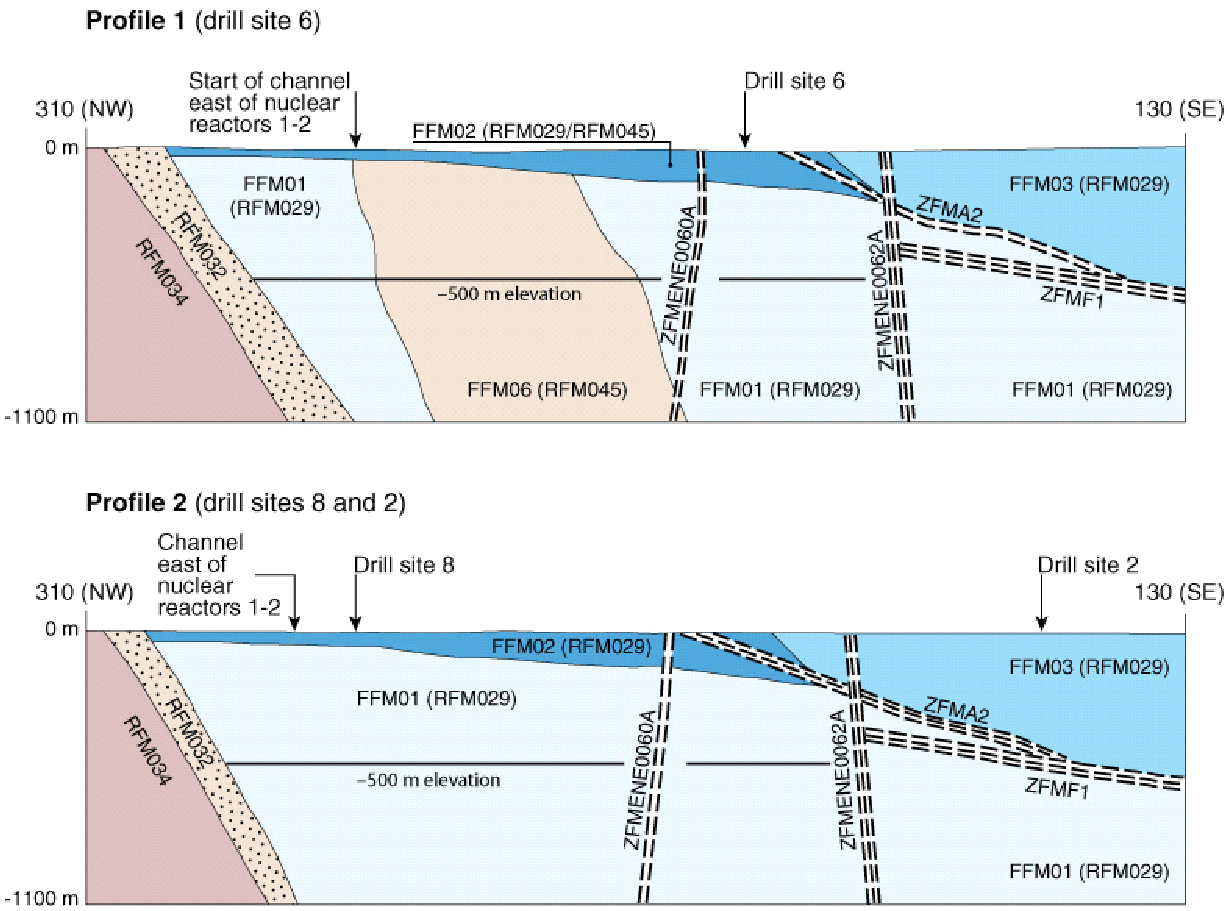


Figure 5-2. *Simplified profiles in a NW-SE direction (310°–130°) that pass through drill sites 2 and 8 (lower profile) and drill site 6 (upper profile). The labelled fracture domains (FFM01, FFM02, FFM03 and FFM06) occur inside rock domains RFM029 and RFM045. Only the high confidence deformation zones A2 (gently dipping), F1 (sub-horizontal), ENE0060A (steeply dipping, longer than 3,000 m) and ENE0062A (steeply dipping, longer than 3,000 m) are included in the profiles. Note the increased depth of fracture domain FFM02 as zone A2 is approached in the footwall to the zone, and the occurrence of this domain close to the surface directly above A2. /Figure 5-1 in Olofsson et al. 2007/.*

5.2 General rock mass conditions

The access ramp and the shafts will pass through rock with highly variable conditions. Near to the surface FFM02 will be intersected which is characterized by a number of gently dipping fractures with transmissivity >10^{-3} m^2/s. It can be assumed that the gentle dip of these structures is towards SE. Significant sediment infillings has been found in near-horizontal stress-release fractures in the upper tens of metres of the rock mass in FFM02. Beneath FFM02, in FFM01 the flowing fracture frequency decreases significantly and the rock mass is generally expected to be tight except for sparsely located flowing fractures.

5.3 Passages of water bearing fractures

Water bearing fractures may occur in all ground types but are expected primarily in ground type 2. The engineering challenges are expected to be different for shafts compared to the access ramp and different between the domains FFM01 and FFM02. The hydraulic properties of the gently dipping transmissive fractures documented in the uppermost 200 m in the possible repository access area are plotted in Figure 2-21 along with the transmissivity values for the steeply dipping fractures in the same rock volume.

5.3.1 Shafts

FFM02

Shafts to be sunk in FFM02 will penetrate highly transmissive gently dipping structures which will need to be grouted before the shaft excavation commences. Large inflows and increasing water pressure with depth must be anticipated and avoided. The rock support for these transmissive structures must be designed to withstand hydrostatic water pressures unless adequate drainage is provided.

For the selected shaft locations, and the different type of shafts, the designer shall evaluate the need for lining of shafts within this domain. For shafts which are designed to be fully lined, adequate temporary support must be provided to allow installation of the permanent lining.

FFM01

It is anticipated that the rock condition will be generally of good quality and that bolts and shotcrete will provide adequate support. However, the existence of transmissive structures shall not be neglected, and tools and measures to obtain early warnings needs to be implemented in the control programmes.

5.3.2 Access ramp

FFM02

The ramp will likely intersect highly transmissive gently dipping structures. Large inflows and increasing water pressure with depth should be anticipated and will need to be avoided. Large water flows together with high water pressures will require sealing and support measures with adequate efficiency for a safe and timely excavation progress.

The layout of the ramp geometry shall be optimized with respect to the geometry of the transmissive structures. Excavation of a ramp-leg more or less parallel to a water-bearing zone will require advanced sealing/grouting and support techniques. This may also have a major impact on construction schedule and costs. Penetration of these transmissive fractures zones at as favourable an angle as possible should be a major target.

FFM01

It is anticipated that the rock mass condition will be generally of good quality and the necessary rock support may be accommodated by rock bolts and shotcrete. However, the existence of transmissive structures shall not be neglected, and tools and measures to obtain early warnings need to be implemented in the control programmes.

5.4 Summary

The ground conditions anticipated for the underground openings associated with the repository access are summarized below. It should be realized that this summary represents the general conditions anticipated and must be evaluated in design stage D2.

Table 5-1. Summary of the ground conditions anticipated for the repository access.

Access	Ground type	Behaviour type	Support type	Grouting type
FFM02				
0–100 m	All	GB1, GB3	ST1,ST2,ST4	Grt2 and Grt3
100–300 m	GT1, GT2	GB1, GB3B	ST1, ST2, ST4	Grt1 and Grt2
FFM01	GT1, GT2	GB1, GB2B	ST1 to ST4	Grt1 and Grt2
Minor deformation zones	GT3	All	ST4 and ST5	All

6 Central area

The central area is composed of a series of caverns of various dimensions, located at approximately the same depth as the deposition tunnels. The location of the central area is dependent on both suitable rock conditions and environmental and functional issues related to the siting of the surface facilities. SKB has proposed various alternative siting options that should be evaluated in design stage D2.

6.1 Constraints

If spalling of the rock mass is anticipated the caverns shall be oriented to reduce unfavourable stress concentrations. The spacing or the geometry of the caverns may need to be adjusted should spalling be an issue.

6.2 General rock mass conditions

It is anticipated that the caverns for the central area will be constructed in ground type I and/or II. The support may be required for the walls as well as the roof and may require special construction sequencing depending on the cavern size.

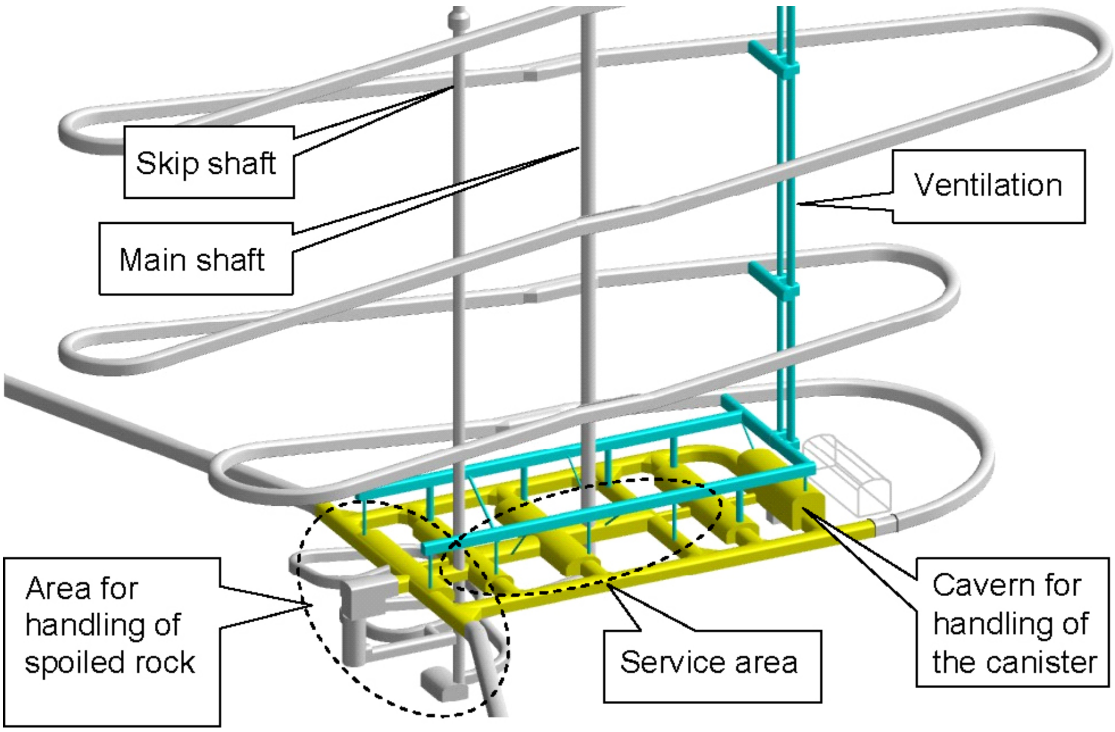


Figure 6-1. *Simplified layout of the central area.*

6.3 Summary

The ground conditions anticipated for the underground openings associated with the central area are summarized below. It should be realized that this summary represents the general conditions anticipated and must be evaluated in design stage D2.

Table 6-1. Summary of the ground conditions anticipated for the central area.

	Ground type	Behaviour type	Support type	Grouting type
Central area				
FFM01	GT1, GT2	GB1, GB2A	STC	Grt1
Minor deformation zones	GT2 and GT3	GB1, GB2	STC	Grt2

7 Deposition area

7.1 General rock mass conditions

The deposition area will be located in the rock mass considered to have the lowest fracture frequency and to be the most homogenous. At Forsmark the deposition area will be located in ground type 1 where the ground behaviour GB1 and/or GB2 is expected. Figure 7-1 shows fracture domains FFM01 and FFM06 and the major deformation zones at a depth of 500 m. The outline of the fracture domains FFM01 and FFM06 is similar to lithology domains RFM029 and RFM045, respectively.

7.2 Deformation zones and respect distances

The deposition area shall be located away from major deformation zones which are longer than 3 km. The respect distance for each major deformation zone must be evaluated on an individual basis by SKB. Within the target volume there are only four deformation zones that are large enough to potentially require a respect distance; the three steeply dipping zones ENE0060A, ENE0062 and NW0123, and the one gently dipping zone A2. The three dimensional geometric coordinates that define the respect distance are defined by SKB and provided to the designer in a digital three dimensional model (RVS).

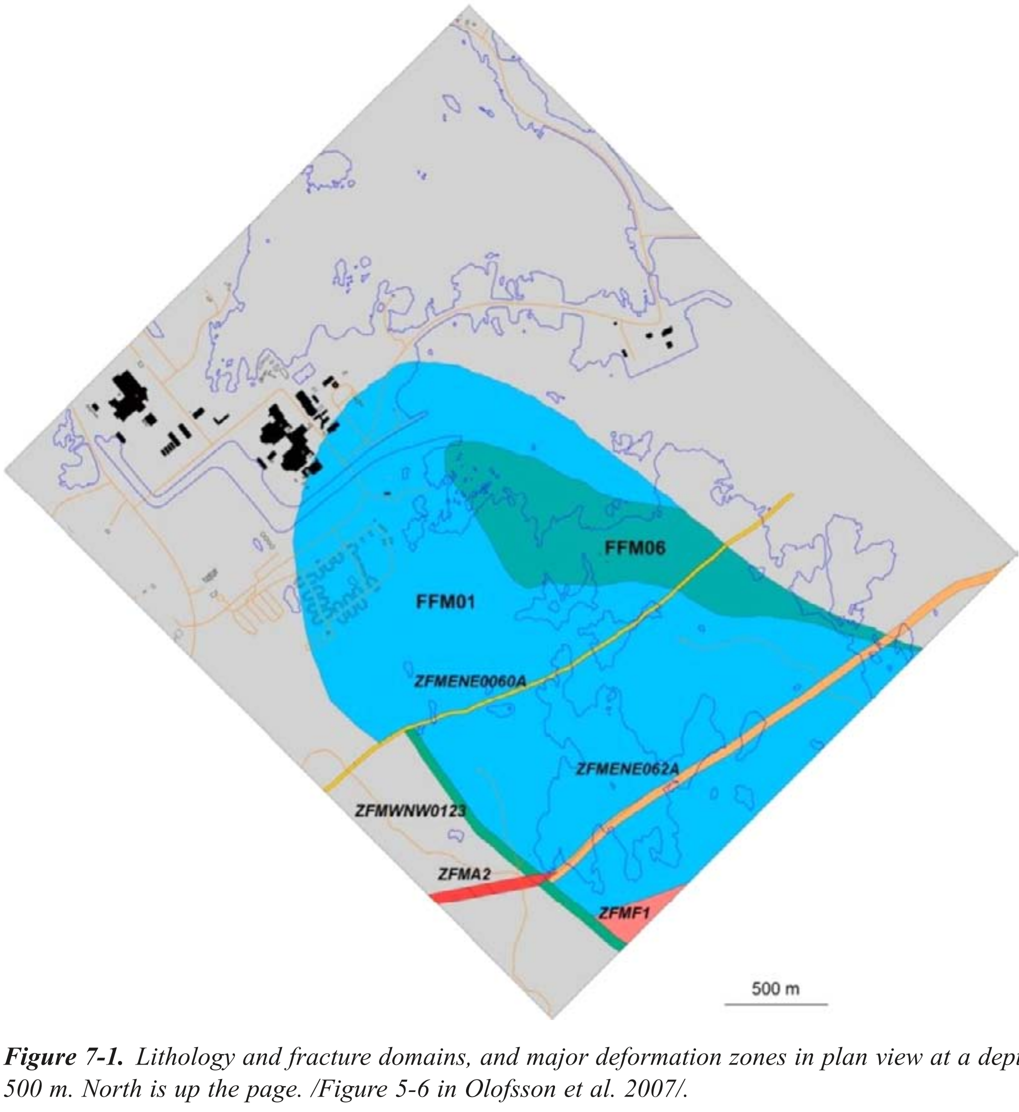


Figure 7-1. Lithology and fracture domains, and major deformation zones in plan view at a depth of 500 m. North is up the page. /Figure 5-6 in Olofsson et al. 2007/.

Deformation zones which are shorter than 3 km are not expected to pose any stability issues for the deposition tunnels. However, such zones may not be suitable for placing deposition holes and may increase the loss of deposition holes (see Section 7.6 for a discussion on the loss of deposition holes).

7.3 Deposition tunnel and deposition hole spacing

For design stage D2, the minimum centre-to-centre spacing for the deposition tunnels shall be 40 m and the minimum centre-to-centre spacing for the deposition holes shall be 6 m in RFM029 and 6.8 m in RFM045 /Back et al. 2007/. This spacing is selected to ensure that the highest permissible temperature in the buffer does not exceed the 100° C criterion. The spacing between the deposition holes is further discussed in Appendix A.

7.4 Spalling in tunnels and deposition holes

The stress magnitudes at Forsmark are elevated compared to other areas in Sweden. These elevated stress magnitudes may induce spalling on the boundary of the excavations in the region of maximum tangential stresses. Hence, the shape and orientation of the opening and the depth of the repository can impact on the stress concentrations and the potential for spalling in the target volume. A complete description of spalling and the methodology used to assess the spalling potential is given in /Martin 2005/. For design stage D2, the spalling potential must be assessed using stress domains given in Table 2-10, including the most likely, the minimum and the maximum values. It is recommended that the minimum and maximum values are used only if the best estimate value in Table 2-10 suggests that stress-induced spalling will be an issue. /Martin 2005/ showed that when the factor of safety for assessing the potential for spalling was less than 1.25, the probability for spalling increased to significant levels. In other words the minimum and maximum magnitude values in Table 2-10 should be used for estimating the potential for spalling for design stage D2 when the best estimate magnitudes in Table 2-10 give factors of safety less than 1.25.

If the risk for spalling potential is judged to be significant using the methodology given in /Martin 2005/ three dimensional elastic stress analyses may be required, especially for deposition holes and tunnel intersections. The intersection of the deposition tunnel with the transport tunnel will also require three dimensional elastic stress analyses, to assess the spalling potential.

7.5 Deposition tunnel alignment

The deposition tunnels shall be aligned with the direction of the maximum horizontal stress to reduce the tangential stress on the boundary of the deposition tunnels and minimise the risk for spalling. /Martin 2005/showed that the risk for spalling in the deposition tunnels could be significantly reduced if not eliminated by orienting the deposition tunnels parallel to the maximum horizontal stress. At Forsmark, the orientation of the maximum horizontal stress is Azimuth 145 ±15 degree. As shown in /Martin 2005/, if the depositions tunnels are aligned within ±30° of the trend of the maximum horizontal stress, the risk of spalling will be significantly reduced. However, it is important when aligning tunnels relative to the direction of the maximum horizontal stress that additional problems are not created by aligning the tunnels parallel to a major joint set. Hence if the prominent sub-vertical fracture set is also aligned with the maximum horizontal stress, as is often the case, the designer must balance the need to reduce the risk for spalling with the potential of intersecting these sub-vertical joints (see Chapter 3, Overview of Forsmark tunnelling experience).

7.6 Loss of deposition holes

The design premises document /SKB 2007/ identified preliminary criteria to be used for assessing the degree-of-utilisation to ensure that the repository is large enough to locate 6,000 canisters. The bases for rejecting a potential deposition position are briefly outlined below.

1. During a future earthquake, the deposition hole may be sheared so much that it can harm the canister. This could occur if the canister is intersected by a fracture, or minor deformation zone, of a radius larger than 75 m.
2. In order to avoid piping erosion of the buffer, only deposition holes with limited inflows can be used. The acceptable inflow criteria into a deposition holes is 0.1 l/min and 5 l/min for 300 m of deposition tunnel length, and for all other openings 10 l/min per 100 m tunnel length /SKB 2007/.
3. Spalling in the deposition hole due to excavation-induced stresses shall be minimised. Stress analyses that utilises the minimum and maximum, as well as the most likely value shall be carried out to assess the spalling potential.
4. Placing a deposition hole in rock with a very low thermal conductivity, i.e. amphibolite, in Forsmark shall not be permitted.

Due to the uncertain spatial distribution of the fracturing in the rock mass described in the site descriptive model, the layout cannot identify which actual deposition positions would be rejected. Therefore the designer shall assess the gross-capacity of the layout within the limits given by the margins of the tectonic lens (FFM01 and FFM06) within the local model volume (Figure 7-1).

7.7 Summary

The ground conditions anticipated for the underground openings associated with the deposition area are summarized below. It should be realized that this summary represents the general conditions anticipated and must be evaluated in design stage D2. It is anticipated that the deposition holes shall be located in ground type 1.

Table 7-1. Summary of the ground conditions anticipated for the deposition area.

	Ground type	Behaviour type	Support type	Grouting type
Deposition area				
FFM01	GT1, GT2	GB1, GB2A	ST1, ST2,ST3	Grt1
Minor deformation zones	GT2 and GT3	GB1, GB2	ST2,ST3,ST4	Grt2

8 Repository depth

In /SKB 2006b/ it was suggested that a repository in typical Scandinavian shield could be safely constructed at a depth interval between 400–700 m. The general site conditions at Forsmark are illustrated in Figure 8-1. As illustrated in Figure 8-1, the general rock mass quality improves significantly in the depth interval 400–700 m. At this depth range there are also several site specific factors related to long-term safety that must also be considered when selecting the repository depth. An overview of these factors are provided in Table 8-1 and /Section 13.6.8 in SKB, 2006b/ describes the role each factor can play in the depth selection. The depth of the repository must, in general, balance the safety requirements for the repository and the constructability of the underground excavations required for the deposition tunnels and deposition holes. The safety requirements are largely influenced by the

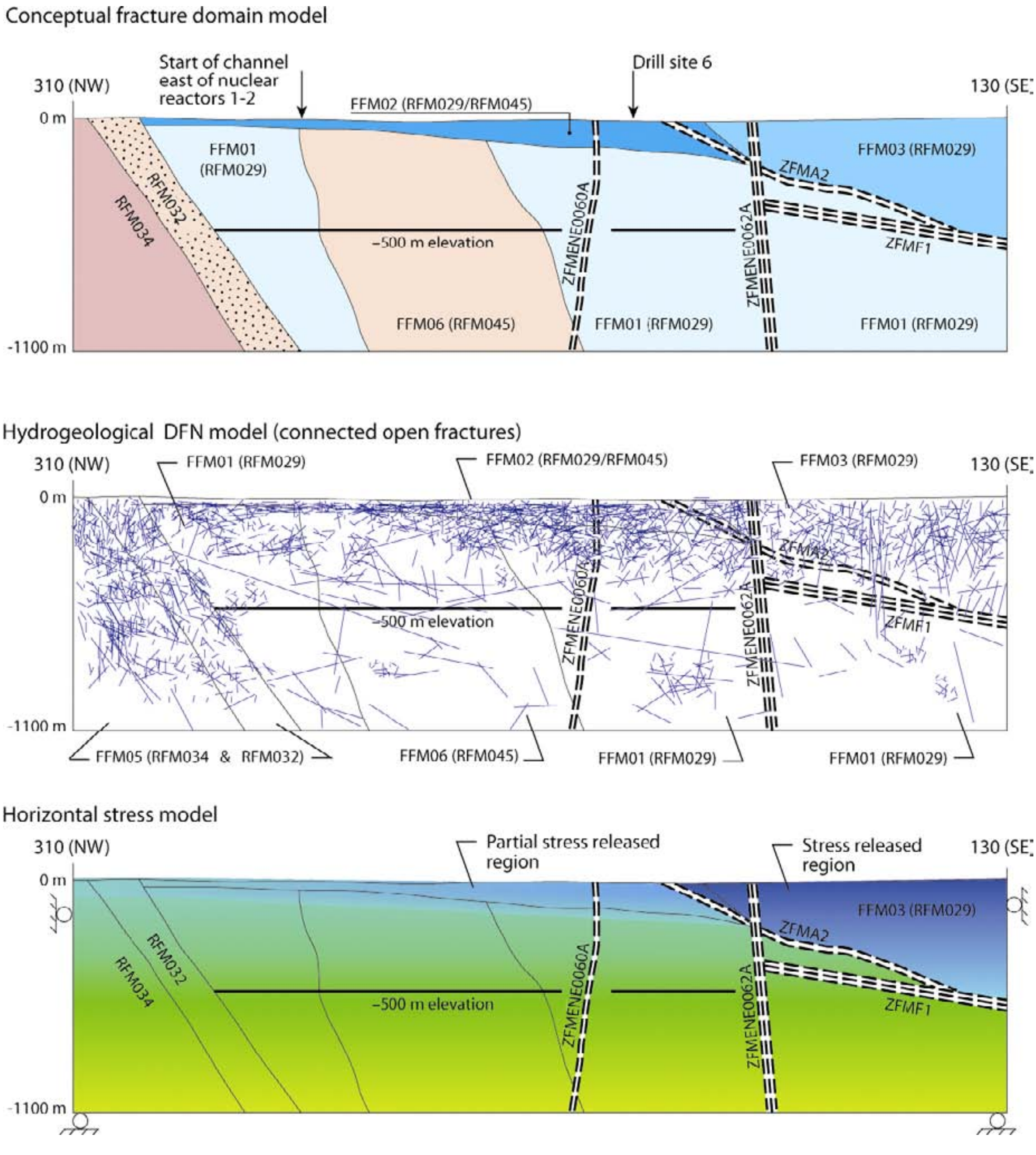


Figure 8-1. Illustration of the general rock mass characteristics at Forsmark, highlighting the fracture domains and their correlation with hydrogeology and rock mechanics (in situ stress) /SKB 2008/.

hydrogeology of the site, i.e. frequency and occurrence of transmissive fractures with depth while the constructability is mainly related to rock mechanics issues, i.e. stability of the deposition holes prior to emplacement. These two factors are prominent at the Forsmark site because of the massive relatively low permeability rock in fracture domain FFM01 and the potential for deposition-hole spalling in this fracture domain. These two factors and their influence on the recommended repository depth are discussed in the sections that follow.

8.1 In situ temperature

The in situ temperatures at several depths are given in Table 2-3. The gradient is approximately 1.3°C/100 m. which would theoretically increase the canister spacing by roughly 100–200 mm/100 m. Hence the rock temperature at the depth range of 400 to 500 m will not play a significant role in influencing the final repository facility depth.

8.2 Fracture frequency

The fracture domain concept is described by /Olofsson et al. 2007/. The rock mass is divided into fracture domains FFM02 and FFM01 within the target volume for a repository located north and under deformation zone A2. The repository will be located in FFM01. The open fracture frequency decreases significantly in FFM01 with depth as shown in Figure 8-2. While there is a general decrease in the number of open fractures below 300 m, the fracture frequency in the target volume is relatively constant at approximately 0.5/m. A rock mass with this low fracture frequency would be classed as sparsely fractured to massive.

8.3 Hydrogeology considerations

As indicated in Chapter 2, the Forsmark site consists of a block of highly transmissive fractures (fracture domain FFM02) sitting on top of a block of sparsely fractured homogeneous granite (FFM01). Within FFM02, most of the flow occurs in sub-horizontal and/or gently dipping fractures. The SDM-Site Forsmark has shown that these gently dipping fractures can be hydraulically connected for several 100 s of metres and that the sub-vertical fractures observed at the site may provide the vertical connection for the more permeable gently dipping fractures. Such features were exposed

Table 8-1. Factors in Engineering and safety assessment considered for the recommendation of repository depth.

