Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

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Technical Note

2012:54

Initial Review Phase for SKB´s safety assessment SR-Site: Geological structures and deformation zones, from site investigation to safety assessment

Report number: 2012:54 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Uppdraget är en del av granskningen som rör den långsiktiga utvecklingen av bergmassan omgivande det tilltänkta slutförvaret. Detta uppdrag fokuserar på att studera SKB:s strukturgeologiska modell. Frågor som berörs är hur SKB har hanterat insamling och sammanställning av geologisk och strukturgeologisk data samt hur dessa har använts vid design av förvaret och i säkerhetsredovisningen. Strukturer i en bergmassa har stor betydelse för grundvattenflöde, skjuvrörelser och för utformningen av förvaret(hänsyn tagen till deformationszoner och sprickor). En annan aspekt är de olika bergarternas olika temperaturledningsförmåga som kopplar till förändrat avstånd mellan enskilda deponeringshål. Frågor som berörs är också metodiken för identifikation av deformationszoner, val av acceptanskriterier för deponeringspositioner samt den framtida karaktäriseringen av bergmassan på djupet.

Författarens sammanfattning

Den plats som Svensk Kärnbränslehantering AB (SKB) valt för djupförvaring (ca 500 m djup) av använt kärnbränsle ligger i en berggrundsmiljö bestående av prekambriska bergarter. Platsen för förvaret är Forsmark beläget vid norra upplandskusten, 122 km norr om Stockholm. I ett geologiskt perspektiv är Forsmark beläget i de centrala delarna av den Fennoskandiska skölden. Upplands flacka landskap sammanfaller i stort med en utsträckt erosionsyta bildad ovan vatten för mer än 540 miljoner år sedan. I själva verket har denna yta återigen exponerats efter att ha varit täckt av palaeozoiska sedimentbergarter (yngre än 540 miljoner år).

Målområdet, den valda platsen tillräckligt stort för att inrymma förvaret, är beläget i de centrala delarna av en storskalig veckstruktur med granitisk berggrund (graniter och granodioriter). Veckstrukturen omges på vardera sidan, mot nordöst och sydväst, av storskaliga, regionala deformationszoner som mot nordväst skär varandra bildande en kil innehållande förvaret. Vid förvaret varierar avståndet mellan dessa zoner från 2,5 till 3,5 km. Berggrunden på förvarsnivå kan även innehålla bergarter (basiska) som på grund av deras lägre termiska ledningsförmåga kan påverka nyttjandegraden av bergsvolymen. Detta eftersom denna egenskap hos de basiska bergarterna medför behov av större separation mellan deponeringspositioner.

Själva förvarsområdet tudelas av en regional deformationszon (brant stående och orienterad ONO, >3km lång) och ett område, vars utsträckning är 100 m bred på vardera sidan om denna zon, tillåts ej att ingå i själva förvarsvolymen. Utmed målområdets avgränsningar förekommer brant stupande deformationszoner orienterade i VNV, NV och ONO.

Berggrunden invid målområdet är med avseende på dess allmänna struktur ej homogent. De ytliga delarna av berggrunden karaktäriseras av en förhöjd täthet av flacka öppna sprickor och andelen öppna sprickor bland de brant stupande sprickorna är även den förhöjd i förhållande till djupare nivåer. Berg med öppna sprickor tilltar i mäktighet mot sydöst och innehåller även flacka deformationszoner. Detta medför att sprickors egenskaper i hällar funna i terrängen inte direkt återspeglar sprickors egenskaper på förvarsnivån. Markmagnetiska mätningar med hög upplösning indikerar att berggrundens generella strukturmönster med avseende på brant stupande spröda deformationszoner ej är homogent. Till exempel, den centrala brant stående deformationszonen som är orienterad i ONO utgör en gräns med huvudsakligen ONO orienterade deformationszoner sydöst därom och NO till NNO orienterade strukturer i norr.

Den deterministiska strukturmodellen som beskriver målområdet uppvisar ett relativt enhetligt mönster av lokala deformationszoner (1km≤length≤3 km); NO till ONO orienterade strukturer dominerar. Strukturer av denna storlek får ej sammanfalla med kapselpositioner i förvaret. På grund av osäkerheter i modeller kan läget på modellerade deformationszoner avvika från dess verkliga läge i förvarsområdet. Modellen ger dock information om mängden av deformationszoner. Utmed större sprickor (mindre deformationszoner och enskilda sprickor större än 150 m) kan sekundära rörelser, av sådan storleksordning att de kan skada kapslar, utlösas av jordskalv. Sådana strukturer får ej skära kapselpositioner. I djupa lägen är det dock svårt att mäta den verkliga längden hos deformationszoner och sprickor. Emellertid, förståelsen av strukturmönstret i förvarsområdet kan stödjas av modellering med hög upplösning baserad på detaljerade geologiska data (borrhål och tunneldata) och geo-fysikaliska undersökningar. Den statistiska fördelningen av mindre deformationszoner (< 1 km) och sprickor i målområdet, inkluderande förvarsområdet, presenteras i stokastiska modeller (DFN).