Engineering factors	Safety assessment factors
Initial temperature: Up – lower in situ temperature favourable for canister spacing.	**Initial temperature :** Considered in design, no direct effect.
Water inflow, grouting efforts: Up – lower groundwater pressure favourable. Down – if hydraulic conductivity decreases with depth.	**Salinity and up-coning;** Up – possibly lower inflow to facility. **Groundwater pressure:** Up – marginal importance.
Rock stability, rock stress: Above a tentative triggering depth were stress conditions may be unfavourable for tunnelling.	**Rock stress:** Above a tentative triggering depth were stress conditions may be unfavourable for long term effects around the deposition holes.
Available space, layout adaptation – 3D structural model: Undecided, site specific.	**3D structural model – layout adaptation, degree of utilization** Site specific – fracturing, thermal properties, hydraulic properties, stability.
Degree of utilization – fracturing, thermal properties, inflow, stability: Site specific.	**Length and transport resistance of travel paths** Down, longer paths generally favourable.
Environment (short term): Up, less excavated rock volume, less inflow (drawdown).	**Fracture frequency and Transmissivity:** Undecided, site specific.
Time and cost: Up, shorter access shafts and ramp.	**Inadvertent human intrusion:** Down, lower risk of intrusion, difficult to quantify.
Design of underground openings: Not affected.	**Freezing:** Down – reduces risk associated to permafrost **Surface erosion:** No importance.

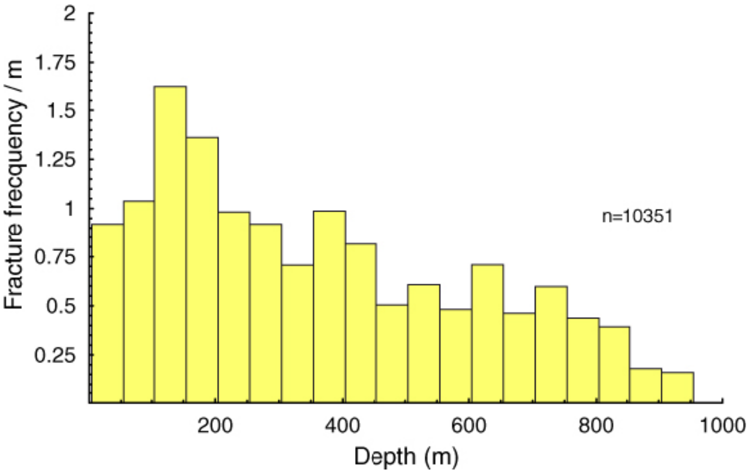


Figure 8-2. *Distribution of open fracture frequency with depth in the target volume, data obtained from Sicada in April 2007.The low frequency of open fractures from 0 to 100 m is related to drilling and logging procedures, i.e. percussion drilling was used to collar many of the cored holes to 100 m depth.*

in the excavations for the Forsmark intake canal (Figure 8-3) and also encountered during the SFR construction. The occurrence of such shallow dipping features at the repository level connected via widely spaced sub-vertical fracture zones, such as observed in the water channel excavation should be avoided if possible. The SDM-Site Forsmark has shown that over 70% of the gently dipping water bearing fractures occur above 400 m depth, and that over 90% of these features occur above 450 m depth, resulting in an observed frequency of flowing features below 400 m depth of 0.005/m, i.e. an average rock mass hydraulic conductivity in the order of 6.3×10^{-11} m/s (Table 2-12). Hence placing the repository below 450 m significantly reduces the risk of encountering large scale hydraulically connected features.

While there is a significant decrease in the frequency and transmissivity of the gently dipping fractures with depth in FFM01, the same trends are less pronounced for the steeply dipping transmissive fractures and/or deformation zones (see Section 2.5). The influence of hydraulic gradients and depth dependence of hydraulic conductivity/transmissivity would be very limited in the rock mass outside deformations zones due to the very low frequency of open fractures below 400 m depth. Hence there appears to be no significant benefit of placing the repository below 400 m with respect to the steeply dipping structures.

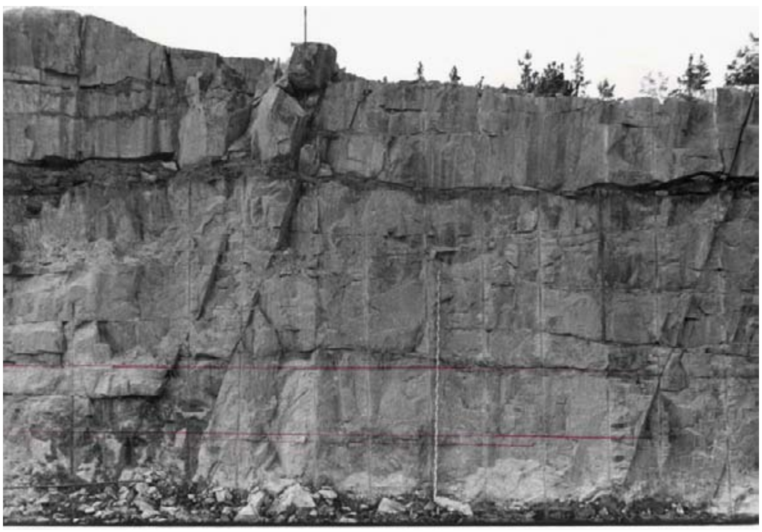


Figure 8-3. *Example of the sub-vertical fractures connecting gently dipping open fractures. Photo from the Forsmark nuclear power plant water intake canal construction.*

The increased ground water pressure below 400 m depth may make grouting somewhat more time consuming but will not impact constructability.

8.4 Spalling considerations

In general, stress magnitudes tend to increase with depth. Because spalling is a function of the stress magnitudes relative to the rock strength, it is generally assumed that the potential for spalling also increases with depth, assuming the rock strength remains constant. The stress conditions at Forsmark are given in /Martin 2007/ and below 300 m depth, there appears to be little evidence that the horizontal stress magnitudes in fracture domain FFM01 increase significantly with depth. Hence placing the repository at 400 m or 500 m depth does not significantly increase the risk for excavation-induced spalling in the deposition holes.

Spalling in the deposition tunnels is not considered to be an issue provided the tunnels are aligned parallel or sub-parallel to the maximum horizontal stress (~140 deg Azimuth).

8.5 Available space – site adaptation

With the approach at this design stage that the target volume for a repository is located north of deformation zone A2, the available space for a repository within the tectonic lens will be larger with depth due to the southerly dip of A2 (Figure 2-12). There is however an uncertainty in exactly how the gently dipping deformation zone F1 under A2 at 500 m depth may influence the available space. This has to be explored by the designer.

8.6 Construction costs and environmental impact

Both the construction cost and the environmental impact is to some degree a function of the repository depth. The deeper excavation and the marginally larger repository due to increasing in situ temperature with depth will consume more resources. This is however marginal for the repository in a depth interval between 450 and 500 m in the anticipated rock conditions.

8.7 Other considerations

Other safety factors in Table 8-1and discussed in /SKB 2006b/ and are considered to have a very minor impact on repository depth selection.

8.8 Recommended repository depth

Considering the factors in placing the repository at or below a depth of 450 m will significantly reduce the risk of encountering gently dipping water bearing fractures. For the purposes of design stage D2, the maximum depth of the repository shall be 500 m due to in situ stress conditions. Therefore the Designer shall maximise the space available between the depth intervals 450–500 m, with the restriction that the roof of any part of the deposition area shall not be located above a depth of 450 m.

The designers must also consider the practical requirements for inclining the tunnels for drainage purposes. This will result in approximately 25 to 30 m difference in elevation from the highest point of the repository to the lowest point.

Placing the repository at or below a depth of 450 m will not eliminate the risk for encountering water bearing fractures. The designer should be aware of this risk and ensure that subsequent design steps address this issue.

9 Summary of layout/design issues for D2

The design stage D2 is a preliminary design and the focus described in /SKB 2007/ pertains to the design issues and not the construction issues. The outcome of design stage D2 will provide input to design step C, where the construction issues will be addressed in more detail, at least for the access routes such as shafts and ramp.

There are several general engineering guidelines that should be considered in laying out the repository:

1. The deposition holes shall be located in ground type GT1.
2. The central area can be located in any rock mass suitable for constructing large caverns.
3. The access tunnels and shafts should be located to minimise the potential for large groundwater inflows.
4. Layouts for tunnel and shaft access should be oriented such that the intersection lengths with major water bearing zones are as short as practical.
5. A respect distance of at least the transition zone width and a minimum of 100 m is required between major deformation zones (longer than 3 km) and deposition holes. This respect distance is measured perpendicular from the transition zone boundary and should be modelled in three dimensions.
6. The repository depth and layout should minimise stress concentrations on the boundary of the underground excavations (deposition holes and deposition tunnels), unless it can be shown that such stress concentrations do not cause spalling.

In addition to the general guidelines given above there are several issues which need special consideration when designing the repository layout. These are highlighted below.

Issue: Highly transmissive and gently dipping fractured zones

The sub-horizontal fractures/sheet joints in the upper 40–200 m of the rock mass within the target volume of the tectonic lens (fracture domain FFM02) may be highly transmissive. The layout of the access ramp should intersect these transmissive features at as large an angle as possible to improve the possibility to seal by grouting measures.

When shaft sinking through the fracture domain FFM02, pre-grouting of these gentle dipping fractures and stress release fractures may be required.

Issue: General influence of dominant fracture sets

Ramp and Central area:

The alignment of the ramp shall if possible avoid having long sections parallel with the NE-NNE trending fracture sets. This may cause systematic overbreak of the tunnel contour.

The long walls of the rock caverns in the central area shall not be aligned parallel to the NE-NNE trending fracture sets to decrease the need for bolting and reduce the risk for overbreak.

Deposition areas:

The alignment of transport tunnels shall if possible avoid having long sections parallel with the NE-NNE trending fracture sets. This may cause systematic overbreak of the tunnel contour.

Because of vertically dipping fractures, estimating rock support at the intersections of the transport and deposition tunnels shall consider the need for systematic bolting of the walls. The NE-NNE trending fracture sets may be particularly problematic, if not supported.

The intersection of the deposition tunnels with the access tunnels will require special design attention, particularly the transition from the access tunnel to the deposition tunnel. Experience from Äspo HRL and elsewhere suggests that this portion of the intersection will need support, regardless of rock mass quality and ground type.

Issue: Distribution of water bearing fractures

The occurrence of water bearing fractures is expected to be very limited at the repository depth within the target volume. The few transmissive fractures found in the site investigation program in the target area, as well as observations from the SFR indicate that detecting these features with traditional probe hole drilling from the tunnel face may be very difficult. In addition, grouting methods from the tunnel where the flow from such features is highly channelized, may also prove challenging. The designer may wish to consider special procedures for controlling the flow from such features not considered in the grouting types in Table 4-5.

Issue: Stress conditions

The risk for local stress-induced problems (spalling) at any depth at Forsmark cannot be ruled out due to local heterogeneities in the rock mass, e.g. the experienced at shallow depths during tunnel constructions for unit 3 at the Forsmark nuclear power plant /Carlsson and Christiansson 2007/. When minor spalling occurs worker safety will be an issue and roof support will be required.

Circular openings excavated by mechanical means are particularly susceptible to construction issues associated with stress-induced spalling. The Designer should consider alternative shapes for openings that are excavated at an unfavourable orientation relative to the maximum horizontal stress.

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Appendix A

Thermal dimensioning of the canister spacing

A.1 Introduction

In order to meet the temperature requirements on the bentonite buffer, calculation of c/c distance between canisters have been performed for Domain RFM029 and RFM045 in Forsmark. The strategy for thermal dimensioning of the layout of the repository is described in /Hökmark et al. 2009/. The calculations have been performed on the basis of the following pre-requirements:

1. Maximum allowed peak temperature in the bentonite buffer in all deposition holes; 100°C
2. Maximum thermal power in the canister; 1,700 W
3. Distance between deposition tunnels; 40 m
4. Distance between deposition holes; ≥ 6 m
5. No optimizing of the layout is performed

The requirements mean that the necessary c/c distance for the canister with the lowest thermal conductivity in the rock mass, will be dimensioning for **all** canisters. The calculation method is summarized as follows:

- An uncertainty margin to the 100°C threshold is determined; see Section 5 and Table A-3 to Table A-6.
- An approximate value (or "guess" value) of the canister spacing is determined preliminarily from the distribution of thermal conductivities in the rock mass at the 5 m scale (domain RFM029: /Back et al. 2007/, domain RFM045: /Sundberg et al. 2008/) and the analytical solution /Hökmark et al. 2009/, see Section 5.
- Canister spacing is calculated with the numerical solution described in /Hökmark et al. 2009/ on the basis of data from the "worst case" thermal property realisations from the stochastic modelling in the 1 m scale of thermal properties in each rock domain /Back et al. 2007, Sundberg et al. 2008/, see Section 2 and 5.

A.2 Summary of results

The results of the calculations for a repository at 470 m depth are summarized in Table A-1 . The threshold is calculated as follows: 100°C-margin (=4.5°C, see Table A-5) = 95.5°C.

A.3 Implementation

In the thermal site descriptive model /Back et al. 2007, Sundberg et al. 2008/, stochastic modelling of the spatial thermal conductivity in the rock mass have been performed. For Domain RFM029, 1,000 realisations have been performed /Back et al. 2007/, and for Domain RFM045, 500 realisations were made /Sundberg et al. 2008/. Each realisation contains 125,000 cells at 1 m^3 (simulation volume of 50·50·50 m). A relationship between thermal conductivity and heat capacity is established in /Back et al. 2007/. This relationship, together with a random distribution of an uncertainty factor, has been used to assign a heat capacity value to each cell /Sundberg et al. 2008/. A code identifying the actual TRC is also connected to each cell.

Table A-1. Calculated spacing between canisters at 470 m depth (11.3°C initial temperature) and 40 m tunnel spacing in the different rock domains in the Forsmark area.

Domain	Base case Threshold	Canister cc
29	95.5°C	6.0 m
45	95.5°C	6.8 m

The realisations are used as input to a numerical calculation model with a deposition tunnel and 9 canisters, described in /Hökmark et al. 2009/. The realisations are in a local coordinate system due to considerations made in the thermal modelling /e.g. Back et al. 2007/, in order to take into account the geological anisotropy. In the numerical model, data is collected from each cell in the realisation and transformed into the coordinate system for the numerical model. In the numerical model, the origin is at the centre of the central canister (half the height of canister 5) with the x-axis parallel to the deposition tunnel. In a pre-processing step, the realisations are ranked in an expected order, from the realisation with the lowest thermal conductivity in a weight volume around each canister, to the realisation with the highest thermal conductivity. Numerical calculations are made for a number of realisations, normally the ones with the highest ranking, i.e. the lowest weighted thermal conductivity. The two outermost canisters on each side are ignored due to possible boundary effects, which mean that only canisters 3-7 are considered /Hökmark et al. 2009/.

The methodology implies that all relevant scales for the spatial variability of the thermal conductivity are considered. Also the anisotropy in the geology is taken into account. The model also makes it possible to simulate temperature dependence in the thermal properties. This has been done for both rock domains.

A.4 Data

Input data to the thermal dimensioning is described in Table A-2.

Table A-2. Description of input data to numerical model. The thermal realisations are described in /Back et al. 2007/ and /Sundberg et al. 2008/.

Description	Value	Comment
Temperature at 470 m depth, °C	11.3	/Sundberg et al. 2008/
Temperature gradient, °C/m	0.012	/Sundberg et al. 2008/
Tunnel spacing, m	40	
Tunnel direction, °	145	See SER-report
Thermal conductivity of tunnel backfill, W/(m·K)	0.7	
Thermal conductivity of bentonite, W/(m·K)	1	
Gap coefficient	16	/Hökmark et al. 2009/
Effective thermal conductivity of bentonite and gap in radial direction from canister, W/(m·K)		Calculated from gap coefficient and conductivity of bentonite /Hökmark et al. 2009/
Thermal conductivity of canister, W/(m·K)	30	
Size of realisation, m^3	50·50·50	125,000 m^3
Cell size in realisation file, m^3	1·1·1	
Thermal realisations RFM029, based on TSDM 2.2	SKB's model database	File name: geomerge_std_d29_1m.out
Number of realisations	500–1,000	D45: 500; RFM029: 1,000
Thermal realisations RFM045, based on TSDM 2.3	SKB's model database	File name: geomerge_std_d45_1m.out
Number of realisations	500	
Temperature dependence in thermal properties, based on TSDM 2.3	See report	/Sundberg et al. 2008/
Transformation parameters realisations RFM029		/Back et al. 2007/
α_1 (trend-90°)	67°	
β_1 (plunge)	38°	
α_2 (strike-90°+90°)	150°	
β_2 (dip)	80°	
Transformation parameters realisations RFM045		/Sundberg et al. 2008/
α_1 (trend-90°)	55°	
β_1 (plunge)	42°	
α_2 (strike-90°+90°)	112.5°	
β_2 (dip)	60°	

A.5 Results

Temperature margin

The uncertainties relevant to the dimensioning issue are listed and discussed in /Hökmark et al. 2009/ and applied to the Forsmark rock domains in Table A-3 to Table A-5. The rock thermal conductivity has an influence on the margin and is typically 2.5 W/(m·K) for low conductivity rock in domain RFM045 and 2.9 W/(m·K) for domain RFM029.

The temperature margin is 4.5°C for the numerical solution in order to establish definitive spacing. The temperature threshold used in the numerical calculations is **95.5°C** (100°–4.5°C). The temperature margin for the analytical solution in order to establish a guess (start) value is determined to approximately two degrees higher; 6.5°C which gives the temperature threshold 93.5°C.

Guess values

Guess values for the spacing between canisters based on the 0.1-percentile for the thermal conductivity distribution in 5 m scale in the different domains /Back et al. 2007, Sundberg et al. 2008/ are established to 6.2 m in domain RFM029 and 7.8 m in domain RFM045, based on nomographic chart in /Hökmark et al. 2009/. The 1-percentile of the thermal conductivity gives spacing of <6 m and 7.1 m respectively (Figure A-1). Note that the nomographic chart is based on a slightly overestimated value of the heat capacity. For the purpose of establishing spacing guess values this is of no importance. Thermal conductivities for the 5 m scale for different percentiles and domains are shown in Table A-7 below. The spacing guess values based on the 1 percentile of the thermal conductivity distribution were used as start values in the numerical iteration scheme.

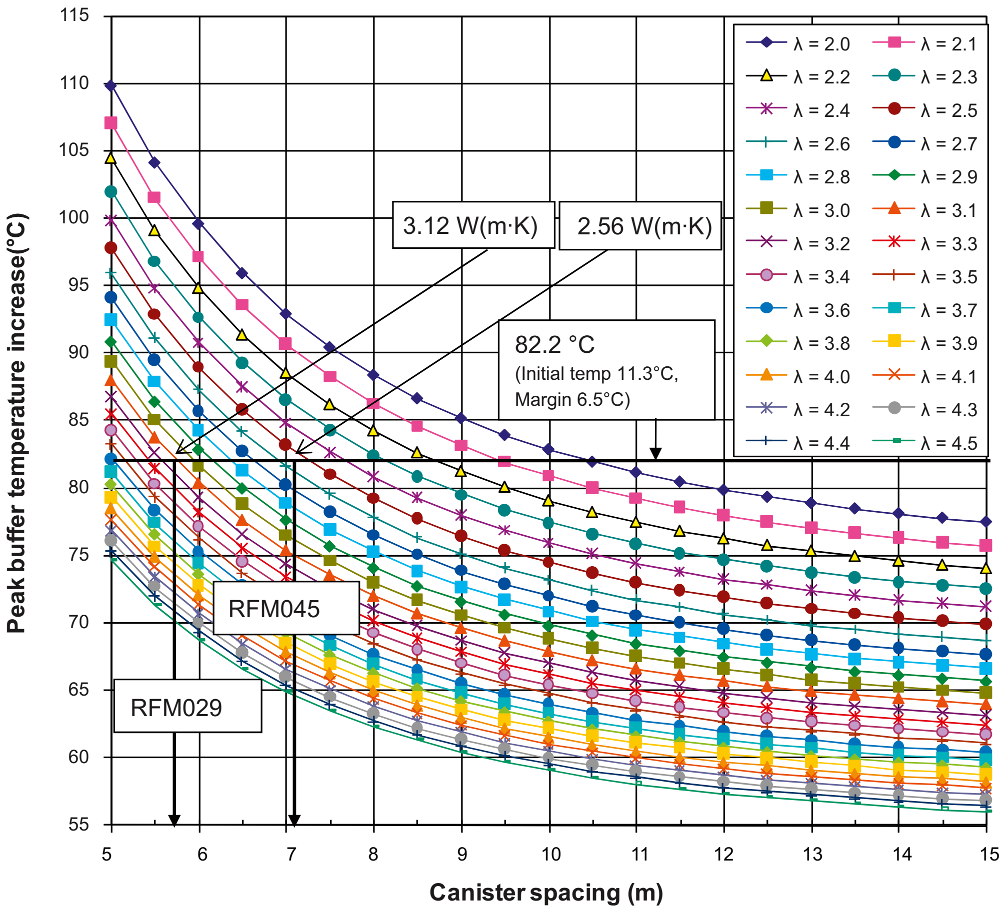


Figure A-1. *Guess values of the canister spacing, exemplified for the 1 percentile of the thermal conductivity distribution in the two domains, based on nomographic chart in /Hökmark et al. 2009/. To get the absolute upper bound peak temperature value the in situ temperature (11.3°C) and the temperature margin established for the analytical solution (6.5°C) must be added to the calculated temperatures. The maximum allowed analytically calculated increase in buffer temperature is therefore 82.2°C. Heat capacity 2.17 MJ/(m³·°C).*

Table A-3. Local solution. Values in parenthesis: Plain top/bottom canisters. Modified from /Hökmark et al. 2009/ with site specific data.

$\Delta T_{tot,}$ difference between rock wall temperature and maximum bentonite temperature		Margin	Comment
Uncertainties related to:			
U1	Geometry of air-filled canister/bentonite slot and variations in barrier conductivity	3.3°C RFM029 3°C RFM045	The influence can be interpolated for different conductivities from /Hökmark et al. 2009/. The thermal conductivity at low percentiles are approx 3 W/(m·K) for RFM029 and 2.5 W/(m·K) for RFM045
U2	Moisture redistribution in barrier	0.2°C	
U3	Spalling	0.1°C	
U4	Vertical variation of rock conductivity along deposition hole	0.25°C	
U5	Vertical distribution of heat generation in the canisters	0.2°C	
Sum ΔT_{tot}		4.05°C RFM029 3.75°CRFM045	

Table A-4. Uncertainties in numerically calculated rock wall temperature. Modified from /Hökmark et al. 2009/ with site specific data.

T_{wall} ,Rock wall temperature at canister mid-height at the time of buffer temperature peak		Rock conductivity 2.5 W/(m·K)	Comment
Uncertainties related to:			
U6	Anisotropy within rock type	0.7°C RFM029 0.5°C RFM045	15% anisotropy factor assumed. Temperature contribution is slightly decreased for domain RFM045 compared to /Hökmark et al. 2009/ since tunnel orientation is not entirely parallel to foliation in combination with lower dip
U7	Bias in thermal properties	0.5°C RFM029 0.8°C RFM045	Interpolated from /Hökmark et al. 2009/
U8	Site model	0.1°C	In /Sundberg et al. 2008/ uncertainty estimated to less than 1% in the lower tail
U9	Initial temperature	0.65°C	Variability between lowest and highest temperature is approx. 0.4°C in Forsmark
U10	Temperature dependence	0°C	Included in numerical calculation, data from /Sundberg et al. 2008/
U11	Pressure dependence	–0.2	
U12	Tunnel backfill	0°C	
U13	Strategy uncertainties	–	
Sum (uncertainties)		1.75°C RFM029 1.85°C RFM045	
Over/underestimate because of numerical model simplifications			
S1	Representation of canister	–0.7°C	Canister thermal conductivity 30 W/(m·K) used in numerical programme
S2-	Numerical precision	–0.8°C	
S3	Boundary conditions	0.2°C RFM029 0.4°C RFM045	10% higher conductivity in two neighbouring tunnels gives 0.4°C in temperature contribution /Hökmark et al. 2009/. The difference between mean thermal conductivity and conductivity around a canister in low conductive rock is typically <5% and 10% for domain RFM029 and RFM045 respectively, see Table 6 below.
Sum (under/overestimates)		–1.3°C RFM029 –1.1°C RFM045	
Total T_{wall}		0.45°C RFM029 0.75°C RFM045	

Table A-5. Total temperature margin in numerical solution to establish a definitive spacing.

Uncertainties related to:	Domain RFM029	Domain RFM045	Comment
Local solution	4.05°C	3.75°C	
Total T_{wall} Numerical solution	0.45°C	0.75°C	
Total Margin	4.5°C	4.5°C	Same for both domains

Table A-6. Relation between thermal conductivity related to the canisters with the highest bentonite temperature and the mean thermal conductivity in the numerical grid for domains RFM029 and RFM045. The volume weighted thermal conductivity is based on the thermal conductivity in the different zones used for the ranking procedure and the volumes for these zones, see /Hökmark et al. 2009/.

Domain	Realisation, canister	Mean thermal conductivity in domain or subdomain	Volume weighted thermal conductivity for canister in numerical grid	Relation (mean-weighted)/weighted
29	r295, caps 6	3.6	3.54	<5%
29	r198, caps 3	3.6	3.55	<5%
45, subdomain B	r450, caps 3	3.32	3.08	8%
45, subdomain B	r473, caps 7	3.32	2.92	14%

Table A-7. Thermal conductivities for the 5 m scale for different percentiles in domain RFM029 and RFM045 /Back et al. 2007, Sundberg et al. 2008/.

	Thermal conductivity (W/(m·K))	
	RFM029	RFM045
0.1 percentile	2.87	2.36
1 percentile	3.12	2.56
2.5 percentile	3.23	2.73

Spacing between canisters – domain RFM029

The calculation result in Table A-8 and Table A-9 shows that all canisters in domain RFM029 fulfil the temperature criterion if the spacing is set at 6.0 m. i.e. at the minimum spacing allowed according to the pre-requirements. This should be expected considering that the guess value is smaller than 6.0 m (Figure A-1) and means that iterations are not needed. The two tables structure the results in a slightly different way. In Table A-8 only one canister (of the middle five) per realisation is displayed (the one with the highest temperature) and the table is sorted on ranking. In Table A-9 more than one canister per realisation may be among the hottest and it is sorted on maximum bentonite temperature (realisations 159 and 553 occur twice).

The results of Table A-8 are presented graphically in Figure A-2. With some exceptions, higher ranking gives a lower bentonite temperature. The peak temperature decreases rapidly and systematically with increasing ranking. With the ranking procedure it seems possible to find the hottest deposition holes if 5–10 realisations are tested. It can be concluded from the tables that temperature dependent thermal properties increase the maximum bentonite temperature with approximately 0.4–0.6°C for the actual domain.

Table A-8. Maximum bentonite temperature for the canister with the lowest thermal conductivity in each of the ten lowest ranked realisations for Domain RFM029, 6 m cc, tunnel cc 40 m, tunnel direction 145°, start temperature 11.3°C, gradient 0.012°C/m.

Ranking (Based on weighted thermal cond.)	Realisation no	Canister no	Min average weighted thermal conductivity W/(m·K)	Max bentonite temperature *without* temp. dep. properties °C	Max bentonite temperature *with* temp. dep. properties °C	Proportion TRC 17 in the nearest zone (2.5 m) %
1	447	7	2.84	94.67	95.18	67
2	232	7	2.94	93.89	94.39	57
3	159	4	2.94	93.39	93.90	54
4	61	5	2.94	93.02	93.54	51
5	256	4	2.96	92.56	93.11	43
6	89	4	2.98	94.16	94.67	47
7	553	6	2.98	92.36	92.91	35
8	593	6	2.99	92.34	92.80	24
9	657	4	2.99	92.00	92.49	28
10	524	6	2.99	92.30	92.68	1

Table A-9. Maximum bentonite temperature for the ten canisters with lowest thermal conductivity in the ten lowest ranked realisations with the lowest thermal conductivity for Domain RFM029, 6 m cc, tunnel cc 40 m, tunnel direction 145°, start temperature 11.3°C, gradient 0.012°C/m.

Ranking	Realisation no	Canister no	Min average weighted thermal conductivity W/(m·K)	Max bentonite temperature *without* temp. dep. rock properties °C	Max bentonite temperature *with* temp. dep. rock properties °C	Proportion TRC 17 in the nearest zone (2.5 m) %
1	447	7	2.84	94.67	95.18	67
6	89	4	2.98	94.16	94.67	47
2	232	7	2.94	93.89	94.39	57
3	159	4	2.94	93.39	93.90	54
4	61	5	2.94	93.02	93.54	51
3	159	5	3.04	92.88	93.38	44
9	657	5	3.06	92.81	93.33	29
7	553	5	3.10	92.78	93.29	30
5	256	4	2.96	92.56	93.11	43
7	553	6	2.98	92.36	92.91	35

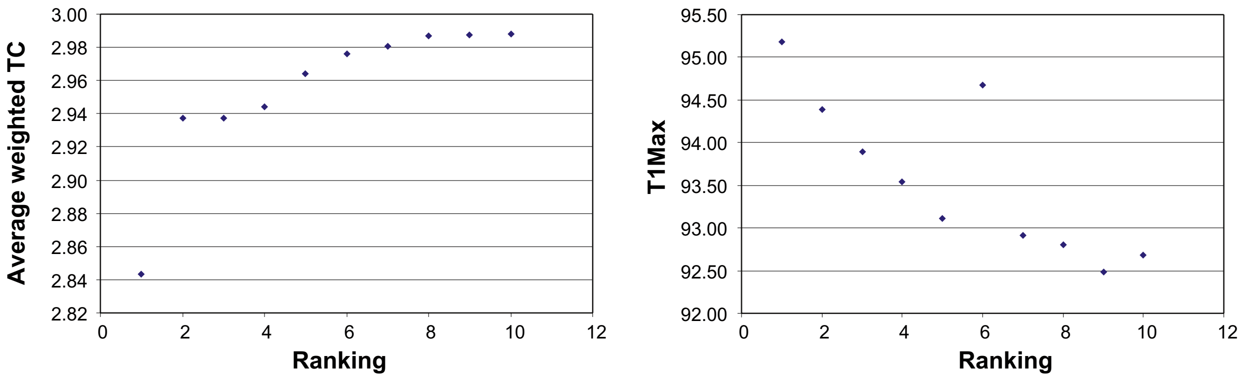


Figure A-2. Maximum bentonite temperature for the canister with the lowest thermal conductivity in each of the ten lowest ranked realisations for Domain RFM029. Left: Ranking vs. weighted thermal conductivity (W/(m·K)), Right: Ranking vs. max bentonite temperature (°C). Temperature-dependent rock thermal properties are used. 6.0 m cc, tunnel cc 40 m, tunnel direction 145°, start temperature 11.3°C, gradient 0.012°C/m.

Spacing between canisters – domain RFM045

A number of iterative calculations, starting with the 7.1 m guess value of the canister spacing, have been made. Only results from calculations giving peak temperatures close to the temperature criterion are included below. The calculation results in Table A-10 for canister spacing 6.6 m show that the temperature threshold (95.5°C) is exceeded by approximately 0.2°C for two canisters. The use of temperature dependent thermal properties increases the maximum bentonite temperature with approximately 0.5°C compared to the use of constant thermal properties.

Increasing the canister spacing to 6.7 m is sufficient to bring the maximum temperature down by about 0.45°C and fulfil the temperature criterion in domain RFM045, see Table A-11. This reduction is in keeping with the analytically derived spacing-temperature relations given in the strategy report /Hökmark et al. 2009/. The results are presented graphically in Figure A-3. In the same way as for domain RFM029, the weighted thermal conductivity reflects the ranking and increased ranking corresponds in general to lower maximum bentonite temperatures. A slightly higher canister spacing, 6.8 m, have earlier been calculated based on the thermal modelling in stage 2.2 /Back et al. 2007/.

Table A-10. Maximum bentonite temperature for the canister with the lowest thermal conductivity in each of the ten lowest ranked realisations for Domain RFM045, 6.6 m cc, tunnel cc 40 m, tunnel direction 145°, start temperature 11.3°C, gradient 0.012°C/m.

Ranking	Realisation no	Canister no	Min average weighted thermal conductivity W/(m·K)	Max bentonite temperature *without* temp. dep. rock properties °C	Max bentonite temperature *with* temp. dep. rock properties °C	Proportion TRC 17 in the closest zone (2.5 m) %
1	450	3	2.46	95.20	95.68	100
2	473	7	2.52	94.35	94.86	75
3	413	4	2.54	95.07	95.56	81
4	457	4	2.55	93.94	94.42	76
5	374	7	2.56	94.22	94.70	88
6	487	7	2.59	–	94.20	85
7	421	4	2.60	–	94.21	90
8	482	5	2.60	–	93.88	64
9	481	4	2.60	–	94.35	88
10	422	6	2.61	–	93.14	71

Table A-11. Maximum bentonite temperature for the canister with the lowest thermal conductivity in each of the six lowest ranked realisations for Domain RFM045, 6.7 m cc, tunnel cc 40 m, tunnel direction 145°, start temperature 11.3°C, gradient 0.012°C/m.

Ranking	Realisation no	Canister no	Min average weighted thermal conductivity W/(m·K)	Max bentonite temperature *without* temp. dep. rock properties °C	Max bentonite temperature *with* temp. dep. rock properties °C	Proportion TRC 17 in the nearest zone (2.5 m) %
1	450	3	2.46	94.73	95.23	100
2	473	7	2.52	–	94.65	76
3	457	4	2.54	–	94.05	78
4	413	4	2.55	–	95.10	79
5	374	7	2.56	–	94.21	88
6	487	7	2.58	–	93.83	88

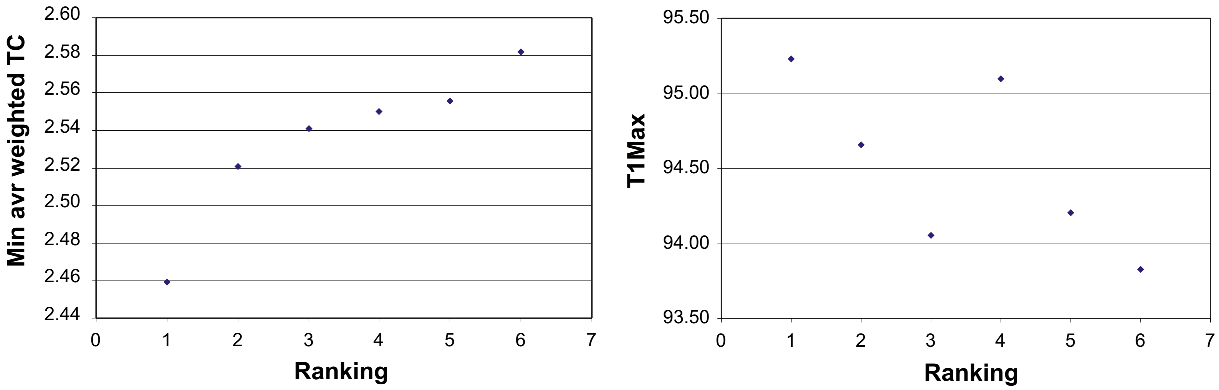


Figure A-3. Canister with the lowest thermal conductivity in each of the six lowest ranked realisations for Domain RFM045. Left: Ranking vs. weighted thermal conductivity (W/(m·K)), Right: Ranking vs. max bentonite temperature (°C). Temperature-dependent rock thermal properties are used, 6.7 m cc, tunnel cc 40 m, tunnel direction 145°, start temperature 11.3°C, gradient 0.012°C/m.

A.6 References

Back P E, Wrafter J, Sundberg J, Rosén L, 2007. Thermal properties. Site descriptive modelling Forsmark – stage 2.2. SKB R-07-47, Svensk Kärnbränslehantering AB.

Hökmark H, Sundberg J, Kristenson O, Lönnqvist M, Hellström G, 2009. Strategy for thermal dimensioning of the final repository for spent nuclear fuel. SKB R-09-04, Svensk Kärnbränslehantering AB.

Sundberg J, Wrafter J, Back P-E, Rosén L, 2008. Thermal properties Forsmark. Modelling stage 2.3. Complementary analysis and verification of the thermal bedrock model, stage 2.2 SKB R-08-65, Svensk Kärnbränslehantering AB.

Appendix B

Properties of deformation zones modelled to intersect the target volume at –400 to –600 m elevation

The geological and hydrogeological properties of the forty-six (46) deformation zones that have been modelled during stage 2.2 /Stephens et al. 2007/ to intersect the Forsmark target volume at –400 to –600 m elevation are summarized in the tables in this appendix. Five (5) of these zones are gently dipping and forty-one (41) zones are steeply dipping structures. Only three of the steeply dipping zones have a trace length at the ground surface that is longer than 3,000 m (ZFMENE0060A with attached branches ZFMENE0060B and ZFMENE0060C, ZFMENE0062A, and ZFMWNW0123). Furthermore, fifteen (15) of the forty-one (41), steeply dipping structures are local minor zones with a trace length at the ground surface less than 1,000 m. All zones except ZFMWNW0123 show solely brittle deformation and can be referred to as fracture zones. The steeply dipping structures are overwhelmingly dominated by zones included in the steeply dipping ENE (NE) and NNE sub-sets (Chapter 5 in /Stephens et al. 2007/).

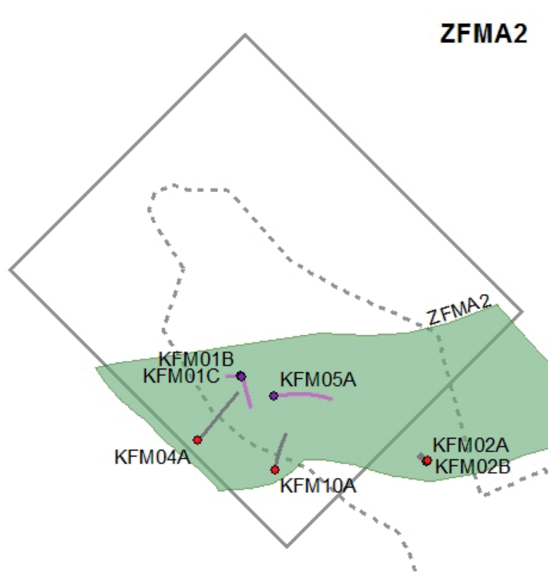
All information bearing on style of deformation, rock alteration, geometry and orientation of fractures in a zone have been extracted from the property tables for deformation zones at Forsmark (Appendices 15 and 16 in /Stephens et al. 2007/). These property tables were produced during the stage 2.2 modelling work. More detailed information, including data sources, span estimates and confidence level in a particular property, can be found in these tables. Data assembled from boreholes KFM02B and KFM08D, which only became available during stage 2.3 after completion of the final modelling work, are included in the parts of a table that document borehole intersections, location in cartographic format, transmissivity and engineering characteristics. A combination of the geological information addressed in /Stephens et al. 2007/ and /Stephens et al. 2008/ and of the hydrogeological information addressed in /Follin et al. 2007a/, /Follin et al. 2007b/ and /Follin et al. 2008/ have been utilized for the definition of these attributes. The attribute referred to as "Engineering characteristics" refers to division of a zone into transition and core segments, and the frequency and mineralogy of open and sealed fractures along each of these segments. The updating of attributes and the integration of geological and hydrogeological data along zones account for differences between the property tables presented here and those presented in /Stephens et al. 2007/.

This Appendix is identical to Appendix 4 in SDM-Site Forsmark /SKB 2008/.

Deformation zone ZFMA2

Borehole intersections (metres along borehole)

KFM01B: DZ1 and extension (16-64 m)
KFM01C: DZ1 (23-48 m) and DZ2 (62-99 m)
KFM02A: Part of DZ6 (417-442 m)
KFM02B: DZ3 (411-431 m)
KFM04A: DZ2 (202-213 m) and DZ3 (232-242 m) and less fractured rock between DZ2 and DZ3 (213-232 m)
KFM05A: DZ1 (102-114 m)
KFM10A: DZ2 (430-449 m) and DZ3 (478-490 m)
KFM01A (percussion part): DZ1 and extension (29-51 m)
HFM01: DZ1 (35-44 m)
HFM14: DZ1 (68-76 m) and DZ2 (92-104 m)
HFM15: DZ1 (86-96 m)
HFM19: DZ1 (121-148 m) and DZ2 (168-185 m)
HFM27: DZ1 (26-30 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination. Altered vuggy rock with quartz dissolution between 483 and 488 m along DZ3 in KFM10A

Strike/dip (right-hand-rule): 080/24

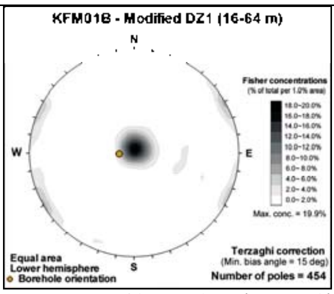
Trace length at ground surface: 3,987 m

Model thickness / model thickness span : 23 m / 9-45 m

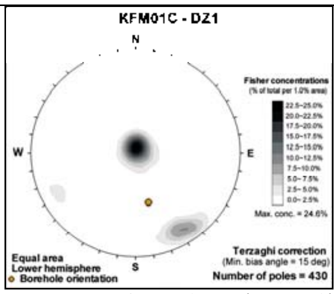
Measured thickness (-400 to -600 m elevation): 28 m in KFM02A (part of DZ6), 16 m in KFM10A (DZ2) combined with 9 m in KFM10A (DZ3)

Comment: Data from KFM02B only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

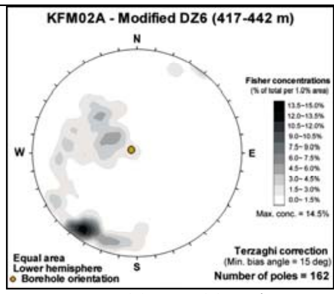
Fractures in the deformation zone



Elevation: -13 to -59 m (RHB 70)



Elevation: -15 to -34 m (RHB 70)



Elevation: -409 to -433 m (RHB 70)

Transmissivity (m²/s)

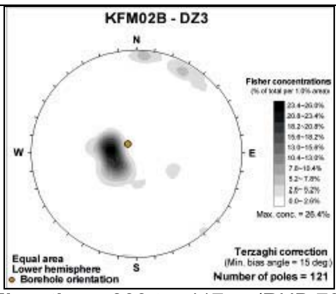
General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.4E-06
Model T, depth range -500 to -600 m: 2.0E-06

Transmissivity (m²/s)

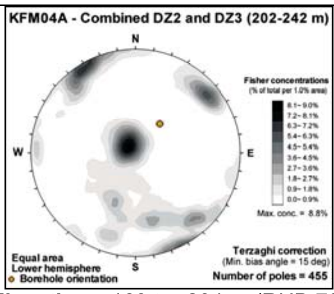
General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.4E-06
Model T, depth range -500 to -600 m: 2.0E-06

Transmissivity (m²/s)

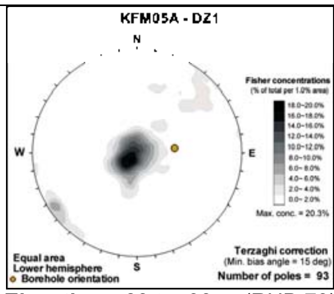
General dip of T fractures: gentle
Measured T range -400 to -600 m: 2.9E-06
Number PFL-features: 14
Model T, depth range -400 to -500 m: 5.4E-06
Model T, depth range -500 to -600 m: 2.0E-06



Elevation: -399 to -417 m (RHB 70)



Elevation: -169 to -204 m (RHB 70)



Elevation: -83 to -93 m (RHB 70)

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Transmissivity (m^2/s)

General dip of T fractures: gentle
Measured T range -400 to -600 m: 3.9E-05
Number PFL-features: 14
Model T, depth range -400 to -500 m: 5.4E-06
Model T, depth range -500 to -600 m: 2.0E-06

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Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.4E-06
Model T, depth range -500 to -600 m: 2.0E-06

</td>
<td>

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.4E-06
Model T, depth range -500 to -600 m: 2.0E-06

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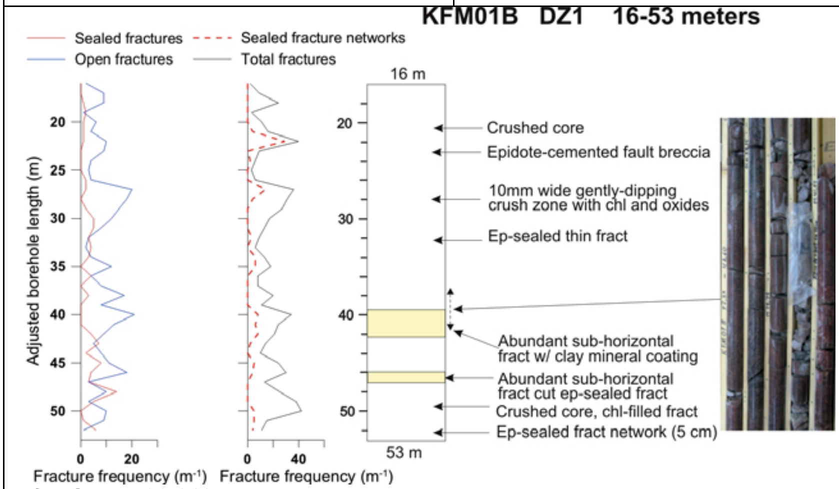

After SKB P-06-212

KFM02A (upper part of DZ6)

</td>
<td>

Engineering characteristics

Percentage of fault core: 7.7% (P-06-212 and P-07-111). No fault core recognised in KFM02B (DZ3) and KFM10A (DZ2 and DZ3).

Boreholes KFM01B, KFM01C and KFM05A not included in fracture statistics below due to interference with near-surface fracturing

Transition part of zone:
Frequency of open fractures: 4.8 m^{-1}
Std dev: 1.6
Mineral coating along open fractures: chlorite, calcite, adularia/hematite, no mineral, clay minerals

Frequency of sealed fractures: 8.1 m^{-1}
Std dev: 5.1
Mineral filling along sealed fractures: calcite, adularia/hematite, chlorite, laumontite

Fault core:
Frequency of open fractures: 2.9 m^{-1}
Std dev 2.1
Mineral coating along open fractures: no mineral, chlorite, adularia/hematite, calcite

Frequency of sealed fractures: 34.5 m^{-1}
Std dev: 28.2
Mineral filling along sealed fractures: adularia/hematite, calcite, laumontite

</td>
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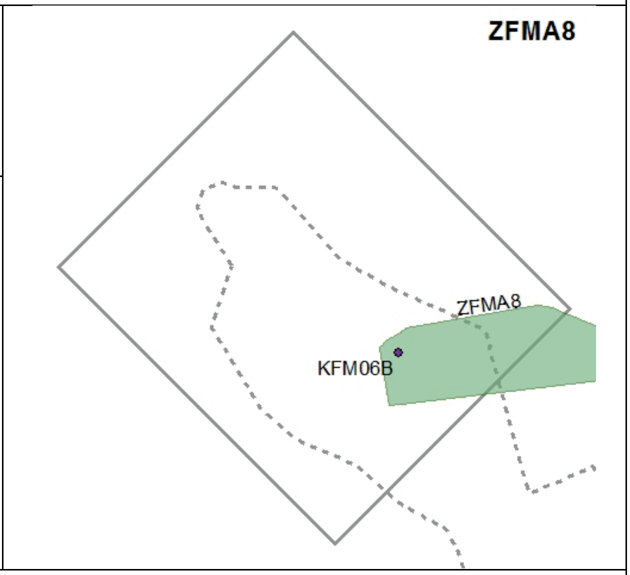
Deformation zone ZFMA8

Borehole intersections (metres along borehole)

KFM06B: DZ1 (55-93 m)
HFM16: DZ1 (12-71 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination. Altered vuggy rock with quartz dissolution between 66 and 70 m along DZ1 in KFM06B

Strike/dip (right-hand-rule): 080/35

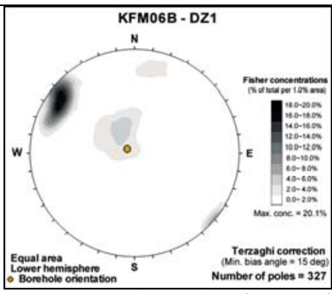
Trace length at ground surface: 1,852 m

Model thickness / model thickness span : 32 m / 6-37 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

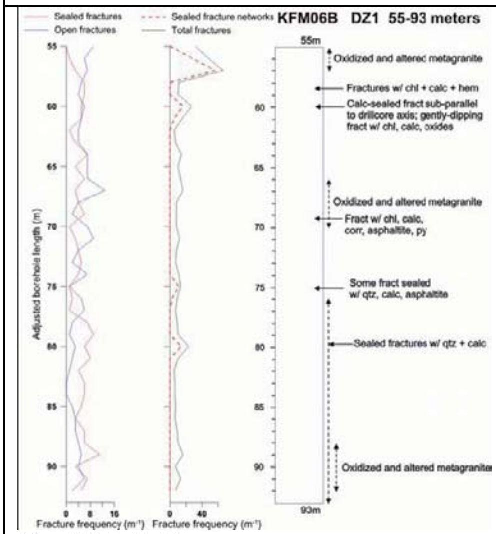
Fractures in the deformation zone



Elevation: -51 to -88 m (RHB 70)

Transmissivity (m²/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 7.1E-06
Model T, depth range -500 to -600 m: 2.6E-06



After SKB P-06-212

Strong hematite alteration and small fractures filled with quartz and calcite that has been partly dissolved and transported away (after SKB P-06-212)

Engineering characteristics

Percentage of fault core: No fault core recognised (P-06-212). No division into transition and core

No fracture statistics since fractures along DZ1 in borehole KFM06B interfere with near-surface fracturing

Deformation zone ZFMB4

Borehole intersections (metres along borehole)

KFM02A: DZ8 (893-905 m)

Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Not present

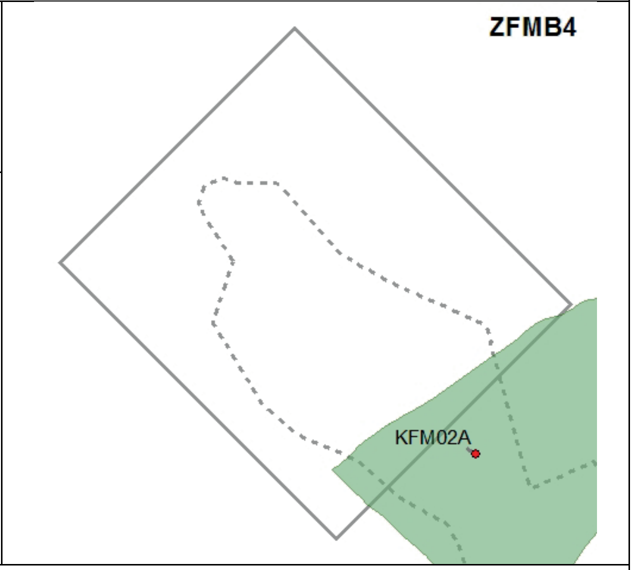
Strike/dip (right-hand-rule): 050/29

Trace length at ground surface: Does not intersect the ground surface

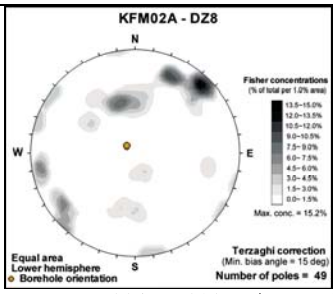
Model thickness / model thickness span : 12 m / 6-37 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:



Fractures in the deformation zone



Elevation: -881 to -893 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: gentle
Measured T range -400 to -600 m: 2.62E-09
Number of PFL-features: 1
Model T, depth range -400 to -500 m: 2.0E-07
Model T, depth range -500 to -600 m: 7.3E-08

KFM02A (DZ8)

Engineering Characteristics

Percentage of fault core: No fault core recognised (P-06-212). No division into transition and core

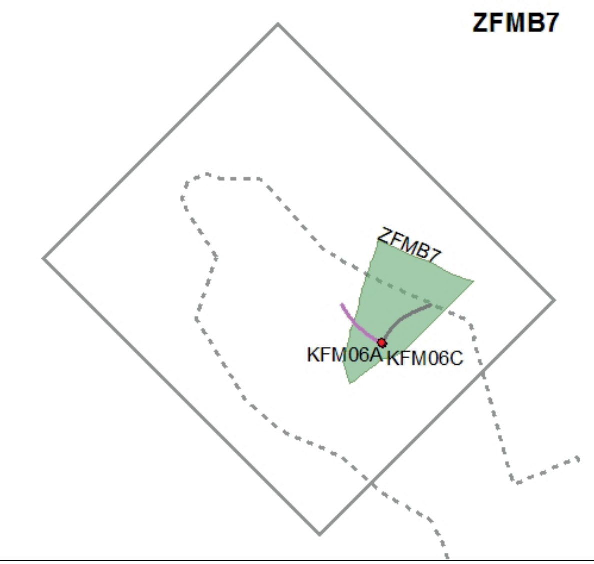
Frequency of open fractures: 1.1 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, no mineral

Frequency of sealed fractures: 3.7 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, no mineral

Deformation zone ZFMB7

Borehole intersections (metres along borehole)

KFM06A: DZ4 (318-358 m)
KFM06C: DZ2 (359-400 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination. Vuggy rock with quartz dissolution at 332-333 m along DZ4 in KFM06A

Strike/dip (right-hand-rule): 020/20

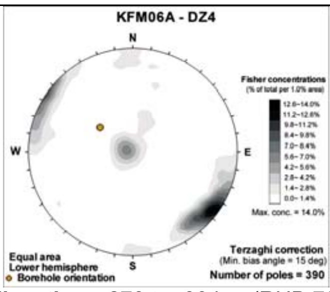
Trace length at ground surface: Does not intersect the ground surface

Model thickness / model thickness span : 28 m / 6-37 m

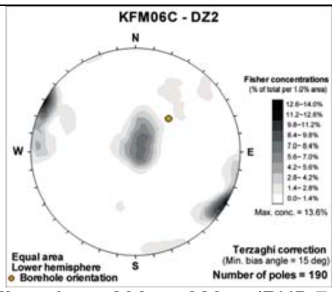
Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -270 to -304 m (RHB 70)



Elevation: -296 to -329 m (RHB 70)

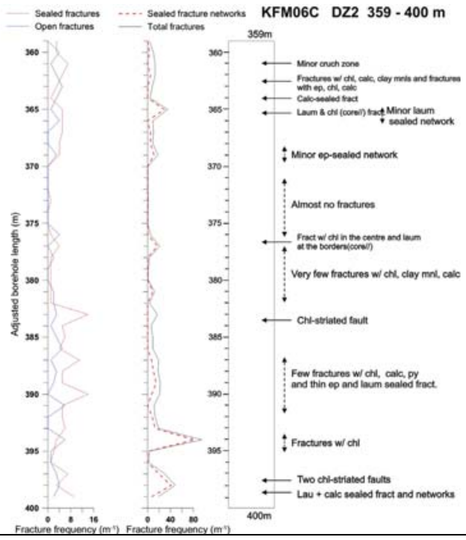
Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.3E-07
Model T, depth range -500 to -600 m: 2.0E-07

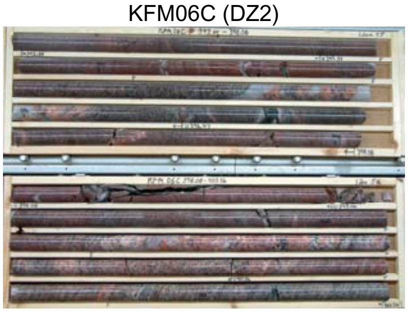
Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.3E-07
Model T, depth range -500 to -600 m: 2.0E-07

After SKB P-07-101



KFM06C (DZ2)



Engineering Characteristics

Percentage of fault core: No fault core recognised (P-06-212 and P-07-101). No division into transition and core

Borehole KFM06A not included in fracture statistics below due to interference with zone ZFMENE0060A