Det saknas en diskussion om hur heterogenitet i rumslig fördelning av indata (t.ex. borrhålslägen, riktningar och mätområde för de högupplösta magnetiska mätningarna i relation till rumsliga förekomsten av grupper/set av deformationszoner) påverkar den deterministiska modellen. Sannolikheten/risken för att tunna flacka deformationszoner förekommer på planerat förvarsdjup är av stor vikt och borde lyftas fram mer.

Det hade varit fördelaktigt om skisser som beskriver geometrin (yttre och inre) hos olika grupper/set av deformationszoner hade presenterats för att stödja information given i tabeller. Visualisering är ett bra sätt att förmedla och beskriva strukturgeologisk information.

Mängden insamlad geologisk och geofysikalisk information är mycket stor och mängden skrivna rapporter är omfattande. All insamlad geologisk och geofysikalisk fältdata är kvalitetsgranskad och lagrad i SKB:s databas SICADA. Dock har några fel i kontrollerade data påträffats (felaktiga data t.ex. i geofysikaliska borrhålsmätningar, och blandning av data, t.ex. i borrhålsradardata). Kvaliteten hos utförda undersökningar och sammanställda rapporter är av hög internationell standard. SKB:s platsundersökningar har utgjort underlag för flertalet doktorsavhandlingar och publikationer i internationella vetenskapliga tidskrifter samt presentationer vid internationella möten. Emellertid behövs ytterligare studier, såsom alternativa modelleringar för att mer i detalj utvärdera de resultat SKB erhållit, och för att bedöma om information/data eller utförande behöver kompletteras.

Projektinformation
Kontaktperson på SSM: Lena Sonnerfelt
Diarienummer ramavtal: SSM2011-3633
Diarienummer avrop: SSM2011-4306
Aktivitetsnummer: 3030007-4019

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

This assignment is part of the review regarding the long-term evolution of the rock surrounding the repository. The assignment focuses on the structural geology model. Issues regarded are the handling and interpretation of geology and structural geology data, and the use of data in repository design and safety assessment. Geological features have impact on groundwater flow, shear movements and on the design of the repository (consideration to deformation zones and fractures). Another aspect is the different thermal properties of different rock types which have impact on the spacing between deposition positions. Issues regarded are also the methodology for identification of deformation zones, selection of acceptance criteria for deposition positions and the planned future geological characterization.

Summary by the author

The site selected by the Swedish Nuclear Fuel and Management Co (SKB) for location of a deep geological repository, i.e. a storage for spent nuclear fuel at about 500 m depth in Precambrian metamorphosed rocks. The location of the site is Forsmark at the northern coast of Uppland and 122 km north of Stockholm. In geological terms Forsmark is located in the central part of the Fennoscandian Shield. The flat ground surface in Uppland today mainly coincides with a vast surface formed by long-lasting subaerial erosion more than 540 million years ago. Actually, the bedrock surface is exposed again after being covered by sedimentary rocks of Palaeozoic age (younger than 540 million years).

The target volume, considered large enough to host a repository, is located in the core of a large-scale fold where the rock is composed of granite-like rocks (granites and granodiorites). The fold is bordered on each side, i.e. to the northeast and southwest, by subvertical regional brittle deformation zones (DZ) trending WNW and NW, respectively. The regional zones form a wedge closing north-westwards. The separation between the WNW and NW trending regional DZ varies from about 2.5 to 3.5 km in the local site area. The bedrock at the planned repository level may also contain rock (amphibolites) that may affect the utilization of the available rock volume; due to lower thermal conductivity a larger separation of canister positions is needed in amphibolites than in granitoids.

The actual target area is crossed by a steeply dipping regional DZ (>3 km) trending ENE dividing the planned repository volume into two parts and along such DZ no canister position closer than 100m is allowed. Along borders of the target area there are steeply dipping regional DZ mainly trending WNW, NW and ENE.

The general structural pattern in the bedrock is not homogeneous at the target volume. The shallow part of the bedrock is characterized by enhanced density of open fractures dominated by gently inclined to subhorizontal fractures and also the proportion of open fractures among the steeply dipping fractures are markedly higher compared to deeper levels. The domain of open fractures increases in thickness south-eastwards. It contains gently inclined DZ. This implies that outcrop fracture data do not directly reflect fracture characteristics at the repository level. The high-resolution ground magnetic measurements indicate that the general pattern of steeply dipping brittle deformation zones (including also minor deformation zones) is not homogeneous. For example, the central regional ENE trending DZ forms a border; to the south mainly ENE trending DZ, to the north a high proportion of NE to NNE trending DZ.