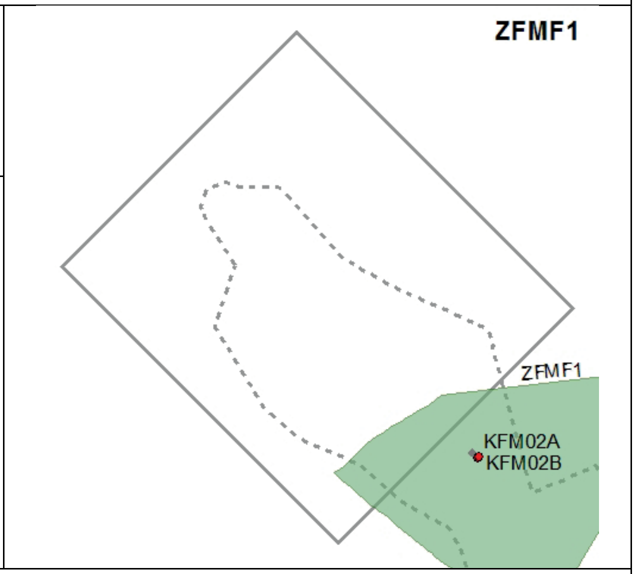
Frequency of open fractures: 2.1 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals

Frequency of sealed fractures: 11.3 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, epidote

Deformation zone ZFMF1

Borehole intersections (metres along borehole)

KFM02A: Part of DZ6 (476-520 m)
KFM02B: DZ5 (462-472 m) and DZ6 (485-511 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Oxidized bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 070/10

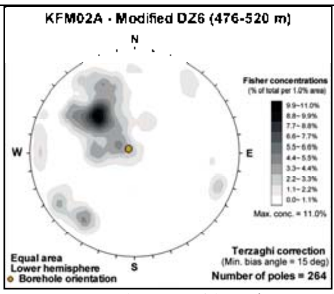
Trace length at ground surface: Does not intersect the ground surface

Model thickness / model thickness span : 44 m / 9-45 m

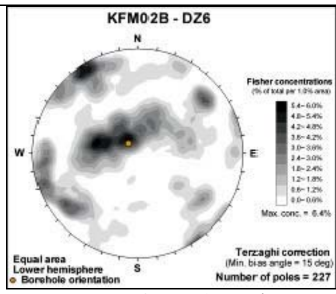
Measured thickness (-400 to -600 m elevation): 44 m

Comment: Data from KFM02B only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

Fractures in the deformation zone



Elevation: -467 to -510 m (RHB 70)



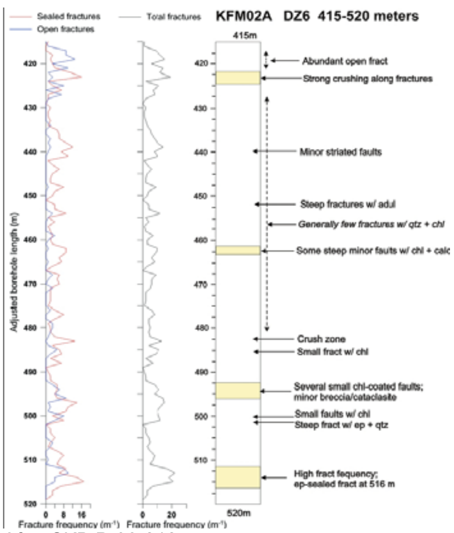
Elevation: -471 to -497 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: gentle
Measured T range -400 to -600 m: 4.66E-06
Number of PFL-features: 22
Model T, depth range -400 to -500 m: 6.9E-06
Model T, depth range -500 to -600 m: 2.5E-06

Transmissivity (m^2/s)

General dip of T fractures: gentle (?)
Measured T range -400 to -600 m: 6.2E-5
Number of PFL-features: 9
Model T, depth range -400 to -500 m: 6.9E-06
Model T, depth range -500 to -600 m: 2.5E-06



After SKB P-06-212

Network of gently dipping, epidote-sealed fractures that are present in a metadiorite and altered metagranite at 516 m (after SKB P-06-212)

Engineering characteristics

Percentage of fault core: 7.3% (P-06-212 and P-07-111)

Transition part of zone:
Frequency of open fractures: 3.1 m^{-1}
Std dev: 2.1
Mineral coating along open fractures: calcite, calcite, chlorite, clay minerals, prehnite, adularia/hematite

Frequency of sealed fractures: 12.5 m^{-1}
Std dev: 11.1
Mineral filling along sealed fractures: calcite, prehnite, epidote, chlorite

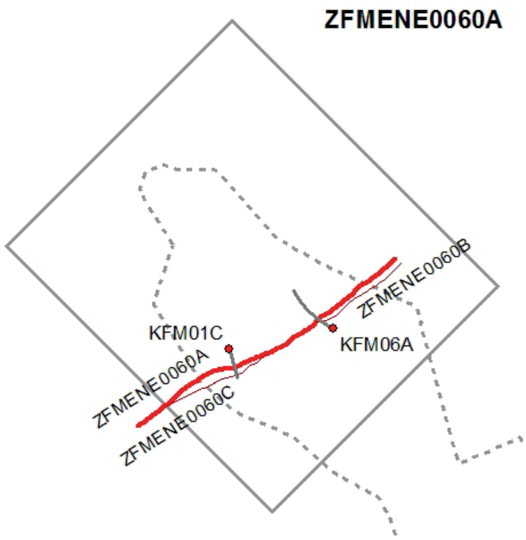
Fault core:
Frequency of open fractures: 5.7 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, adularia/hematite, calcite, clay minerals

Frequency of sealed fractures: 8.2 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, adularia/hematite, prehnite, calcite

Deformation zone ZFMENE0060A

Borehole intersections (metres along borehole)

KFM01C: Part of DZ3 (235-252 m)
KFM06A: DZ4 (318-358 m)
HFM09: DZ1 (18-28 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine grained hematite dissemination. Vuggy rock with quartz dissolution between 332-333 m in KFM06A

Strike/dip (right-hand-rule): 239/85

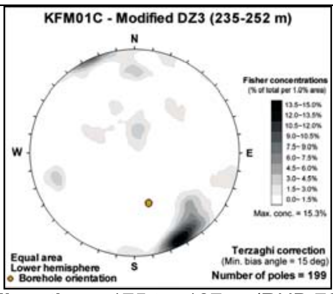
Trace length at ground surface: 3,120 m

Model thickness / model thickness span : 17 m / 10-64 m

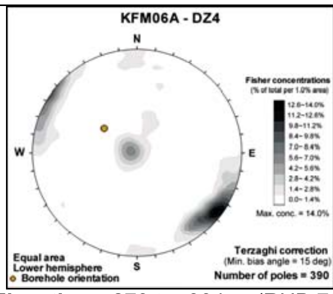
Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -175 to -187 m (RHB 70)



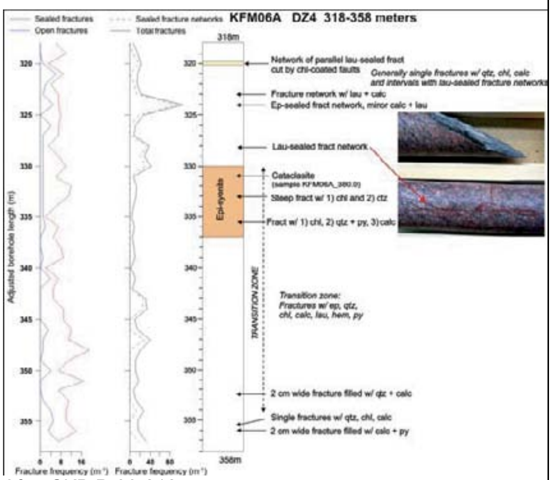
Elevation: -270 to -304 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.3E-08
Model T, depth range -500 to -600 m: 1.2E-08

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.3E-08
Model T, depth range -500 to -600 m: 1.2E-08



After SKB P-06-212

KFM01C (part of DZ3)

Engineering characteristics

Percentage of fault core: 5.3% (P-06-212 and P-07-101)

Transition part of zone:
Frequency of open fractures: 2.3 m^{-1}
Std dev: 1.9
Mineral coating along open fractures: chlorite, calcite, laumontite, adularia/hematite, pyrite, clay minerals

Frequency of sealed fractures: 24.9 m^{-1}
Std dev: 21.8
Mineral filling along sealed fractures: calcite, laumontite, adularia/hematite, chlorite, epidote, quartz, prehnite

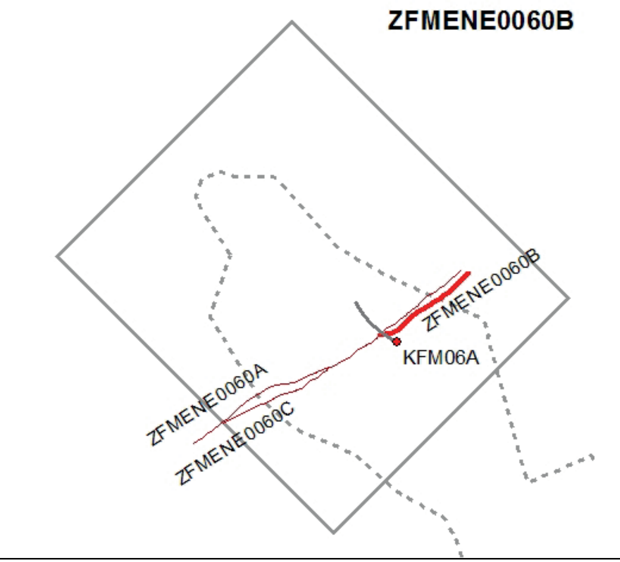
Fault core:
Frequency of open fractures: 3.4 m^{-1}
Std dev: 3.5
Mineral coating along open fractures: calcite, laumontite, chlorite, clay minerals, adularia/hematite, pyrite

Frequency of sealed fractures: 69.7 m^{-1}
Std dev: 52.2
Mineral filling along sealed fractures: laumontite, calcite, chlorite, adularia/hematite

Deformation zone ZFMENE0060B

Borehole intersections (metres along borehole)

KFM06A: DZ2, DZ3 and less fractured rock between DZ2 and DZ3 (195-278 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 234/78

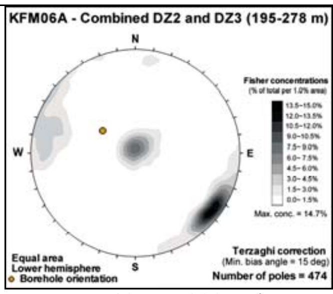
Trace length at ground surface: 1,070 m

Model thickness / model thickness span : 33 m / 3-35 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

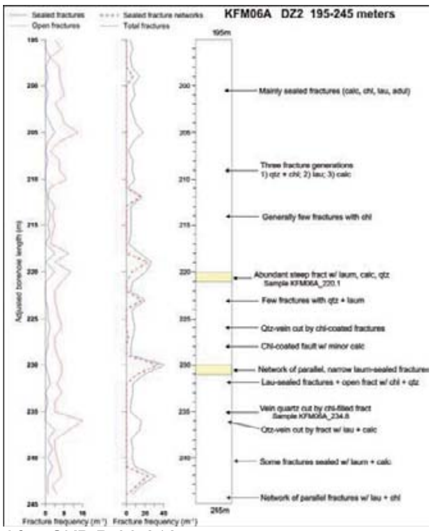
Fractures in the deformation zone



Elevation: -165 to -236 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.8E-06
Model T, depth range -500 to -600 m: 1.4E-06



After SKB P-06-212

KFM06A (DZ3). Strong alteration (red-stained bedrock with hematite dissemination) and abundant sealed fractures are present.

Engineering characteristics

Percentage of fault core: 9.6% (P-06-212)

Transition part of zone:
Frequency of open fractures: 1.0 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, pyrite, clay minerals, no mineral

Frequency of sealed fractures: 6.3 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, adularia/hematite

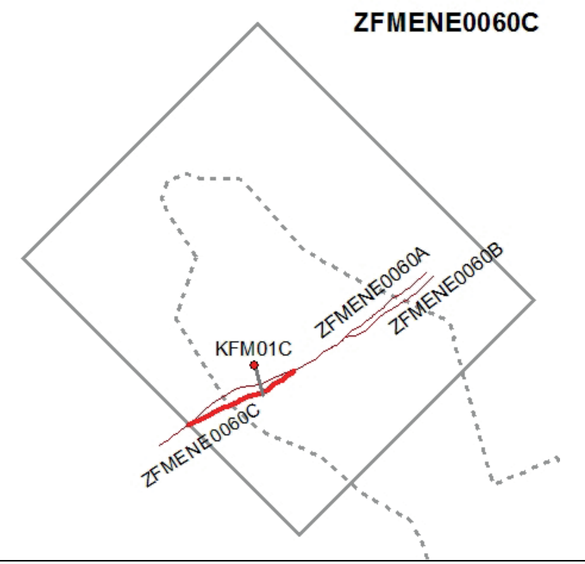
Fault core:
Frequency of open fractures: 3.1 m^{-1}
Std dev: 3.4
Mineral coating along open fractures: calcite, clay minerals, chlorite, no mineral

Frequency of sealed fractures: 41.1 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, epidote, chlorite, adularia/hematite

Deformation zone ZFMENE0060C

Borehole intersections (metres along borehole)

KFM01C: Part of DZ3 (305-330m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 241/75

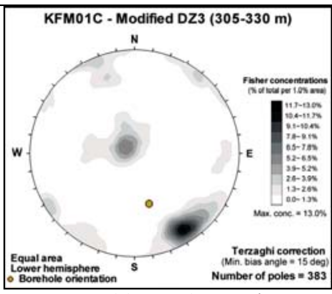
Trace length at ground surface: 1,161 m

Model thickness / model thickness span : 20 m / 3-45 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -227 to -245 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.0E-08
Model T, depth range -500 to -600 m: 2.0E-08

KFM01C (part of DZ3)

Engineering characteristics

Percentage of fault core: 16% (P-07-101)

Transition part of zone:
Frequency of open fractures: 4.3 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, laumontite, calcite, clay minerals

Frequency of sealed fractures: 24.4 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: laumontite, calcite

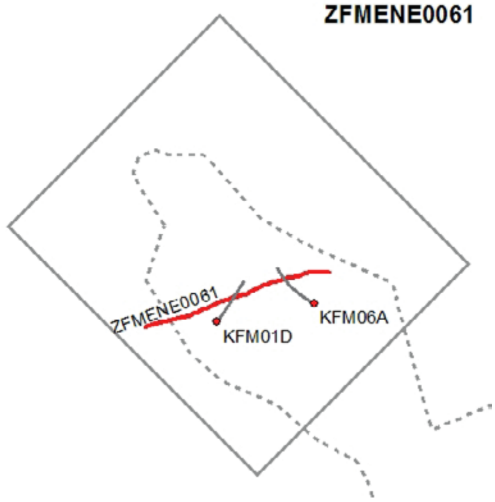
Fault core:
Frequency of open fractures: 5.5 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, laumontite, adularia/hematite, clay minerals

Frequency of sealed fractures: 40.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: laumontite, calcite, chlorite

Deformation zone ZFMENE0061

Borehole intersections (metres along borehole)

KFM01D: DZ4 (670-700 m)
KFM06A: DZ8 (788-810 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine grained hematite dissemination. Alteration in borehole restricted to DZ4 in KFM01D

Strike/dip (right-hand-rule): 252/85

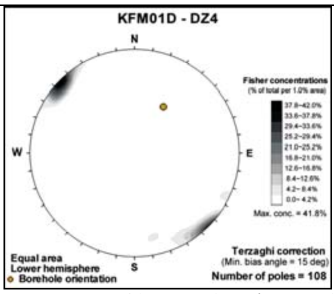
Trace length at ground surface: 2,081 m

Model thickness / model thickness span : 11 m / 3-45 m

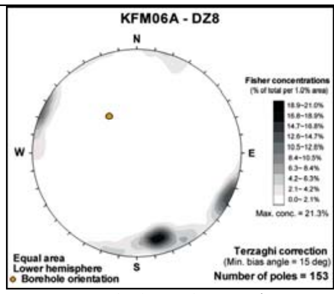
Measured thickness (-400 to -600 m elevation): 11 m

Comment:

Fractures in the deformation zone



Elevation: -519 to -540 m (RHB 70)



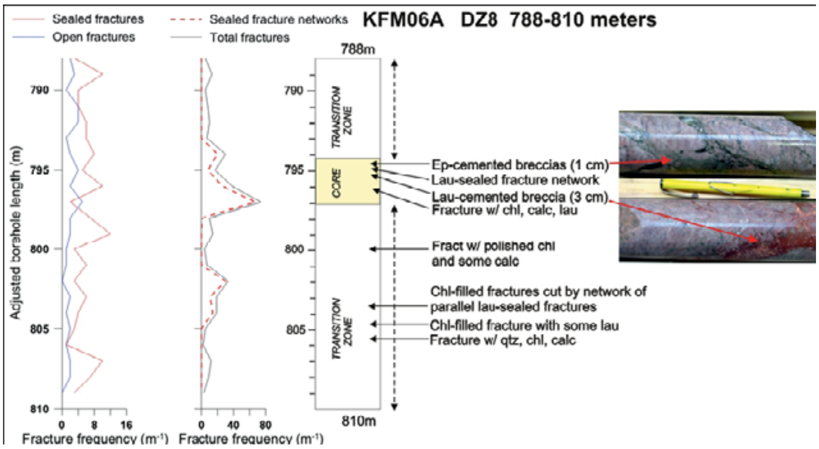
Elevation: -659 to -677 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.00E-10
Number of PFL-features: 0
Model T, depth range -400 to -500 m: 4.3E-10
Model T, depth range -500 to -600 m: 1.6E-08

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 4.3E-10
Model T, depth range -500 to -600 m: 1.6E-08



After SKB P-06-212

Engineering characteristics

Percentage of fault core: 9.6% (P-06-212 and P-07-101)

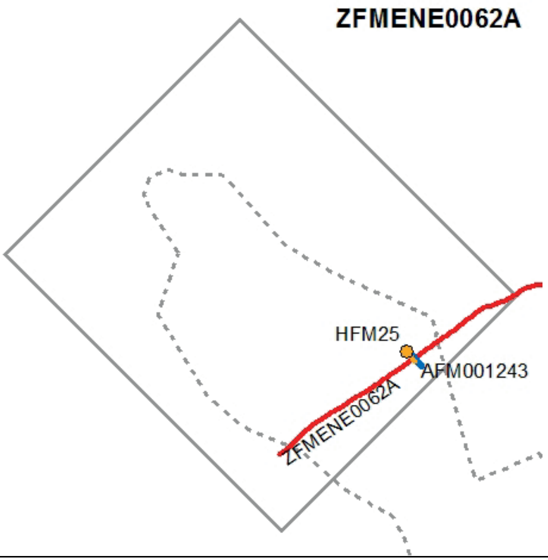
Transition part of zone:
Frequency of open fractures: 1.4 m^{-1}
Std dev: 0.4
Mineral coating along open fractures: calcite, chlorite, quartz, clay minerals, laumontite
Frequency of sealed fractures: 6.3 m^{-1}
Std dev: 3.2
Mineral filling along sealed fractures: calcite, chlorite, laumontite, no mineral, quartz

Fault core:
Frequency of open fractures: 2.6 m^{-1}
Std dev: 2.7
Mineral coating along open fractures: calcite, chlorite, clay minerals, laumontite
Frequency of sealed fractures: 30.6 m^{-1}
Std dev: 27.4
Mineral filling along sealed fractures: laumontite, calcite, chlorite, adularia/hematite, quartz, epidote

Deformation zone ZFMENE0062A

Borehole intersections (metres along borehole)

HFM25: DZ4 (143-155 m) and DZ5 (169-187 m)
Surface excavation at AFM001243



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 058/85

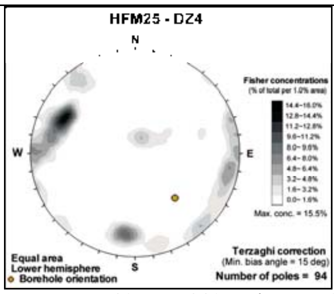
Trace length at ground surface: 3,543 m

Model thickness / model thickness span : 44 m / 10-64 m

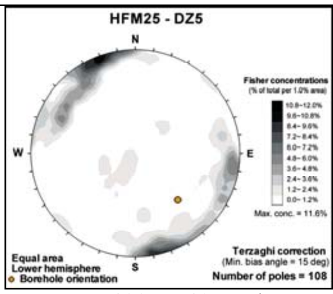
Measured thickness (-400 to -600 m elevation): No intersection

Comment: Based only on surface excavation (AFM001243) and percussion borehole intersections (HFM25) close to surface

Fractures in the deformation zone



Elevation: -105 to -113 m (RHB 70)



Elevation: -122 to -134 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 4.4E-08
Model T, depth range -500 to -600 m: 4.4E-08

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 4.4E-08
Model T, depth range -500 to -600 m: 4.4E-08

Surface excavation AFM001243

Engineering characteristics

Percentage of fault core: No data from cored boreholes. For this reason, no fracture frequency statistics

Deformation zone ZFMENE0103

Borehole intersections (metres along borehole)

KFM05A: DZ4 (892-916 m)

Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

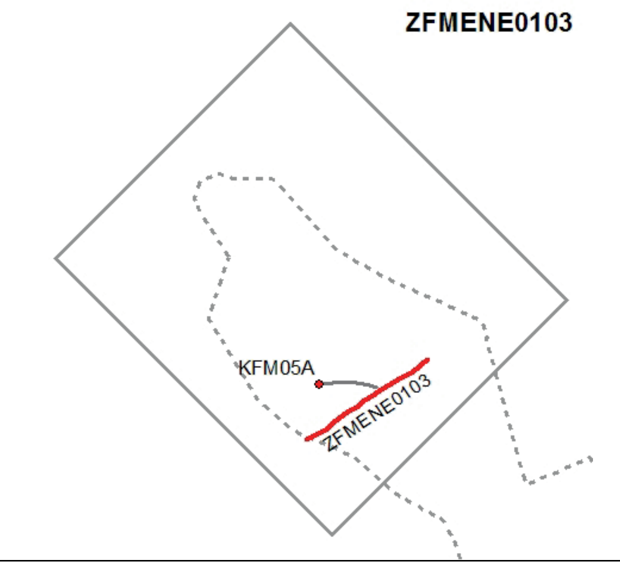
Strike/dip (right-hand-rule): 236/84

Trace length at ground surface: 1,399 m

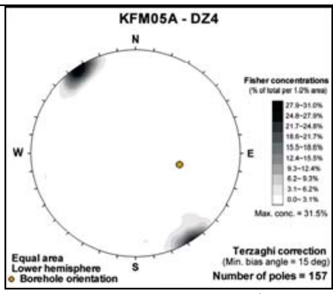
Model thickness / model thickness span : 13 m / 3-45 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:



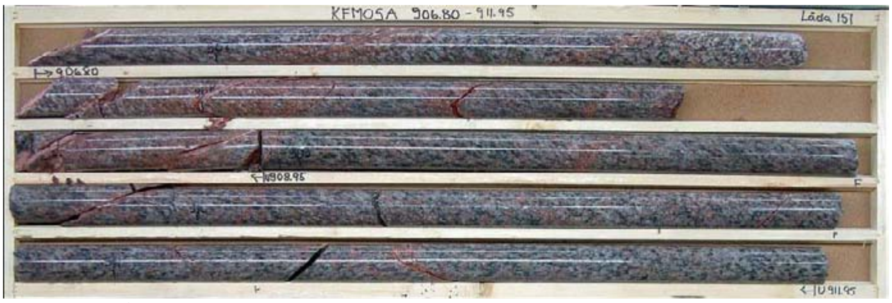
Fractures in the deformation zone



Elevation: -738 to -757 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.9E-09
Model T, depth range -500 to -600 m: 7.1E-10



DZ4 in KFM05A

Engineering characteristics

Percentage of fault core: No data available along DZ4 in KFM05A to assess core and transition. No division made

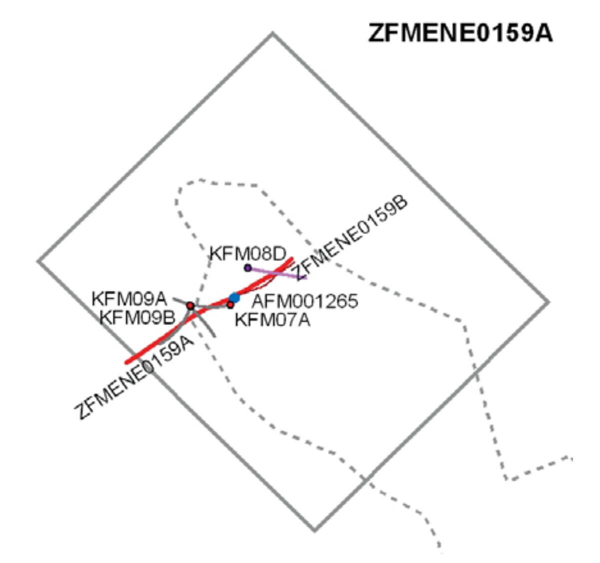
Frequency of open fractures: 0.4 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, adularia/hematite, calcite, no mineral, quartz, laumontite

Frequency of sealed fractures: 10.3 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, laumontite, adularia/hematite, chlorite

Deformation zone ZFMENE0159A

Borehole intersections (metres along borehole)

KFM07A: DZ3 (417-422 m)
KFM08D: DZ2 (318-324 m)
KFM09A: DZ3 (217-280 m)
KFM09B: Part of DZ1 (106-132 m)
Surface excavation at AFM001265



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 239/80

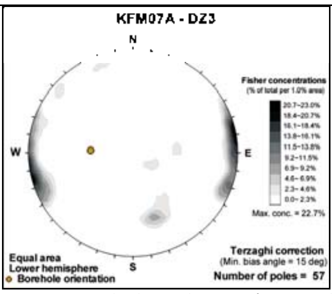
Trace length at ground surface: 1,909 m

Model thickness / model thickness span : 21 m / 3-45 m

Measured thickness (-400 to -600 m elevation): 2 m

Comment: KFM08D only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

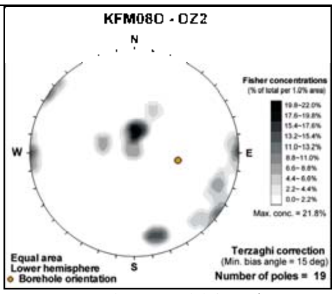
Fractures in the deformation zone



Elevation: -353 to -357 m (RHB 70)

Transmissivity (m^2/s)

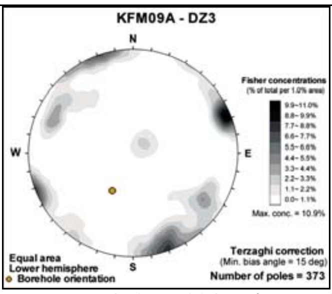
General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.8E-10
Model T, depth range -500 to -600 m: 1.0E-09



Elevation: -255 to -261 m (RHB 70)

Transmissivity (m^2/s)

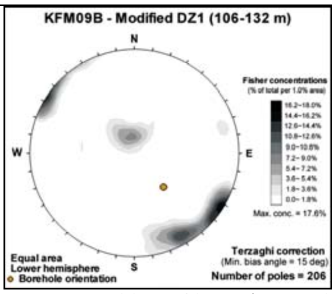
General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.8E-10
Model T, depth range -500 to -600 m: 1.0E-09



Elevation: -178 to -231 m (RHB 70)

Transmissivity (m^2/s)

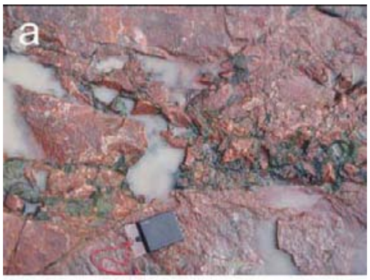
General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.8E-10
Model T, depth range -500 to -600 m: 1.0E-09



Elevation: -83 to -104 m (RHB 70)

Transmissivity (m^2/s)

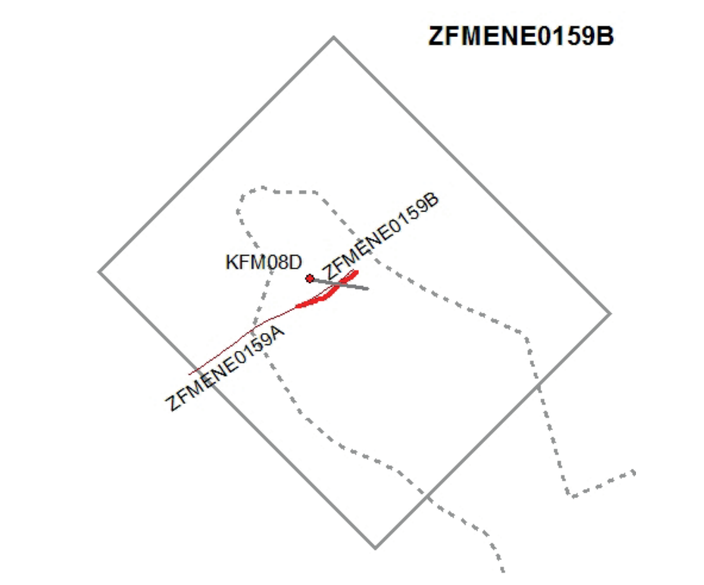
General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.8E-10
Model T, depth range -500 to -600 m: 1.0E-09

 KFM09A (DZ3)	 Surface excavation AFM001265. Chlorite- and epidote-sealed breccia at intersection between NNE-SSW and ENE-WSW fractures. Note the strong wall-rock alteration (red-staining) (after P-06-136)	**Engineering characteristics** ***Percentage of fault core:*** 10.6% (P-06-212. P-07-101 and P-07-111). Borehole KFM08D not included in fracture statistics due to possible interference with zone ZFMENE0159B ***Transition part of zone:*** **Frequency of open fractures:** 2.5 m^{-1} **Std dev:** 0.6 **Mineral coating along open fractures:** calcite, chlorite, clay minerals, laumontite, adularia/hematite, pyrite **Frequency of sealed fractures:** 15.6 m^{-1} **Std dev:** 1.3 **Mineral filling along sealed fractures:** calcite, chlorite, laumontite, adularia/hematite ***Fault core:*** **Frequency of open fractures:** 2.5 m^{-1} **Std dev:** 1.5 **Mineral coating along open fractures:** calcite, chlorite, adularia/hematite, pyrite, clay minerals, laumontite, quartz **Frequency of sealed fractures:** 43.8 m^{-1} **Std dev:** 13.6 **Mineral filling along sealed fractures:** laumontite, calcite, chlorite, adularia/hematite, epidote

Deformation zone ZFMENE0159B

Borehole intersections (metres along borehole)

KFM08D: DZ3 (371-396 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 238/80

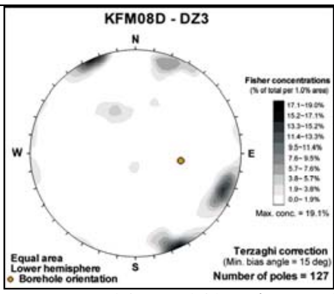
Trace length at ground surface: 673 m

Model thickness / model thickness span : 10 m / 2-43 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment: KFM08D only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

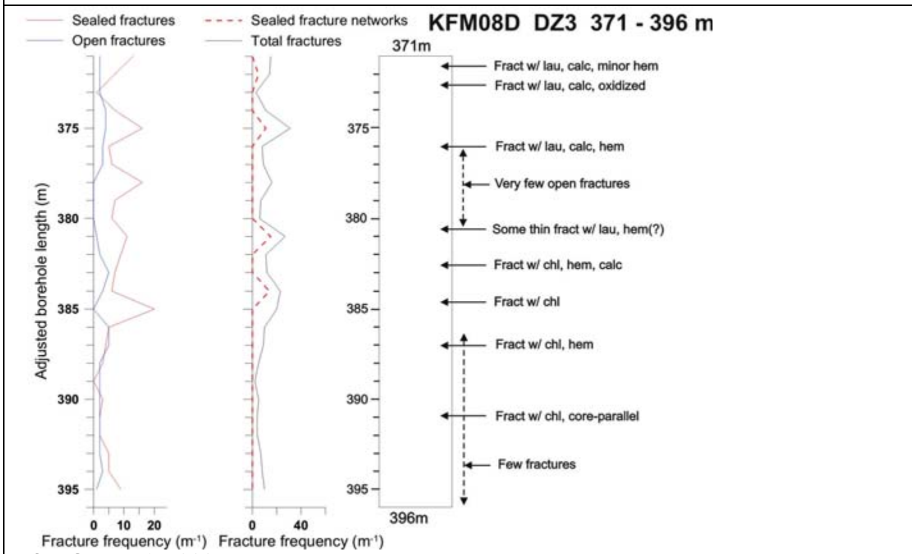
Fractures in the deformation zone



Elevation: -217 to -319 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.8E-09
Model T, depth range -500 to -600 m: 1.0E-09



After SKB P-07-111

Engineering characteristics

Percentage of fault core: No fault core recognised (P-07-111). No division into transition and core

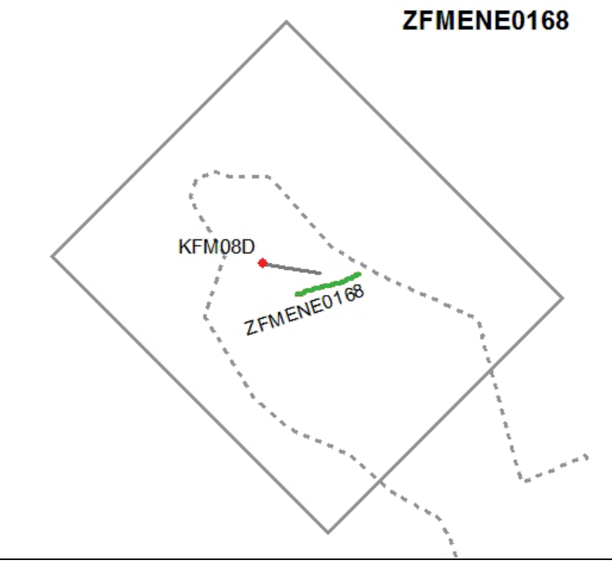
Frequency of open fractures: 2.3 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, clay minerals, pyrite

Frequency of sealed fractures: 8.9 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, prehnite, adularia/hematite

Deformation zone ZFMENE0168

Borehole intersections (metres along borehole)

KFM08D: DZ11 (819-842 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 253/90

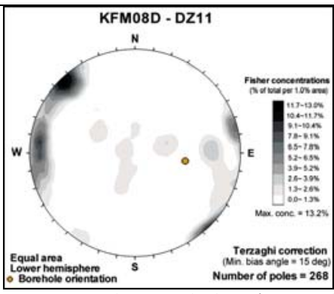
Trace length at ground surface: 639 m

Model thickness / model thickness span : 10 m / 2-43 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment: KFM08D only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

Fractures in the deformation zone



Elevation: -654 to -672 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.8E-09
Model T, depth range -500 to -600 m: 1.0E-09

KFM08D (DZ11)

Engineering characteristics

Percentage of fault core: No data available along DZ11 in KFM08D to assess core and transition. No division made

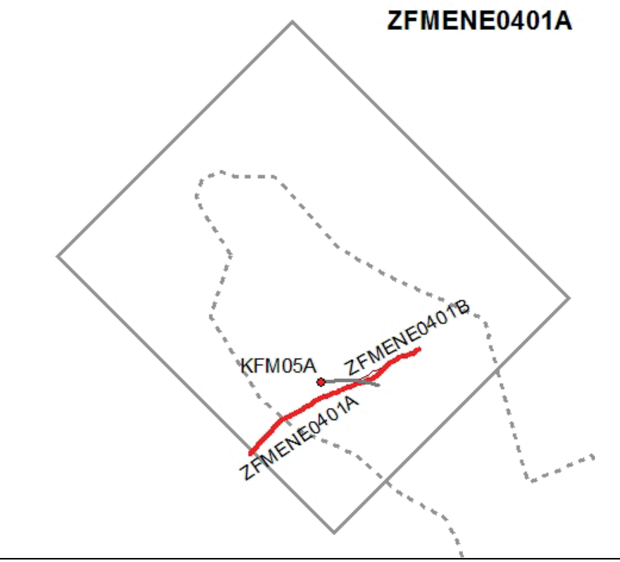
Frequency of open fractures: 2.0 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, quartz, clay minerals, adularia/hematite, calcite

Frequency of sealed fractures: 17.2 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: adularia/hematite, chlorite, quartz

Deformation zone ZFMENE0401A

Borehole intersections (metres along borehole)

KFM05A: Part of DZ3 (685-720 m)
HFM13: DZ1 (162-176 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 240/89

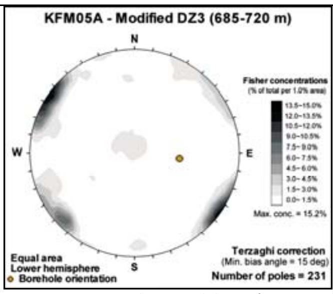
Trace length at ground surface: 1,961 m

Model thickness / model thickness span : 10 m / 3-45 m

Measured thickness (-400 to -600 m elevation): 10 m

Comment:

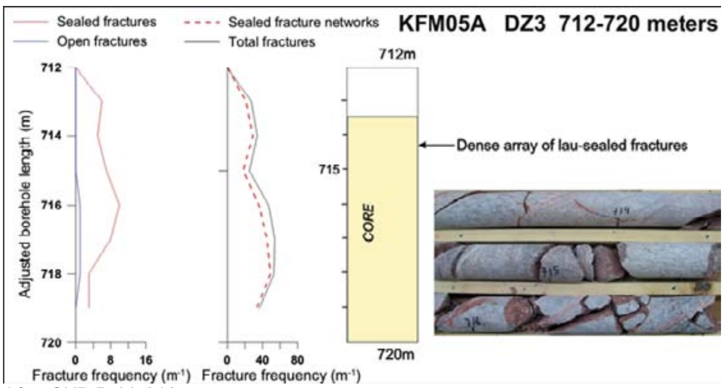
Fractures in the deformation zone



Elevation: -570 to -598 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.20E-08
Number of PFL-features: 2
Model T, depth range -400 to -500 m: 7.9E-07
Model T, depth range -500 to -600 m: 2.9E-09



After SKB P-06-212

Engineering characteristics

Percentage of fault core: 17.1% (P-06-212)

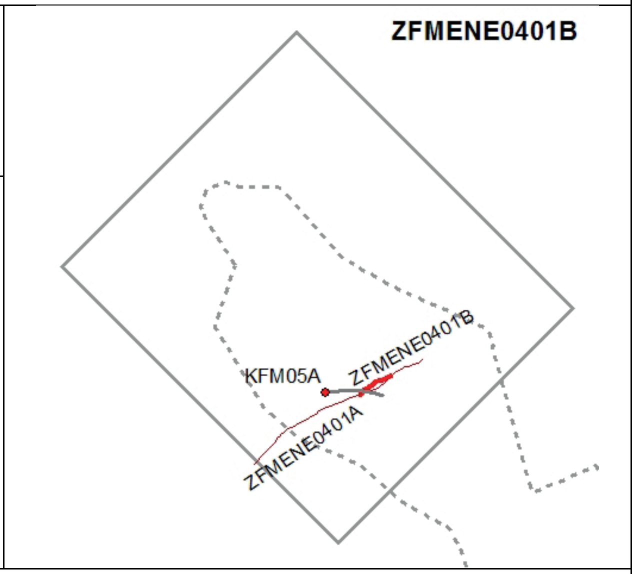
Transition part of zone:
Frequency of open fractures: 0.8 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, laumontite, adularia/hematite, quartz
Frequency of sealed fractures: 8.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, quartz, chlorite, adularia/hematite, laumontite

Fault core:
Frequency of open fractures: 0.5 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, adularia/hematite, chlorite, laumontite
Frequency of sealed fractures: 42.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: laumontite, adularia/hematite, calcite, chlorite

Deformation zone ZFMENE0401B

Borehole intersections (metres along borehole)

KFM05A: Part of DZ3 (590-616 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 061/88

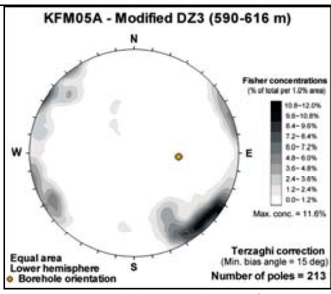
Trace length at ground surface: 358 m

Model thickness / model thickness span : 7 m / 2-30 m

Measured thickness (-400 to -600 m elevation): 7 m

Comment:

Fractures in the deformation zone

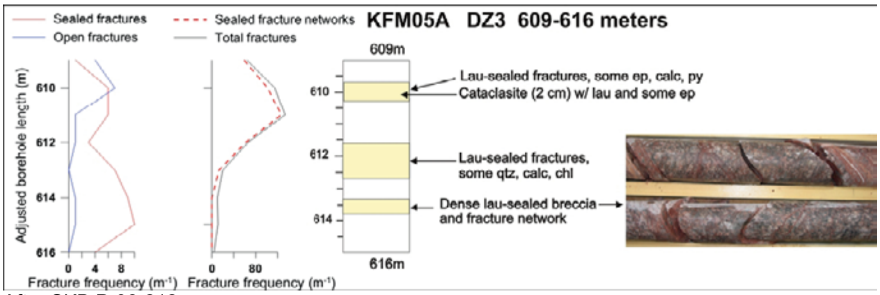


Elevation: -493 to -514 m (RHB 70)

Transmissivity (m²/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.00E-10
Number of PFL-features: 0
Model T, depth range -400 to -500 m: 1.0E-10
Model T, depth range -500 to -600 m: 1.0E-10

Strong fracturing with local brecciation in several intervals between c. 610 and 614 m. Cataclasite also present at c. 610 m. Laumontite is conspicuous and epidote is also present in the inferred zone core between c. 610 and 614 m



After SKB P-06-212

Engineering characteristics

Percentage of fault core: 19.2% (P-06-212)

Transition part of zone:
Frequency of open fractures: 1.5 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, laumontite

Frequency of sealed fractures: 9.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, laumontite, epidote, adularia/hematite, chlorite

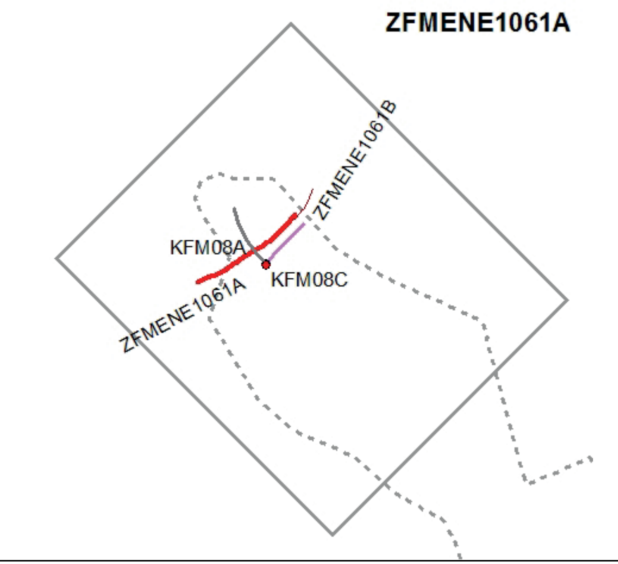
Fault core:
Frequency of open fractures: 2.6 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, laumontite, adularia/hematite, calcite

Frequency of sealed fractures: 78.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: laumontite, calcite, chlorite, adularia/hematite

Deformation zone ZFMENE1061A

Borehole intersections (metres along borehole)

KFM08A: Part of DZ1 (244-315 m)
KFM08C: DZ4 (829-832 m)
KFM08C: DZ5 (946-949 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Oxidized bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 056/81

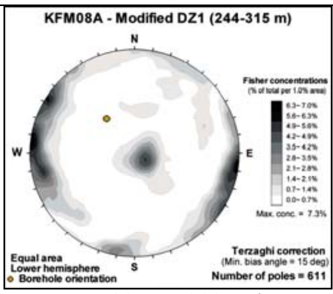
Trace length at ground surface: 1,158 m

Model thickness / model thickness span : 45 m / 3-45 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

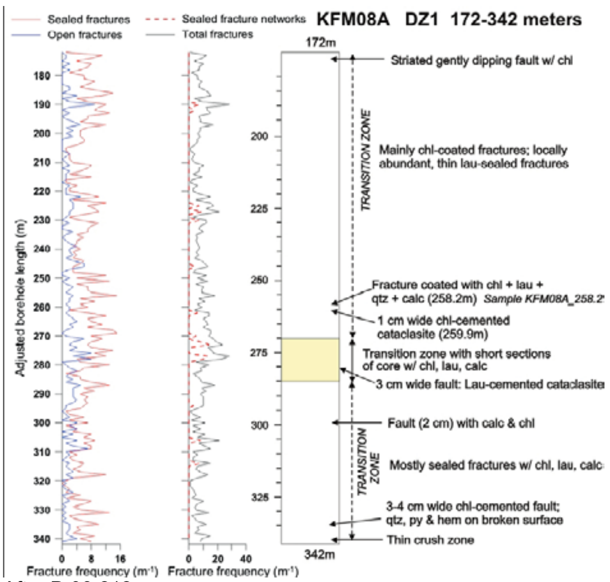
Fractures in the deformation zone



Elevation: -204 to -262 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.0E-08
Model T, depth range -500 to -600 m: 7.4E-09



After P-06-212

Engineering characteristics

Percentage of fault core: 4.2% (P-06-212). Borehole KFM08C not included in fracture statistics due to interference with zone ZFMENE1061B

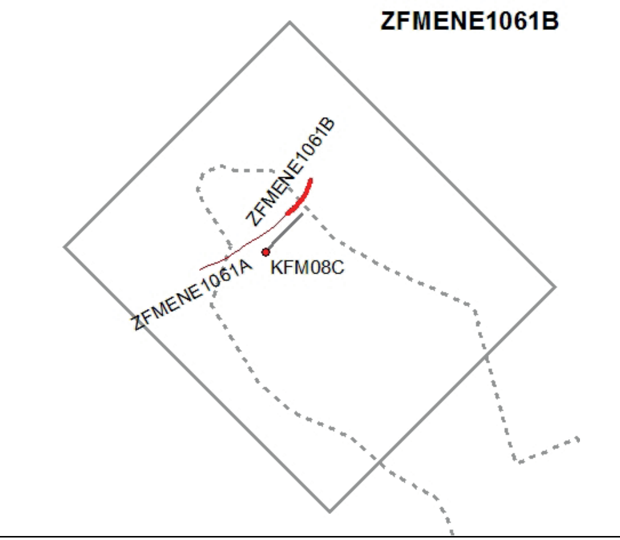
Transition part of zone:
Frequency of open fractures: 2.8 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, pyrite, clay minerals, laumontite, adularia/hematite, quartz
Frequency of sealed fractures: 7.8 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, laumontite, adularia/hematite

Fault core:
Frequency of open fractures: 4.6 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, pyrite, laumontite
Frequency of sealed fractures: 10.7 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, laumontite

Deformation zone ZFMENE1061B

Borehole intersections (metres along borehole)

KFM08C: DZ4 (829-832 m).



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Oxidized bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 033/81

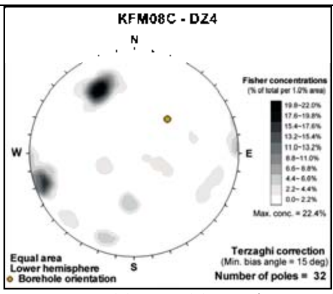
Trace length at ground surface: 436 m

Model thickness / model thickness span : 2 m / 2-30 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -685 to -687 m (RHB 70)

Transmissivity (m²/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.0E-09
Model T, depth range -500 to -600 m: 3.8E-10

KFM08C (DZ4)

Engineering characteristics

Percentage of fault core: 50% (P-07-101)

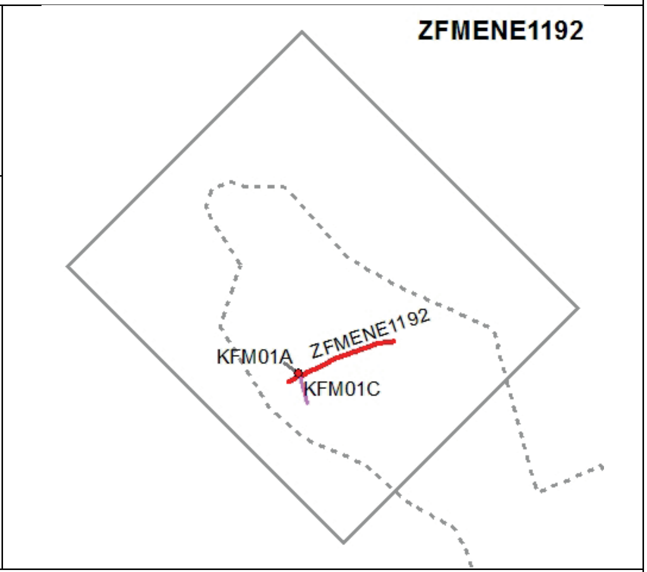
Transition part of zone:
Frequency of open fractures: 16.5 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, adularia/hematite, clay minerals
Frequency of sealed fractures: 14.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, adularia/hematite

Fault core:
Frequency of open fractures: 22.0 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, adularia/hematite, clay minerals
Frequency of sealed fractures: 13.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, adularia/hematite

Deformation zone ZFMENE1192

Borehole intersections (metres along borehole)

KFM01A: DZ5 (267-285 m)
KFM01A: DZ2 (386-412 m)
KFM01C: DZ1 (23-48 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Oxidized bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 064/88

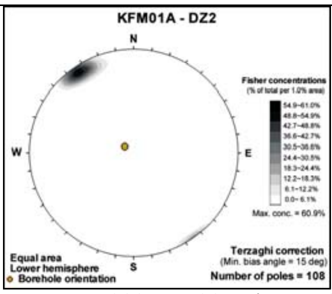
Trace length at ground surface: 1,090 m

Model thickness / model thickness span : 3 m / 3-45 m

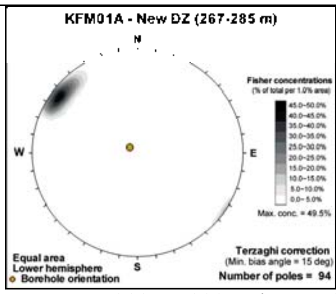
Measured thickness (-400 to -600 m elevation): No intersection

Comment:

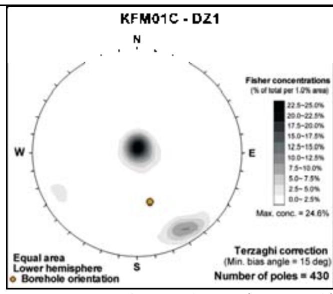
Fractures in the deformation zone



Elevation: -380 to -406 m (RHB 70)



Elevation: -262 to -280 m (RHB 70)



Elevation: -15 to -34 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.m.
Measured T range -400 to -600 m: 1.0E-10
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.0E-10
Model T, depth range -500 to -600 m: 1.0E-10

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.0E-10
Model T, depth range -500 to -600 m: 1.0E-10

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.0E-10
Model T, depth range -500 to -600 m: 1.0E-10

KFM01A (DZ2)

Engineering characteristics

Percentage of fault core: No data available along DZ2 and DZ5 in KFM01A to assess core and transition. Borehole KFM01C not included in fracture statistics due to interference with near-surface fracturing

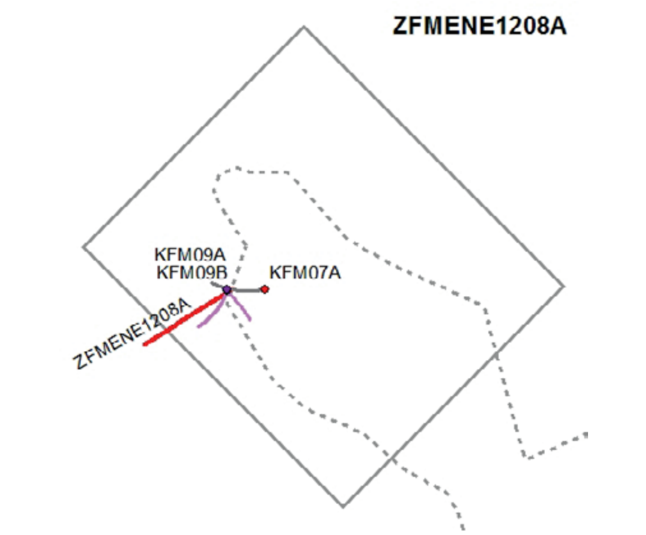
Frequency of open fractures: 2.4 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, laumontite, calcite, adularia/hematite, pyrite

Frequency of sealed fractures: 2.4 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: laumontite, adularia/hematite, chlorite, calcite

Deformation zone ZFMENE1208A

Borehole intersections (metres along borehole)

KFM07A: Part of DZ4 (857-897 m)
KFM09A: DZ1 (15-40 m)
KFM09B: Part of DZ1 (9-43 m)
HFM23: DZ1 (26-42 m)
HFM28: DZ1 (12-65 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 238/81

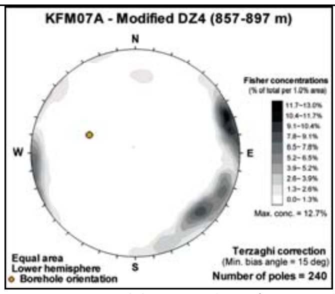
Trace length at ground surface: 1,081 m

Model thickness / model thickness span : 26 m / 3-45 m

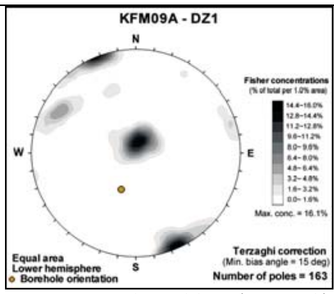
Measured thickness (-400 to -600 m elevation): No intersection

Comment:

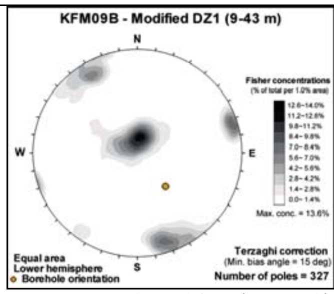
Fractures in the deformation zone



Elevation: -711 to -742 m (RHB 70)



Elevation: -9 to -30 m (RHB 70)



Elevation: -3 to -31 m (RHB 70)

Transmissivity (m^2/s)

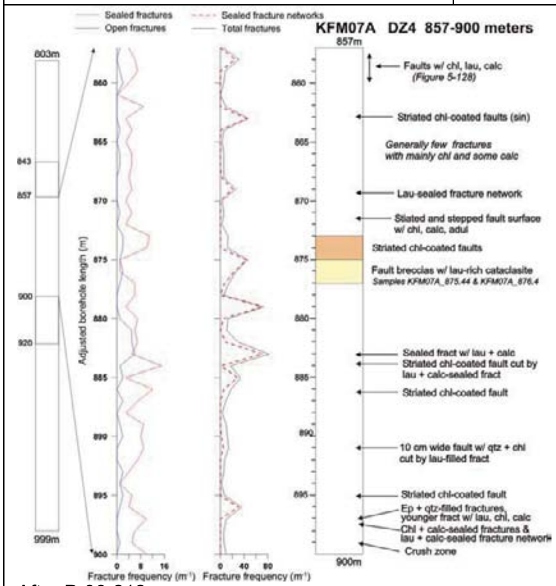
General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.6E-10
Model T, depth range -500 to -600 m: 1.0E-10

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.6E-10
Model T, depth range -500 to -600 m: 1.0E-10

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.6E-10
Model T, depth range -500 to -600 m: 1.0E-10



After P-06-212

Engineering characteristics

Percentage of fault core: 5.0% (P-06-212). Boreholes KFM09A and KFM09B not included in fracture statistics due to interference with near-surface fracturing

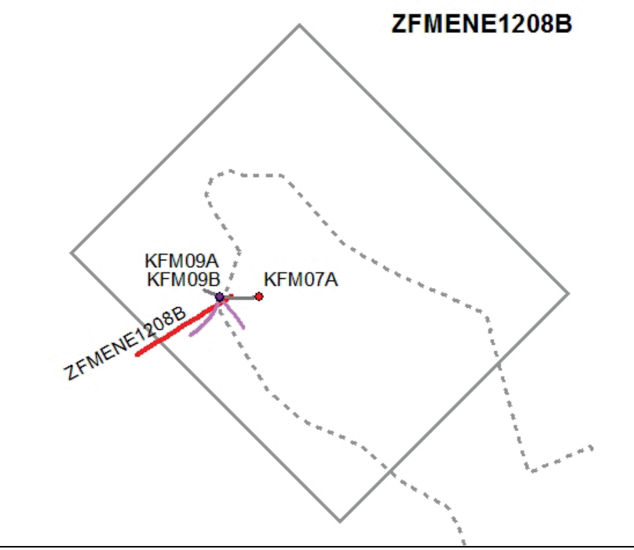
Transition part of zone:
Frequency of open fractures: 1.4 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, quartz, adularia/hematite, laumontite, pyrite, clay minerals
Frequency of sealed fractures: 14.7 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, laumontite, adularia/hematite, calcite, epidote, quartz, pyrite

Fault core:
Frequency of open fractures: 1.5 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, clay minerals, adularia/hematite
Frequency of sealed fractures: 36.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: adularia/hematite, quartz, chlorite, epidote, calcite, laumontite

Deformation zone ZFMENE1208B

Borehole intersections (metres along borehole)

KFM07A: Part of DZ4 (803-840 m)
KFM09A: DZ2 (86-116 m)
KFM09B: Part of DZ1 (59-78 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 238/81

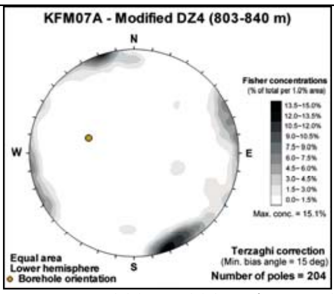
Trace length at ground surface: 1,112 m

Model thickness / model thickness span : 13 m / 3-45 m

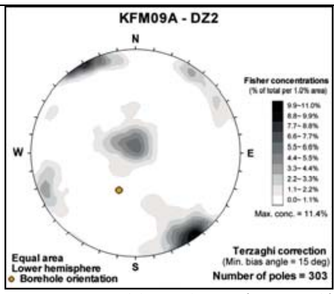
Measured thickness (-400 to -600 m elevation): No intersection

Comment:

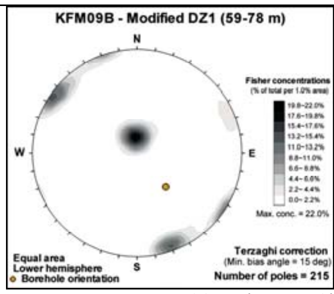
Fractures in the deformation zone



Elevation: -669 to -698 m (RHB 70)



Elevation: -69 to -94 m (RHB 70)



Elevation: -44 to -60 m (RHB 70)

Transmissivity (m^2/s)

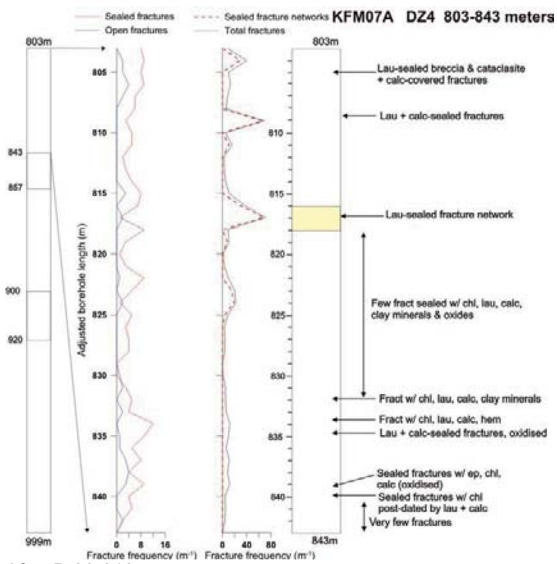
General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.0E-09
Model T, depth range -500 to -600 m: 1.9E-09

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.0E-09
Model T, depth range -500 to -600 m: 1.9E-09

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.0E-09
Model T, depth range -500 to -600 m: 1.9E-09



After P-06-212

Engineering characteristics

Percentage of fault core: 5.4% (P-06-212). Boreholes KFM09A and KFM09B not included in fracture statistics due to interference with near-surface fracturing

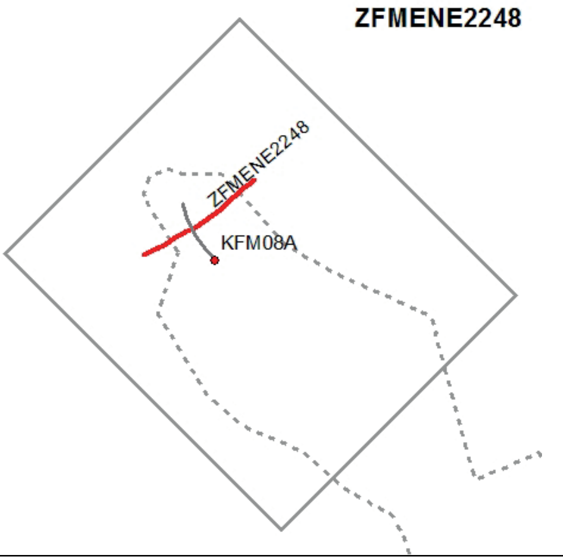
Transition part of zone:
Frequency of open fractures: 0.9 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, adularia/hematite, laumontite
Frequency of sealed fractures: 9.70 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: laumontite, chlorite, calcite, adularia/hematite

Fault core:
Frequency of open fractures: 1.0 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: adularia/hematite, quartz, clay minerals
Frequency of sealed fractures: 53.5 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: adularia/hematite, laumontite, quartz, chlorite

Deformation zone ZFMENE2248

Borehole intersections (metres along borehole)

KFM08A: DZ5 and extension along borehole interval 840-843 m (775-843 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 234/80

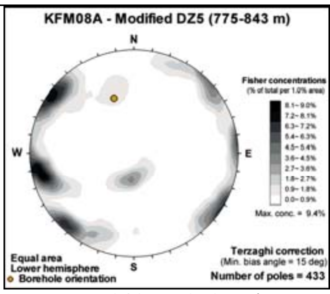
Trace length at ground surface: 1,298 m

Model thickness / model thickness span : 38 m / 3-45 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone

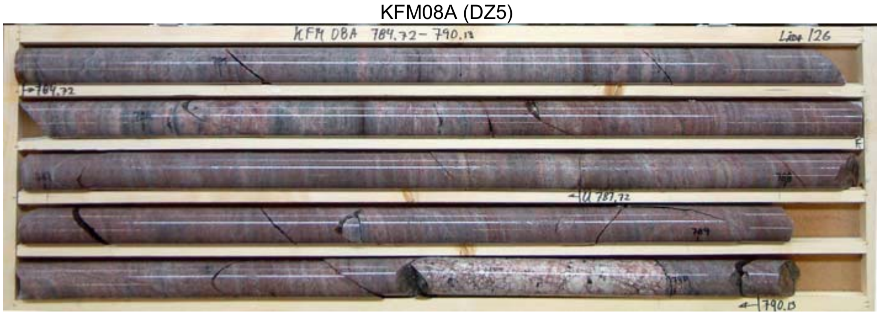


Elevation: -612 to -658 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 6.0E-10
Model T, depth range -500 to -600 m: 2.2E-10

KFM08A (DZ5)



Engineering characteristics

Percentage of fault core: No data available along DZ5 in KFM08A to assess core and transition. No division made

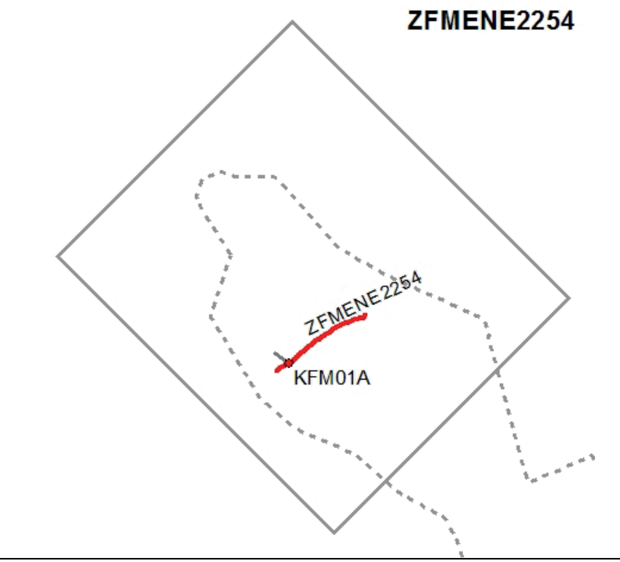
Frequency of open fractures: 0.8 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, adularia/hematite, pyrite

Frequency of sealed fractures: 9.9 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, adularia/hematite

Deformation zone ZFMENE2254

Borehole intersections (metres along borehole)

KFM01A: DZ3 (639-684 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination.

Strike/dip (right-hand-rule): 238/83

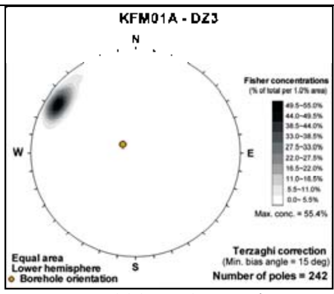
Trace length at ground surface: 1,021 m

Model thickness / model thickness span : 3 m / 3-45 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

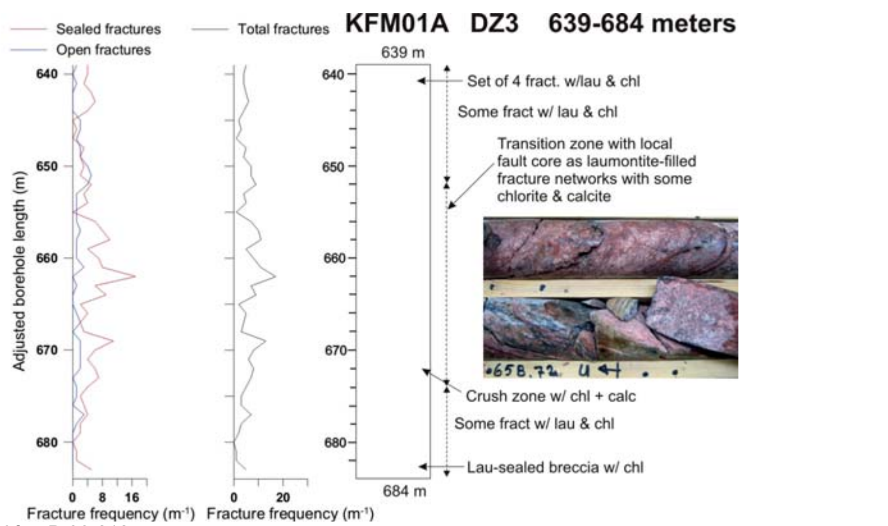
Fractures in the deformation zone



Elevation: -630 to -674 m (RHB 70)

Transmissivity (m²/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 7.4E-10
Model T, depth range -500 to -600 m: 2.7E-10



After P-06-212

Engineering characteristics

Percentage of fault core: Local fault core, position not specified (P-06-212). No division into transition and core

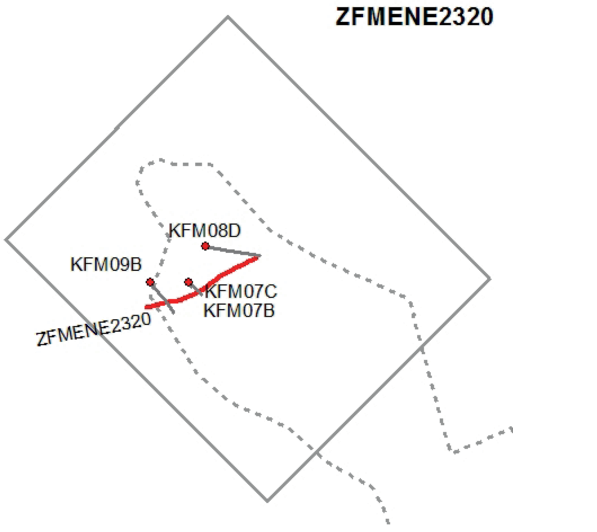
Frequency of open fractures: 1.2 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, laumontite, adularia/hematite

Frequency of sealed fractures: 4.3 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: laumontite, chlorite, adularia/hematite

Deformation zone ZFMENE2320

Borehole intersections (metres along borehole)

KFM07B: DZ4 (225-245 m)
KFM07C: DZ2 (308-388 m) and DZ3 (429-439 m)
KFM08D: DZ7 (621-634 m)
KFM09B: DZ3 (363-413 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination. Chloritised amphibolite along DZ3 in KFM07C. Vuggy rock with quartz dissolution at 382 m along DZ3 in KFM09B

Strike/dip (right-hand-rule): 244/81

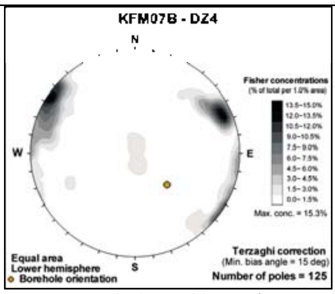
Trace length at ground surface: 1,251 m

Model thickness / model thickness span : 20 m / 3-45 m

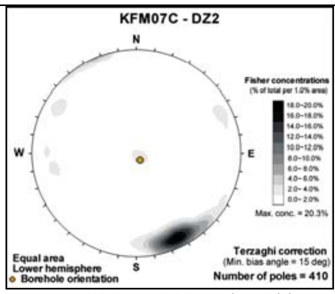
Measured thickness (-400 to -600 m elevation): No intersection

Comment: KFM08D only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

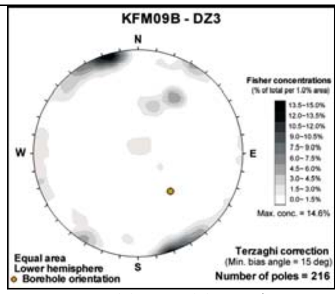
Fractures in the deformation zone



Elevation: -178 to -194 m (RHB 70)



Elevation: -303 to -383 m (DZ2)(RHB 70)



Elevation: -287 to -325 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.2E-10
Model T, depth range -500 to -600 m: 2.0E-10

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.00E-10
Number of PFL-features: 0
Model T, depth range -400 to -500 m: 5.2E-10
Model T, depth range -500 to -600 m: 2.0E-10

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.2E-10
Model T, depth range -500 to -600 m: 2.0E-10

KFM07C (DZ2)

Engineering characteristics

Percentage of fault core: 9.2% (P-07-101, P-07-111)

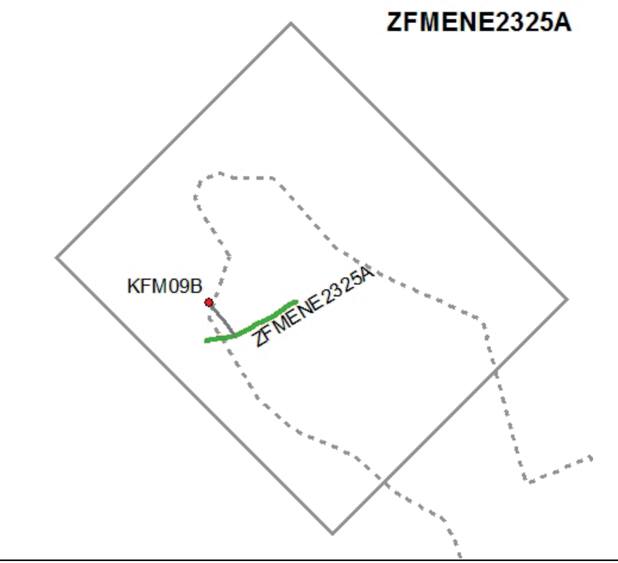
Transition part of zone:
Frequency of open fractures: 1.7 m^{-1}
Std dev: 0.4
Mineral coating along open fractures: calcite, chlorite, laumontite, clay minerals, pyrite, adularia/hematite
Frequency of sealed fractures: 10.8 m^{-1}
Std dev: 9.7
Mineral filling along sealed fractures: calcite, laumontite, chlorite, adularia/hematite

Fault core:
Frequency of open fractures: 2.1 m^{-1}
Std dev: 1.6
Mineral coating along open fractures: calcite, chlorite, laumontite, clay minerals, quartz, pyrite
Frequency of sealed fractures: 32.4 m^{-1}
Std dev: 15.4
Mineral filling along sealed fractures: laumontite, calcite, chlorite, adularia/hematite, pyrite

Deformation zone ZFMENE2325A

Borehole intersections (metres along borehole)

KFM09B: DZ4 (520-550 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 246/82

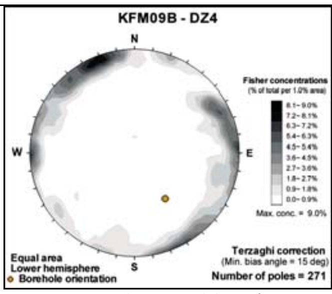
Trace length at ground surface: 963 m

Model thickness / model thickness span : 23 m / 2-43 m

Measured thickness (-400 to -600 m elevation): 23 m

Comment:

Fractures in the deformation zone



Elevation: -404 to -426 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: 1.10E-09
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.3E-10
Model T, depth range -500 to -600 m: 2.7E-10

KFM09B (DZ4)

Engineering characteristics

Percentage of fault core: 6.7% (P-07-101)

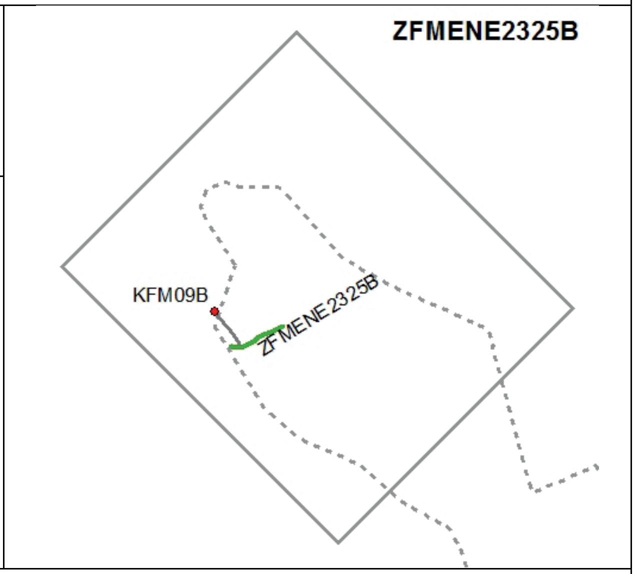
Transition part of zone:
Frequency of open fractures: 0.9 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, adularia/hematite, clay minerals, laumontite, pyrite
Frequency of sealed fractures: 22.6 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, laumontite, adularia/hematite, epidote

Fault core:
Frequency of open fractures: 6.5 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, adularia/hematite, clay minerals
Frequency of sealed fractures: 68.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, adularia/hematite, clay minerals, chlorite

Deformation zone ZFMENE2325B

Borehole intersections (metres along borehole)

KFM09B: DZ5 (561-574 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination. Vuggy rock with quartz dissolution between 568 and 574 m along DZ5 in KFM09B.

Strike/dip (right-hand-rule): 245/81

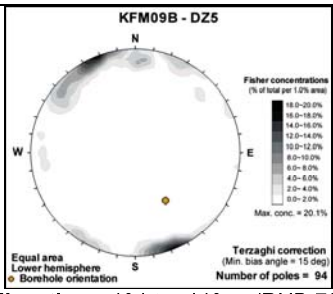
Trace length at ground surface: 553 m

Model thickness / model thickness span : 10 m / 2-43 m

Measured thickness (-400 to -600 m elevation): 10 m

Comment:

Fractures in the deformation zone

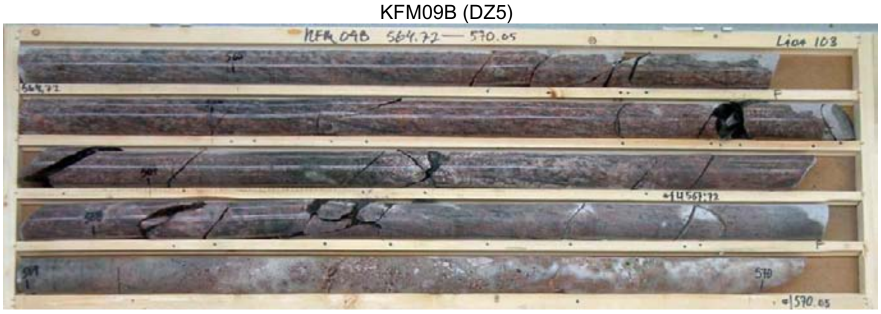


Elevation: -434 to -443 m (RHB 70)

Transmissivity (m²/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: 2.86E-07
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.4E-07
Model T, depth range -500 to -600 m: 8.9E-08

KFM09B (DZ5)



Engineering characteristics

Percentage of fault core: No fault core recognised along DZ5 in KFM09B (P-07-101). No division into transition and core

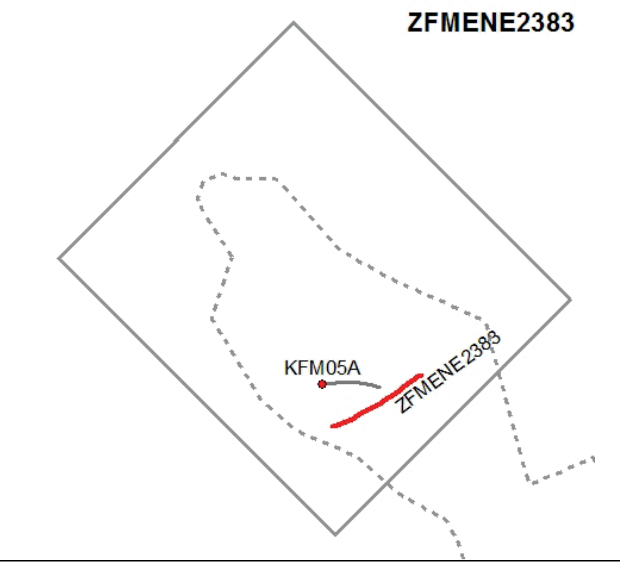
Frequency of open fractures: 3.3 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, quartz

Frequency of sealed fractures: 7.8 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, quartz, epidote, clay minerals

Deformation zone ZFMENE2383

Borehole intersections (metres along borehole)

KFM05A: DZ5 and extension along borehole interval 950-992 m (936-992 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 239/80

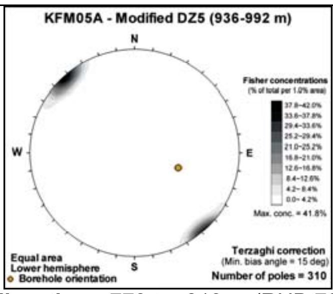
Trace length at ground surface: 1,000 m

Model thickness / model thickness span : 34 m / 3-45 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -773 to -819 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.1E-09
Model T, depth range -500 to -600 m: 1.1E-09

KFM05A (DZ5)

Engineering characteristics

Percentage of fault core: No data available along DZ5 (and extension) in KFM05A to assess core and transition. No division made

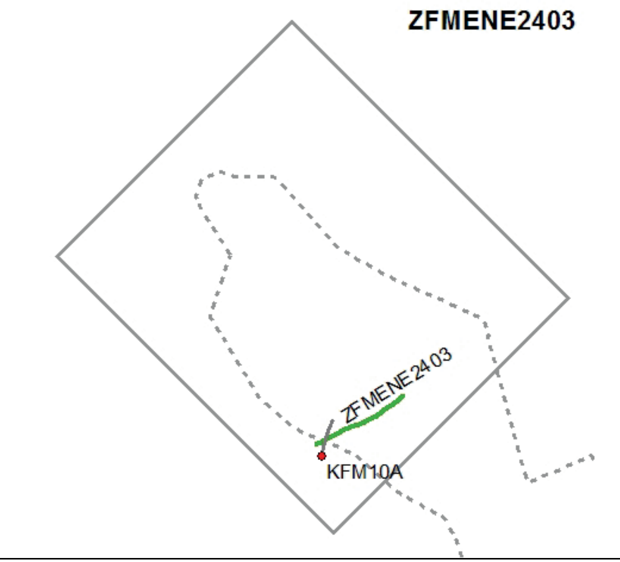
Frequency of open fractures: 0.7 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, adularia/hematite

Frequency of sealed fractures: 9.9 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, adularia/hematite, laumontite

Deformation zone ZFMENE2403

Borehole intersections (metres along borehole)

KFM10A: DZ4 (275-284 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 062/90

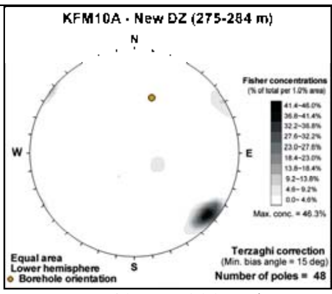
Trace length at ground surface: 958 m

Model thickness / model thickness span : 4 m / 2-43 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -197 to -203 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.0E-10
Model T, depth range -500 to -600 m: 1.0E-10

KFM10A (DZ4)

Engineering characteristics

Percentage of fault core: No data available along DZ4 in KFM10A to assess core and transition. No division made

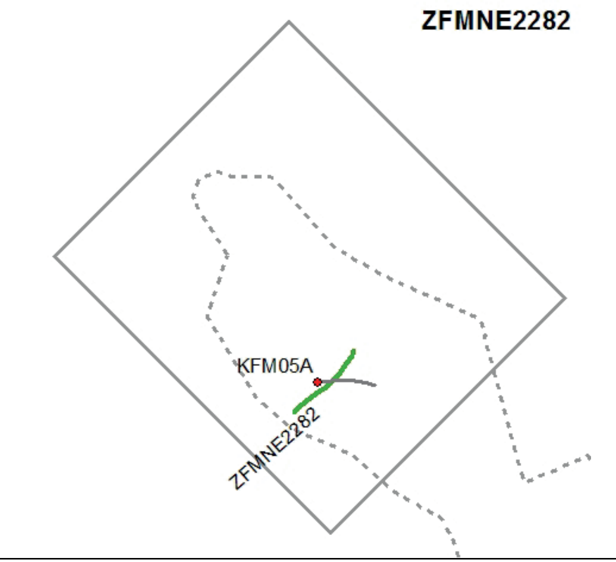
Frequency of open fractures: 1.6 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, adularia/hematite, laumontite

Frequency of sealed fractures: 24.7 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: laumontite, calcite, adularia/hematite, prehnite

Deformation zone ZFMNE2282

Borehole intersections (metres along borehole)

KFM05A: DZ2 and extension along borehole interval 395-416 m (395-436 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 046/81

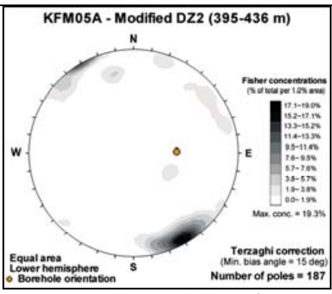
Trace length at ground surface: 842 m.

Model thickness / model thickness span : 11 m / 2-43 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

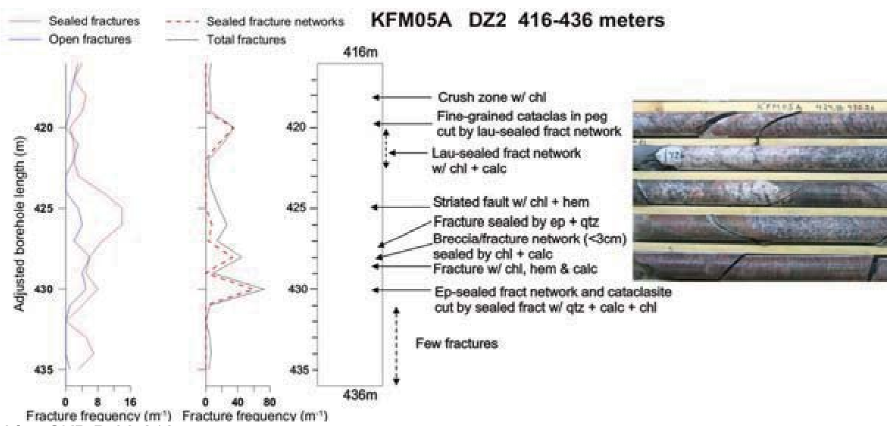
Fractures in the deformation zone



Elevation: -332 to -366 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.0E-10
Model T, depth range -500 to -600 m: 1.0E-10



After SKB P-06-212

Engineering characteristics

Percentage of fault core: No fault core recognised along DZ2 in KFM05A (P-06-212). No division into transition and core

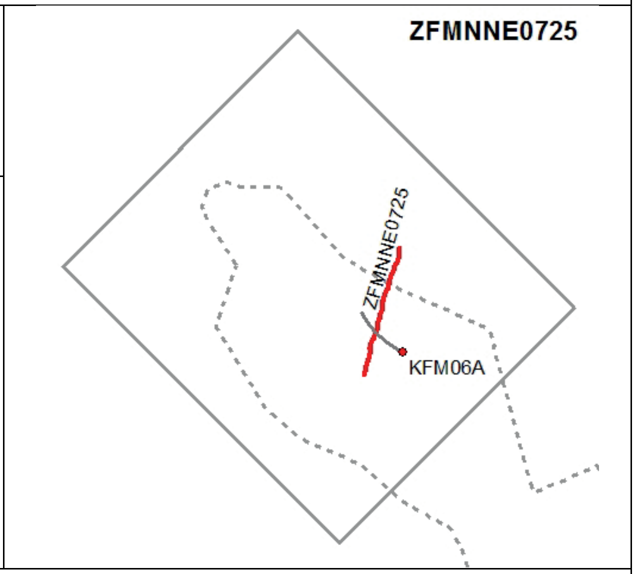
Frequency of open fractures: 1.2 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, laumontite

Frequency of sealed fractures: 10.4 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, adularia/hematite, prehnite, laumontite

Deformation zone ZFMNNE0725

Borehole intersections (metres along borehole)

KFM06A: DZ7 (740-775 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 196/84

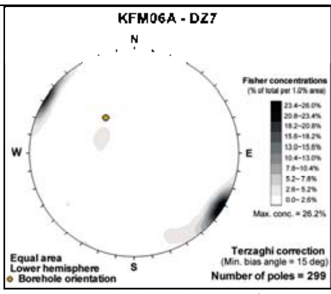
Trace length at ground surface: 1,274 m

Model thickness / model thickness span : 12 m / 3-45 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

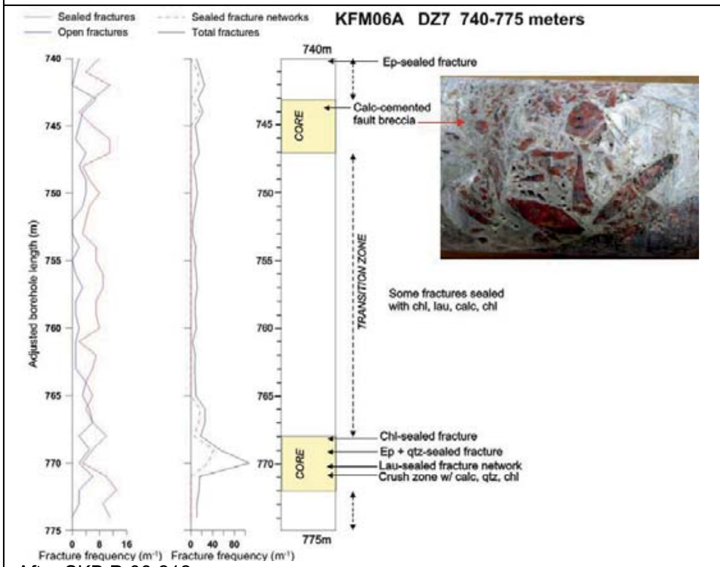
Fractures in the deformation zone



Elevation: -620 to -649 m (RHB 70)

Transmissivity (m²/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 2.1E-06
Model T, depth range -500 to -600 m: 7.8E-07



After SKB P-06-212

Engineering characteristics

Percentage of fault core: 25.7% (P-06-212)

Transition part of zone:
Frequency of open fractures: 1.9 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, adularia/hematite, laumontite

Frequency of sealed fractures: 8.5 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, quartz, adularia/hematite

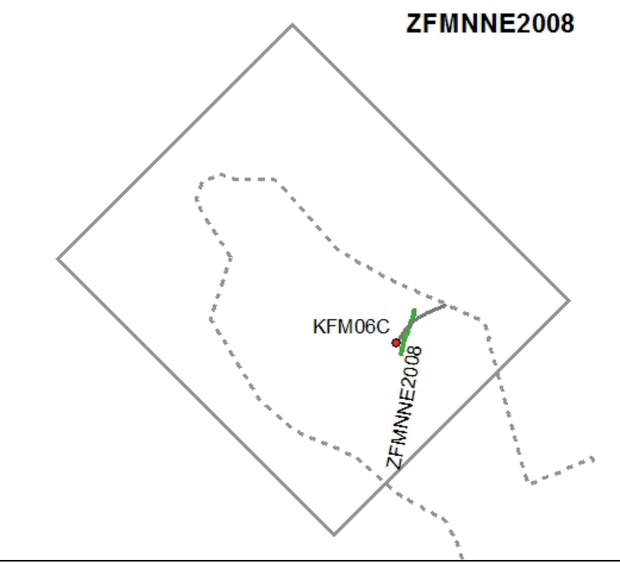
Fault core:
Frequency of open fractures: 11.7 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, clay minerals

Frequency of sealed fractures: 19.7 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, adularia/hematite, quartz, epidote

Deformation zone ZFMNNE2008

Borehole intersections (metres along borehole)

KFM06C: DZ6 (283-306 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 198/84

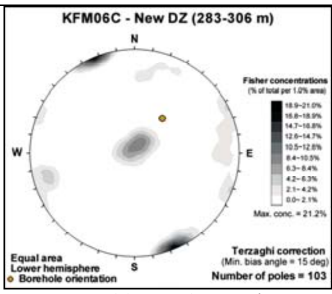
Trace length at ground surface: 441 m

Model thickness / model thickness span : 6 m / 2-30 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -235 to -254 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 4.4E-08
Model T, depth range -500 to -600 m: 1.6E-08

Engineering characteristics

Percentage of fault core: No data available along DZ6 in KFM06C to assess core and transition. No division made

Frequency of open fractures: 2.5 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, adularia/hematite, clay minerals, pyrite,

Frequency of sealed fractures: 4.3 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, adularia/hematite

Deformation zone ZFMNNE2255

Borehole intersections (metres along borehole)

KFM06A: DZ5 (619-624 m)

Deformation style. alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

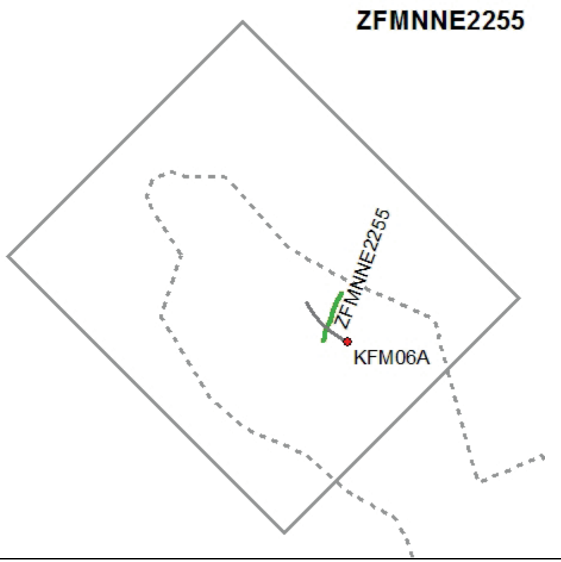
Strike/dip (right-hand-rule): 200/81

Trace length at ground surface: 507 m

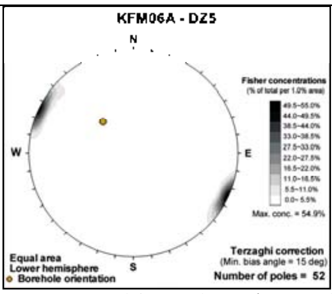
Model thickness / model thickness span : 2 m / 2-43 m

Measured thickness (-400 to -600 m elevation): 2 m

Comment:



Fractures in the deformation zone



Elevation: -521 to -525 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: 2.61E-09
Number of PFL-features: 1
Model T, depth range -400 to -500 m: 8.7E-10
Model T, depth range -500 to -600 m: 3.2E-10

KFM06A (DZ5)

Engineering characteristics

Percentage of fault core: No data available along DZ5 in KFM06A to assess core and transition. No division made

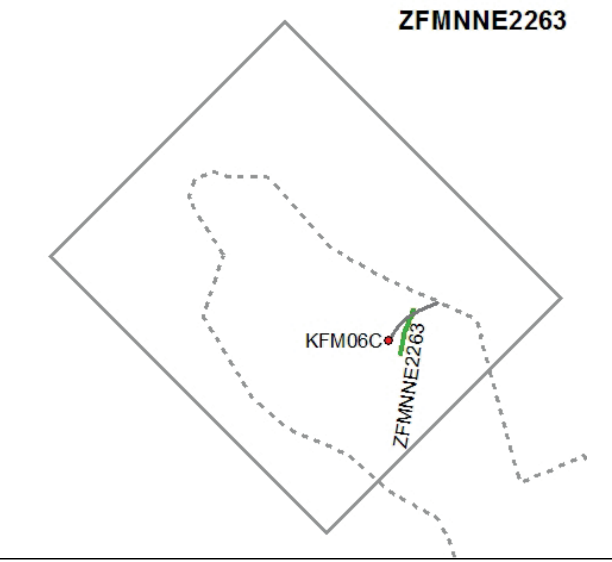
Frequency of open fractures: 3.2 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, quartz, clay minerals, pyrite

Frequency of sealed fractures: 11.6 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: quartz, chlorite, calcite

Deformation zone ZFMNNE2263

Borehole intersections (metres along borehole)

KFM06C: DZ3 (415-489 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination. Vuggy rock with quartz dissolution between 451-452 m along DZ3 in KFM06C

Strike/dip (right-hand-rule): 197/63

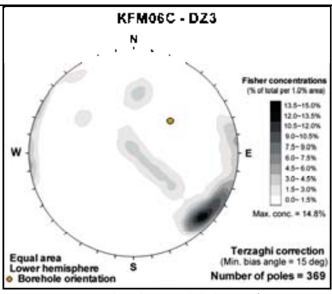
Trace length at ground surface: 446 m

Model thickness / model thickness span : 30 m / 2-30 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -341 to -399 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.84E-07
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 8.2E-08
Model T, depth range -500 to -600 m: 3.1E-08

KFM06C (DZ3)

Engineering characteristics

Percentage of fault core: No fault core recognised along DZ3 in KFM06C (P-07-101). No division into transition and core

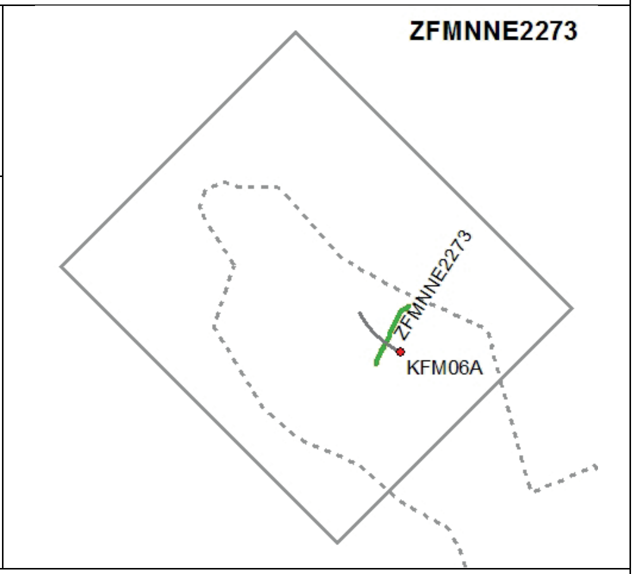
Frequency of open fractures: 1.5 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, adularia/hematite

Frequency of sealed fractures: 23.7 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: adularia/hematite, calcite, chlorite, quartz

Deformation zone ZFMNNE2273

Borehole intersections (metres along borehole)

KFM06A: DZ12 (518-545 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 209/77

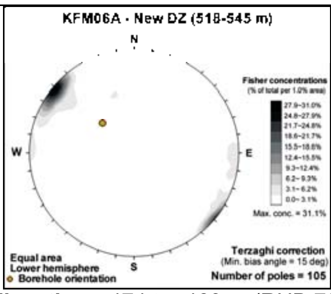
Trace length at ground surface: 657 m

Model thickness / model thickness span : 9 m / 2-43 m

Measured thickness (-400 to -600 m elevation): 9 m

Comment:

Fractures in the deformation zone



Elevation: -474 to -460 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.00E-10
Number of PFL-features: 0
Model T, depth range -400 to -500 m: 1.0E-10
Model T, depth range -500 to -600 m: 1.0E-10

KFM06A (DZ12)

Engineering characteristics

Percentage of fault core: No data available along DZ12 in KFM06A to assess core and transition. No division made

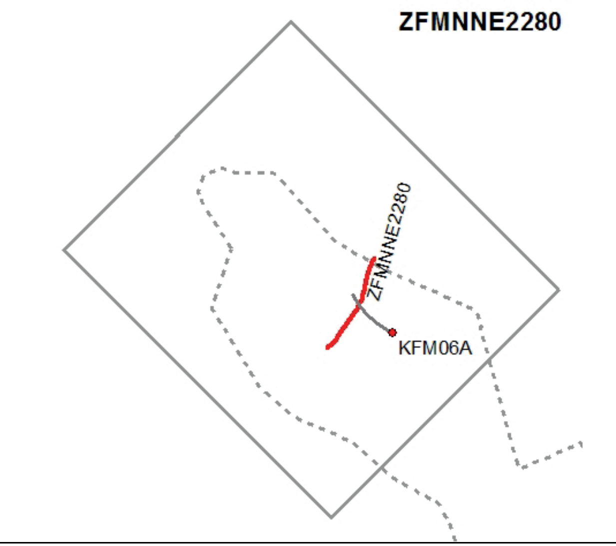
Frequency of open fractures: 1.1 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite

Frequency of sealed fractures: 4.4 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, adularia/hematite

Deformation zone ZFMNNE2280

Borehole intersections (metres along borehole)

KFM06A: DZ11 (950-990 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 206/84

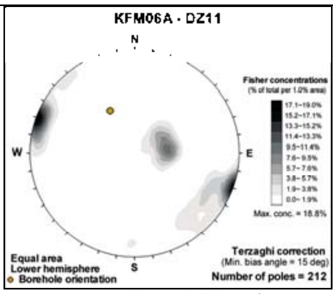
Trace length at ground surface: 1,035 m

Model thickness / model thickness span : 14 m / 3-45 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment:

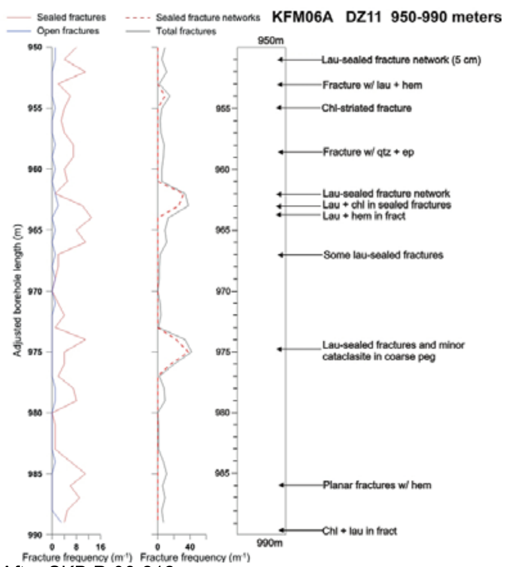
Fractures in the deformation zone



Elevation: -788 to -819 m (RHB 70)

Transmissivity (m²/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.3E-09
Model T, depth range -500 to -600 m: 1.2E-09



After SKB P-06-212

Engineering characteristics

Percentage of fault core: 12.5% (P-06-212)

Transition part of zone:
Frequency of open fractures: 0.4 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, laumontite, prehnite

Frequency of sealed fractures: 5.1 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, adularia/hematite, laumontite, calcite, quartz

Fault core:
Frequency of open fractures: 0.6 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: adularia/hematite, laumontite, calcite, clay minerals

Frequency of sealed fractures: 33.8 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: adularia/hematite, chlorite, laumontite, calcite, prehnite

Deformation zone ZFMNNE2293

Borehole intersections (metres along borehole)

KFM08D: DZ9 (737-749 m)

Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

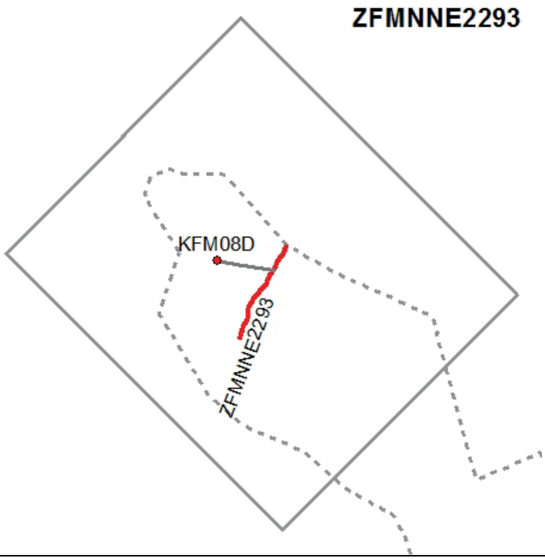
Strike/dip (right-hand-rule): 208/80

Trace length at ground surface: 996 m

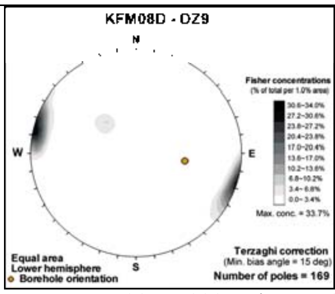
Model thickness / model thickness span : 15 m / 2-43 m

Measured thickness (-400 to -600 m elevation): 15 m

Comment: KFM08D only available after completion of geological model stage 2.2, i.e. not included in geological modelling work



Fractures in the deformation zone

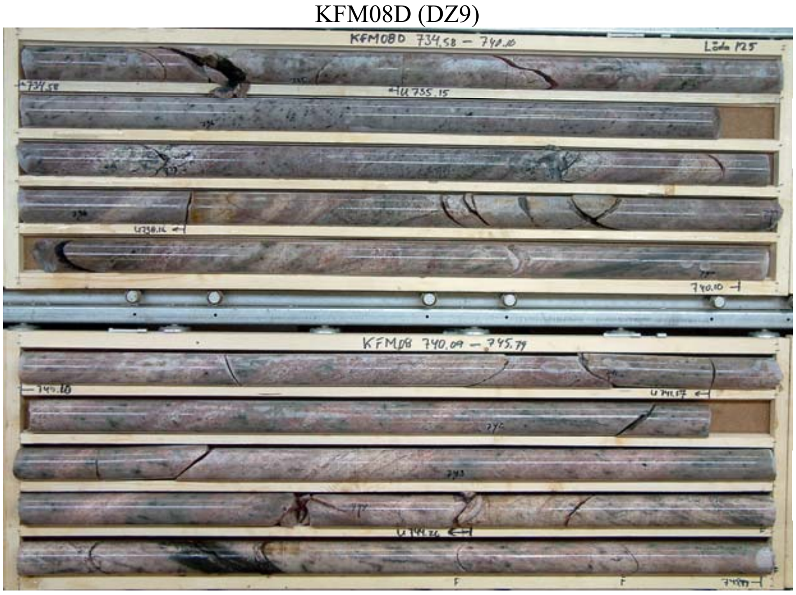


Elevation: -590 to -600 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.6E-08
Model T, depth range -500 to -600 m: 5.9E-09

KFM08D (DZ9)



Engineering characteristics

Percentage of fault core: No data available along DZ11 in KFM08D to assess core and transition. No division made

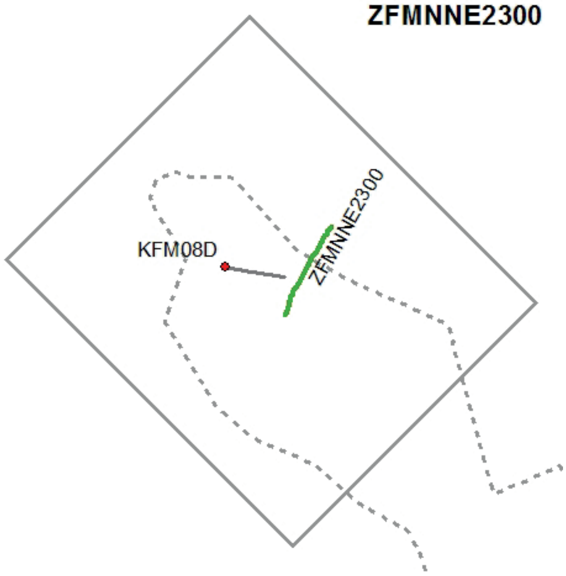
Frequency of open fractures: 2.7 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, adularia/hematite, clay minerals

Frequency of sealed fractures: 15.6 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, adularia/hematite, chlorite, quartz

Deformation zone ZFMNNE2300

Borehole intersections (metres along borehole)

KFM08D: DZ12 (903 m and beneath the borehole length)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 208/80

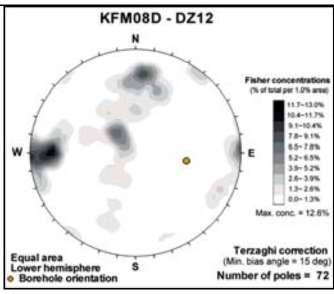
Trace length at ground surface: 946 m

Model thickness / model thickness span : 10 m / 2-43 m

Measured thickness (-400 to -600 m elevation): No intersection

Comment: KFM08D only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

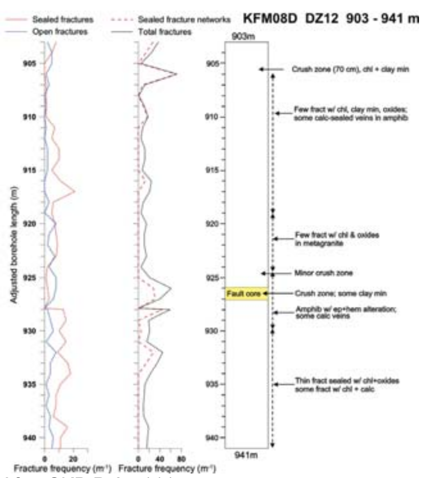
Fractures in the deformation zone



Elevation: -719 m to beneath the borehole length (RHB 70)

Transmissivity (m²/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 1.6E-08
Model T, depth range -500 to -600 m: 5.9E-09



After SKB P-07-111

KFM08D (DZ12)

Engineering characteristics

Percentage of fault core: 2.6% (P-07-111)

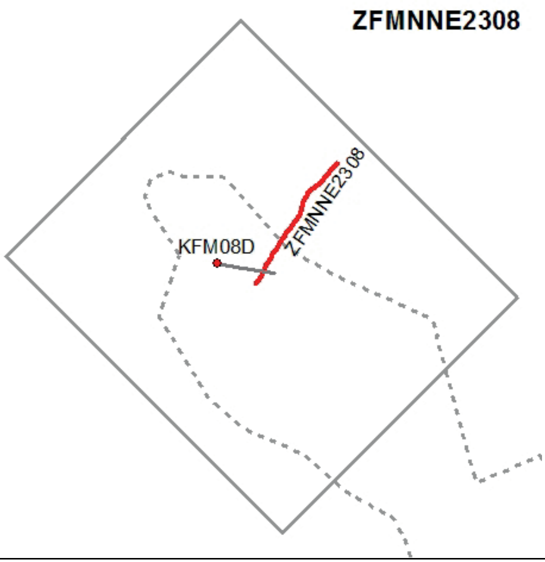
Transition part of zone:
Frequency of open fractures: 3.7 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, clay minerals, calcite, adularia/hematite
Frequency of sealed fractures: 16.2 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, adularia/hematite, quartz, chlorite

Fault core:
Frequency of open fractures: 20.0 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: clay minerals, adularia/hematite, chlorite
Frequency of sealed fractures: 1.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: adularia/hematite, chlorite, clay minerals

Deformation zone ZFMNNE2308

Borehole intersections (metres along borehole)

KFM08D: DZ8 (644-689 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 214/80

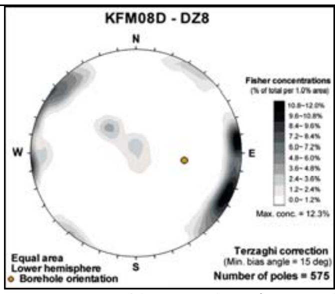
Trace length at ground surface: 1,419 m

Model thickness / model thickness span : 15 m / 3-45 m

Measured thickness (-400 to -600 m elevation): n.a. See comment below

Comment: KFM08D only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

Fractures in the deformation zone

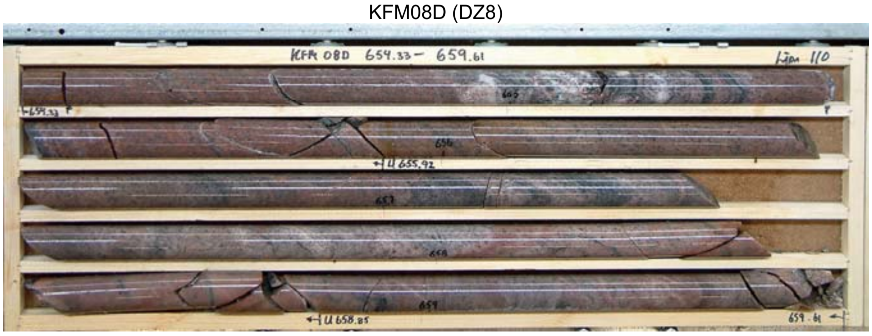


Elevation: -518 to -553 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.9E-07
Number of PFL-features: 3
Model T, depth range -400 to -500 m: 1.6E-08
Model T, depth range -500 to -600 m: 5.9E-09

KFM08D (DZ8)



Engineering characteristics

Percentage of fault core: No data available along DZ8 in KFM08D to assess core and transition. No division made

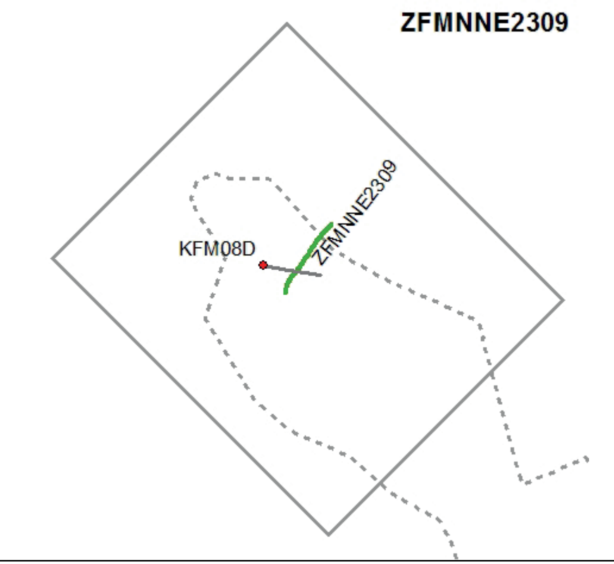
Frequency of open fractures: 3.2 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, quartz, clay minerals

Frequency of sealed fractures: 15.9 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, quartz, adularia/hematite

Deformation zone ZFMNNE2309

Borehole intersections (metres along borehole)

KFM08D: DZ5 (546-571 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 215/80

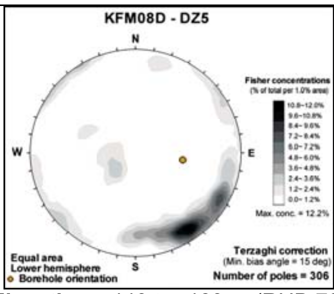
Trace length at ground surface: 804 m

Model thickness / model thickness span : 10 m / 2-43 m

Measured thickness (-400 to -600 m elevation): n.a. See comment below

Comment: KFM08D only available after completion of geological model stage 2.2, i.e. not included in geological modelling work

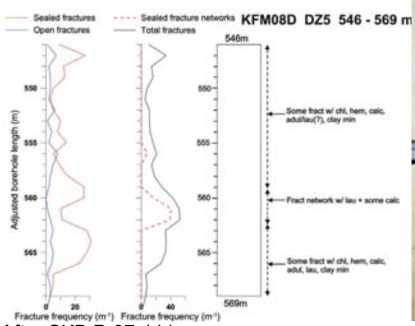
Fractures in the deformation zone



Elevation: -440 to -460 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: 1E-10
Number of PFL-features: 0
Model T, depth range -400 to -500 m: 1.6E-08
Model T, depth range -500 to -600 m: 5.9E-09



After SKB P-07-111

KFM08D (DZ5)

Engineering characteristics

Percentage of fault core: No fault core recognised along DZ5 in KFM08D (P-07-111). No division into transition and core

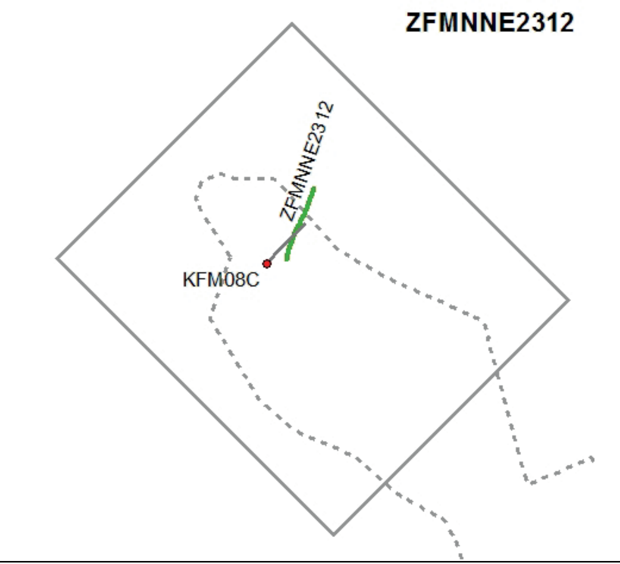
Frequency of open fractures: 3.1 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, adularia/hematite, laumontite

Frequency of sealed fractures: 17.6 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: adularia/hematite, chlorite, calcite

Deformation zone ZFMNNE2312

Borehole intersections (metres along borehole)

KFM08C: DZ2 (419-542 m)
HFM38: DZ1 (149-164 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination. Vuggy rock with quartz dissolution in the borehole intervals 454-463 m, 497-499 m, and 511-532 m along DZ2 in KFM08C

Strike/dip (right-hand-rule): 202/84

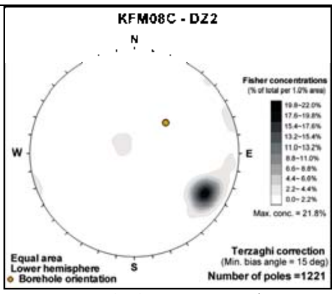
Trace length at ground surface: 742 m.

Model thickness / model thickness span : 43 m / 2-43 m

Measured thickness (-400 to -600 m elevation): 43 m

Comment:

Fractures in the deformation zone



Elevation: -353 to -454 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.76E-07
Number of PFL-features: 13
Model T, depth range -400 to -500 m: 1.1E-07
Model T, depth range -500 to -600 m: 4.1E-08

KFM08C (DZ2)

Engineering characteristics

Percentage of fault core: No fault core recognised along DZ2 in KFM08C (P-07-101). No division into transition and core

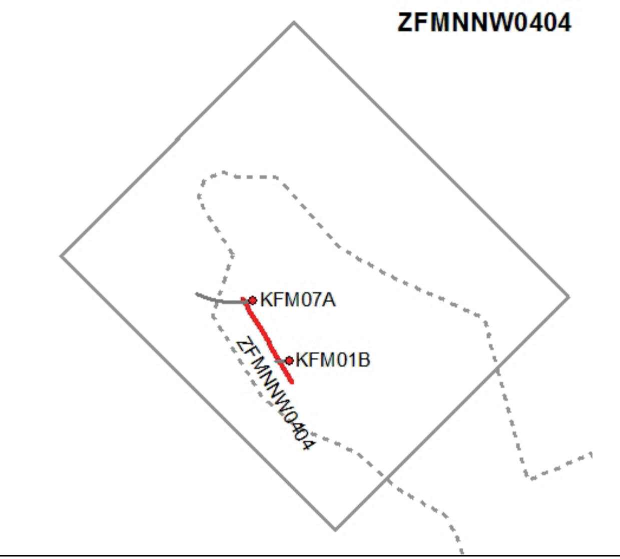
Frequency of open fractures: 2.2 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, adularia/hematite

Frequency of sealed fractures: 9.6 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, adularia/hematite, quartz

Deformation zone ZFMNNW0404

Borehole intersections (metres along borehole)

KFM01B: DZ3 (415-454 m)
KFM07A: DZ1 (108-185 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Oxidized bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 150/90

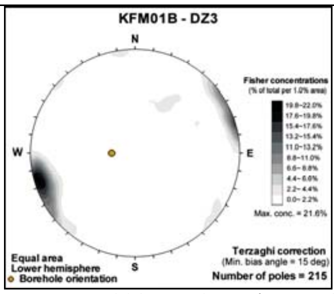
Trace length at ground surface: 947 m

Model thickness / model thickness span : 10 m / 2-43 m

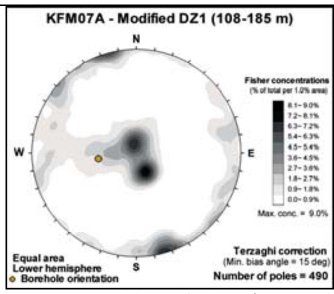
Measured thickness (-400 to -600 m elevation): 10 m

Comment:

Fractures in the deformation zone



Elevation: -398 to -435 m (RHB 70)



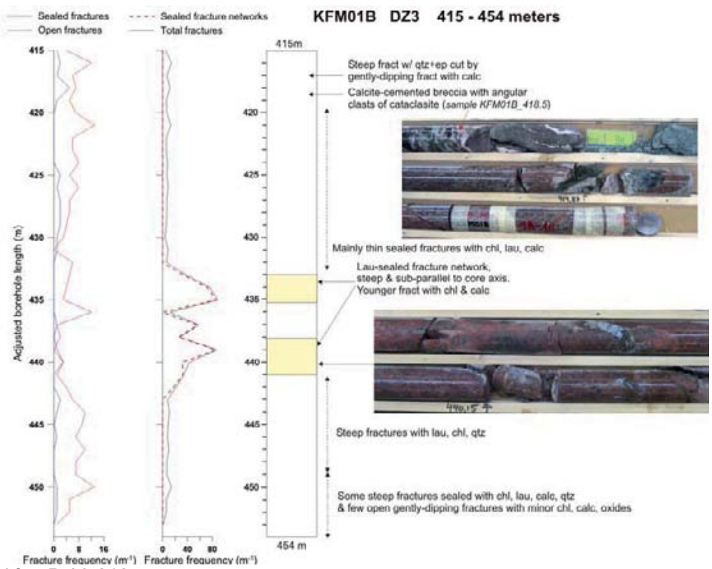
Elevation: -90 to -156 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: Not measured
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.2E-10
Model T, depth range -500 to -600 m: 1.2E-10

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.2E-10
Model T, depth range -500 to -600 m: 1.2E-10



After P-06-212

Engineering characteristics

Percentage of fault core: 14.7% (P-06-212)

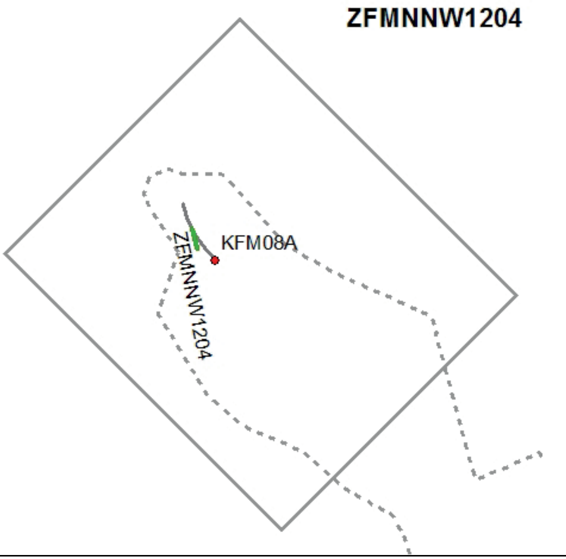
Transition part of zone:
Frequency of open fractures: 2.7 m^{-1}
Std dev: 1.6
Mineral coating along open fractures: chlorite, calcite, clay minerals, adularia/hematite
Frequency of sealed fractures: 5.5 m^{-1}
Std dev: 1.4
Mineral filling along sealed fractures: calcite, chlorite, laumontite

Fault core:
Frequency of open fractures: 1.2 m^{-1}
Std dev: 0.1
Mineral coating along open fractures: chlorite, no mineral, calcite, adularia/hematite, pyrite, clay minerals, laumontite
Frequency of sealed fractures: 48.8 m^{-1}
Std dev: 4.7
Mineral filling along sealed fractures: laumontite, calcite, chlorite, adularia/hematite

Deformation zone ZFMNNW1204

Borehole intersections (metres along borehole)

KFM08A: DZ2 (476-496 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Oxidized bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 345/85

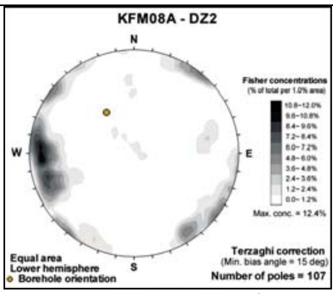
Trace length at ground surface: 201 m

Model thickness / model thickness span : 4 m / 2-30 m

Measured thickness (-400 to -600 m elevation): 4 m

Comment:

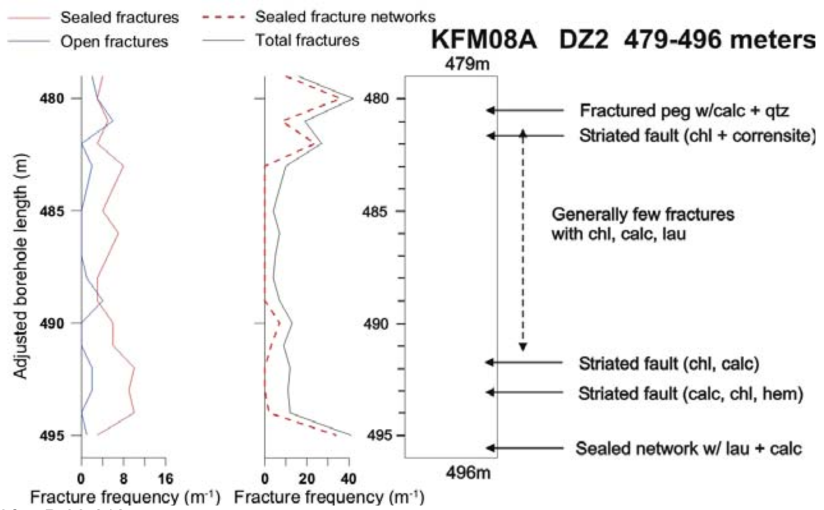
Fractures in the deformation zone



Elevation: -393 to -406 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 6.93E-08
Number of PFL-features: 2
Model T, depth range -400 to -500 m: 4.2E-08
Model T, depth range -500 to -600 m: 1.5E-08



After P-06-212

Engineering characteristics

Percentage of fault core: No fault core recognised along DZ2 in KFM08A (P-06-212). No division into transition and core

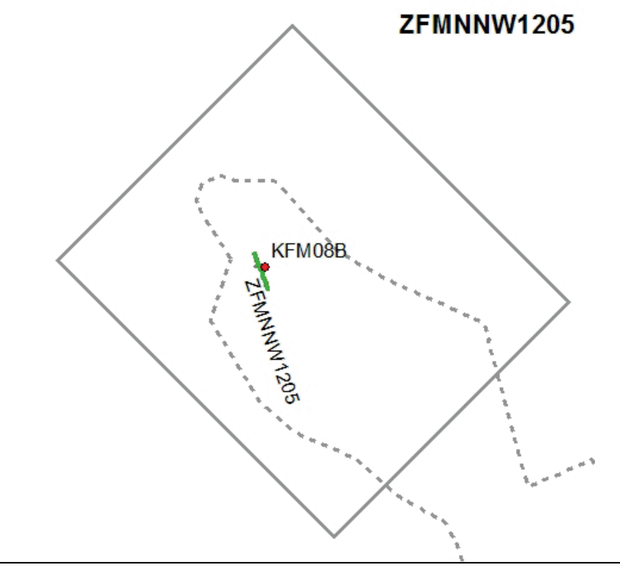
Frequency of open fractures: 1.6 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, pyrite

Frequency of sealed fractures: 13.0 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, adularia/hematite, quartz, pyrite, clay minerals

Deformation zone ZFMNNW1205

Borehole intersections (metres along borehole)

KFM08B: DZ1 (133-140 m) and DZ2 (167-185 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Oxidized bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 159/78

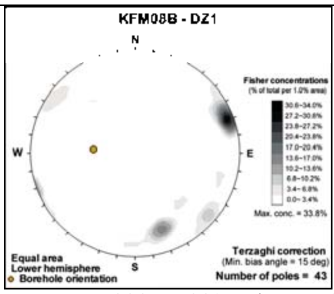
Trace length at ground surface: 368 m

Model thickness / model thickness span : 15 m / 2-30 m

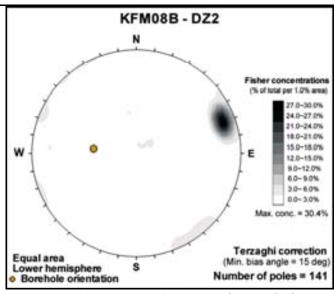
Measured thickness (-400 to -600 m elevation): No intersection

Comment:

Fractures in the deformation zone



Elevation: -111 to -116 m (RHB 70)



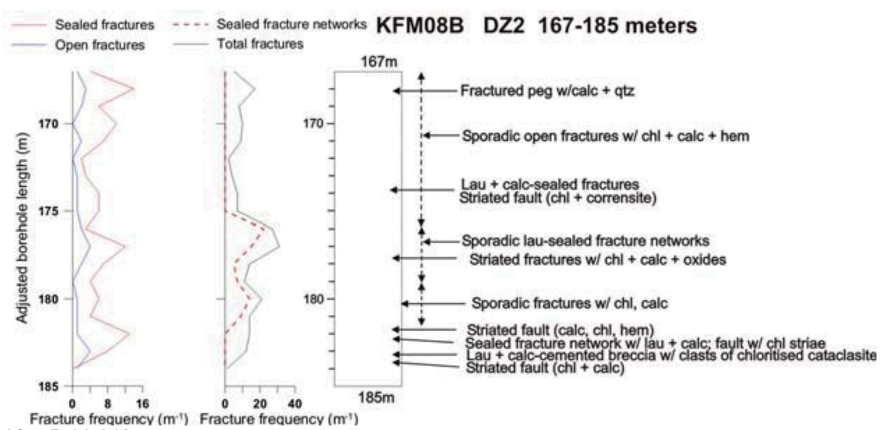
Elevation: -139 to -154 m (DZ2) (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.5E-10
Model T, depth range -500 to -600 m: 1.3E-10

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 3.5E-10
Model T, depth range -500 to -600 m: 1.3E-10



After P-06-212

Engineering characteristics

Percentage of fault core: No fault core recognised along DZ2 in KFM08B (P-06-212). No data available along DZ1 in KFM08B to assess core and transition. For these two reasons, no division made

Frequency of open fractures: 0.9 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, pyrite

Frequency of sealed fractures: 14.4 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, chlorite, adularia/hematite, laumontite

Deformation zone ZFMWNW0044

Borehole intersections (metres along borehole)

KFM06C: DZ4 (502-555 m)

Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

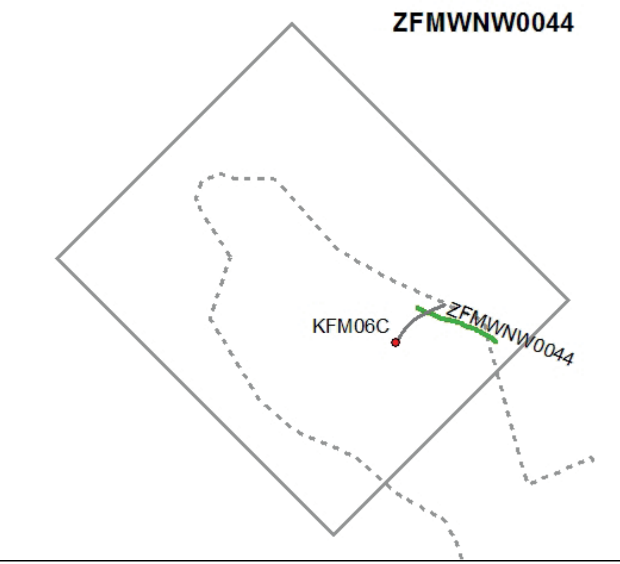
Strike/dip (right-hand-rule): 118/77

Trace length at ground surface: 834 m

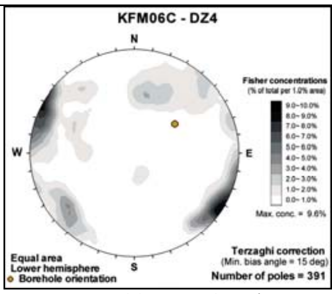
Model thickness / model thickness span : 39 m / 2-43 m

Measured thickness (-400 to -600 m elevation): 39 m

Comment:



Fractures in the deformation zone



Elevation: -409 to -450 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: 1.22E-06
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 4.9E-06
Model T, depth range -500 to -600 m: 3.6E-07

KFM06C (DZ4)

Engineering characteristics

Percentage of fault core: 7.5% (P-07-101)

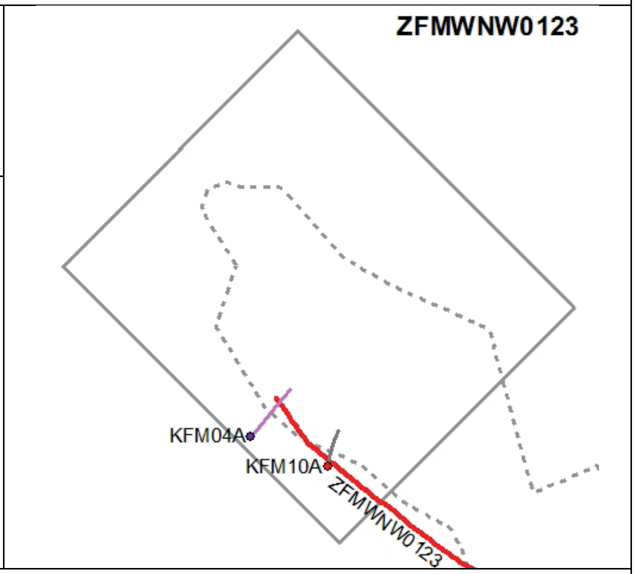
Transition part of zone:
Frequency of open fractures: 1.3 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, adularia/hematite, quartz
Frequency of sealed fractures: 10.8 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, prehnite, adularia/hematite, epidote

Fault core:
Frequency of open fractures: 20.0 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, clay minerals, adularia/hematite, epidote
Frequency of sealed fractures: 24.2 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: epidote, chlorite, calcite, adularia/hematite

Deformation zone ZFMWNW0123

Borehole intersections (metres along borehole)

KFM04A: DZ5 (654 to 661 m)
KFM10A: DZ1 (63 to 145 m)
HFM24: DZ1 (18-32 m). DZ2 (42-63 m) and DZ3 (67-103 m).
HFM29: DZ1 (19-25 m). DZ2 (62-81 m) and DZ3 (146-150 m)



Deformation style, alteration and geometry

Deformation style: Ductile and brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination, epidotization, short intervals of altered vuggy rock along borehole interval 90-120 m in KFM10A (DZ1)

Strike/dip (right-hand-rule): 117/82

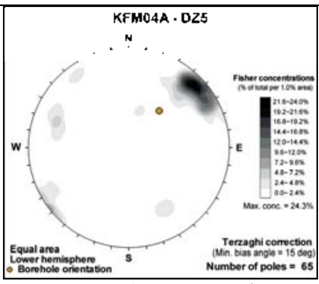
Trace length at ground surface: 5,086 m

Model thickness / model thickness span : 52 m / 10-64 m

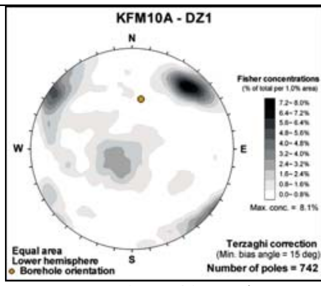
Measured thickness (-400 to -600 m elevation): n.a. See comment below

Comment: KFM04A intersects the zone close to its termination

Fractures in the deformation zone



Elevation: -542 to -547 m (RHB 70)



Elevation: -43 to -105 m (RHB 70)

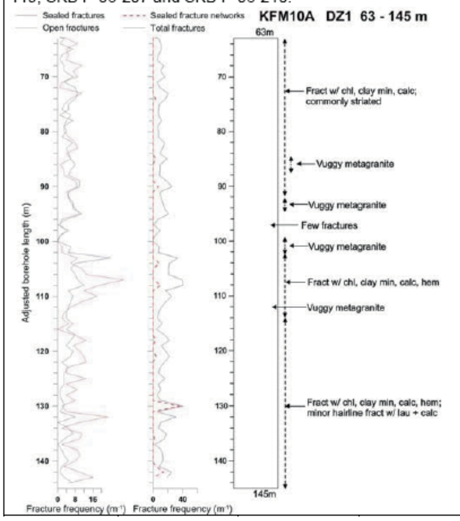
Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 1.00E-10
Number of PFL-features: 0
Model T, depth range -400 to -500 m: 5.2E-08
Model T, depth range -500 to -600 m: 2.0E-09

Transmissivity (m^2/s)

General dip of T fractures: n.a.
Measured T range -400 to -600 m: No intersection
Number of PFL-features: n.a.
Model T, depth range -400 to -500 m: 5.2E-08
Model T, depth range -500 to -600 m: 2.0E-09

Single hole interpretation: For identification and short description of deformation zones in boreholes, see SKB P-04-119, SKB P-06-207 and SKB P-06-210.



KFM10A DZ1

KFM04A DZ5

Engineering characteristics

Percentage of fault core: No fault core recognised along DZ1 in KFM10A (P-07-101). No data available along DZ5 in KFM04A to assess core and transition. For these two reasons, no division made

Borehole KFM04A not included in fracture statistics due to location close to the termination of the zone

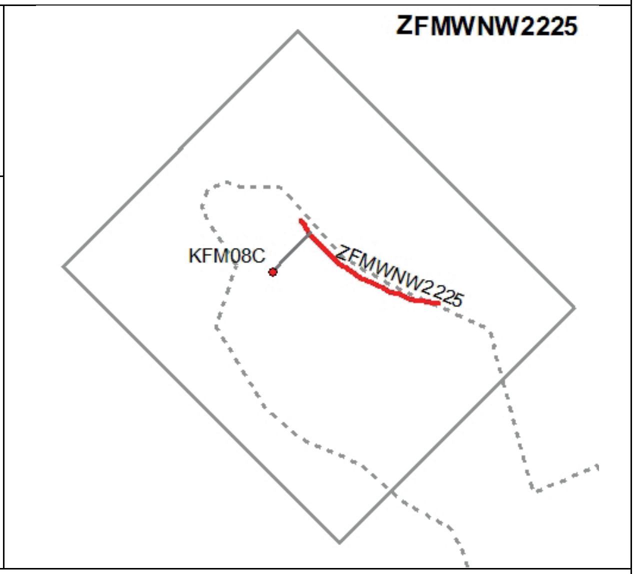
Frequency of open fractures: 5.1 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, clay minerals, chlorite, adularia/hematite

Frequency of sealed fractures: 12.3 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: calcite, adularia/hematite

Deformation zone ZFMWNW2225

Borehole intersections (metres along borehole)

KFM08C: DZ3 (673-705 m)



Deformation style, alteration and geometry

Deformation style: Brittle

Alteration: Red-stained bedrock with fine-grained hematite dissemination

Strike/dip (right-hand-rule): 120/75

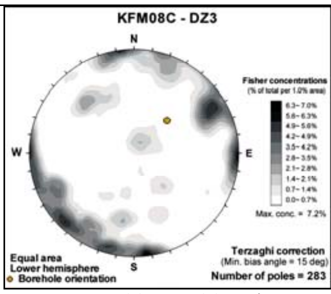
Trace length at ground surface: 1,613 m

Model thickness / model thickness span : 25 m / 3-45 m

Measured thickness (-400 to -600 m elevation): 25 m

Comment:

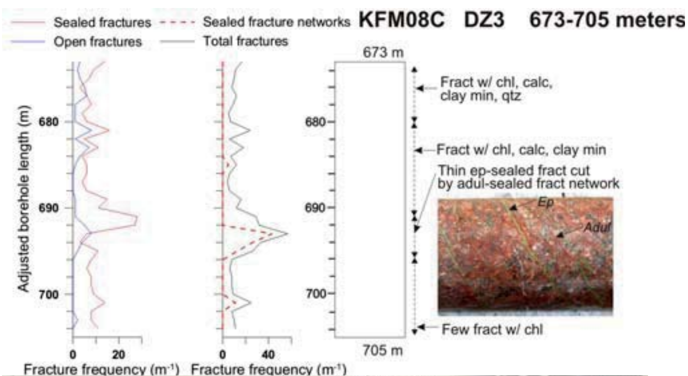
Fractures in the deformation zone

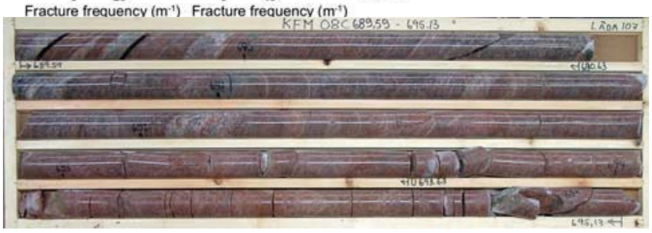


Elevation: -560 to -586 m (RHB 70)

Transmissivity (m^2/s)

General dip of T fractures: steep
Measured T range -400 to -600 m: 2.61E-09
Number of PFL-features: 1
Model T, depth range -400 to -500 m: 8.9E-09
Model T, depth range -500 to -600 m: 3.3E-09





KFM08C DZ3

Engineering characteristics

Percentage of fault core: 15.6% (P-07-101)

Transition part of zone:
Frequency of open fractures: 1.7 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: chlorite, calcite, clay minerals, quartz, pyrite, adularia/hematite
Frequency of sealed fractures: 8.8 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: chlorite, calcite, adularia/hematite, epidote

Fault core:
Frequency of open fractures: 4.0 m^{-1}
Std dev: n.a.
Mineral coating along open fractures: calcite, chlorite, adularia/hematite, clay minerals, quartz, epidote
Frequency of sealed fractures: 31.6 m^{-1}
Std dev: n.a.
Mineral filling along sealed fractures: epidote, chlorite, adularia/hematite, calcite, quartz

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