The deterministic structure model in the target area displays a relatively regular pattern of local DZ (1km≤length≤ 3km); NE to ENE trending DZ dominate. Such DZ are not allowed to intersect canister positions. The actual location of DZ in the repository volume may, however, not fully agree with the model DZ due to modelling uncertainties. On the other hand, the model gives information about the general density of DZ. There are also large fractures (minor DZ and single fractures; extending for more than 300m) along which earthquake induced secondary slip may occur; i.e. displacement that can distort a canister. Such DZ are not allowed to intersect canister positions. It is difficult to measure the true length of DZ and fractures at depth. However, high-resolution modelling based on detailed geologic data (boreholes and tunnel data) supported by geophysical measurements will strongly contribute to the understanding of the structural pattern in the repository volume. The distribution of minor DZ (<1km) and fractures in the target area, including the repository volume, is presented in stochastic (DFN) models.

Missing is a discussion on how heterogeneity in spatial distribution of input data (e.g. borehole location and orientation, and areal coverage of the high-resolution ground magnetic measurements in relation to the different sets of deformation zone sets) effect the deterministic models. The probability/risk for thin gently dipping DZ to occur at planned repository depth and the potential to detect them prior to the excavation of the repository level is crucial and could be enhanced.

It had been advantageous if sketches illustrating the geometry (external and internal) of different sets of DZ were presented to support the information given in tables. Visualization is a good way of communicating structure geological information.

The recorded geological and geophysical data is voluminous and the number of reports written is exhaustive. All geological and geophysical field data are quality checked and stored in SKBs database SICADA. However, some errors (distorted data, e.g. in a few geophysical borehole logs, and mixing of data sets, e.g. in borehole radar files) have been found in checked data.

The quality of performed investigation and reports are of high international standard. The SKB site investigations have formed the basis for several Ph. D theses and publications in international scientific journals and presentations at international symposia. However, further studies are needed, for instance alternative modelling, to evaluate the result gained by SKB in more detail and to judge whether information/data or performances need to be complemented.

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Technical Note 29

2012:54

Initial Review Phase for SKB´s safety assessment SR-Site: Geological structures and deformation zones, from site investigation to safety assessment

Date: Oktober 2012
Report number: 2012:54 **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Contents

1. Introduction

This review assignment is part of the Swedish Radiation Safety Authority's (Strålsäkerhetsmyndigheten, in Swedish; SSM) Initial Review Phase of the Swedish Nuclear Fuel and Management Co's (SKB) safety assessment SR-Site covering final disposal of spent nuclear fuel at the Forsmark site. The present review covers aspects on bedrock geology within the site area and its surroundings, with a special emphasis on structure geology.

The characterization of a site is a multidisciplinary task and the geological character of the bedrock is of importance for the description/understanding of the full character of the site for deep geological disposal (Fig. 1.1).

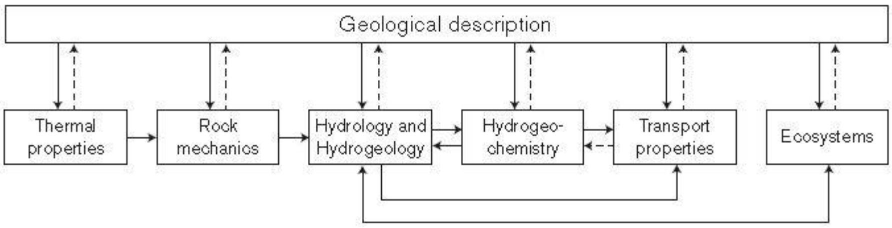

Figure 1.1: The different discipline descriptions in the SDM are interrelated with several feedback loops and with geology providing the essential geometrical framework (TR-11-01; Fig. S-4[1]).

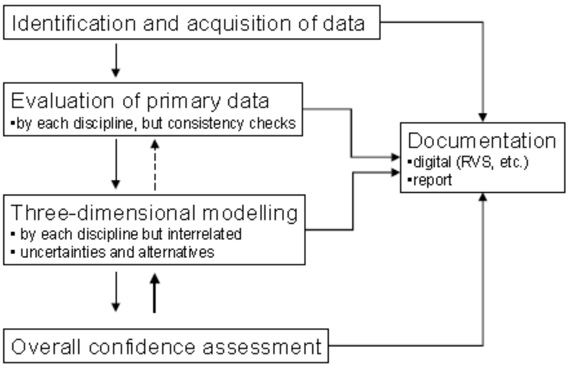

Figure 1.2: The site descriptive modelling process may be split into various components (R-03-05; Fig. 2-1).

The integration of geoscientific information acquired within the site volume was first evaluated separately for each discipline. The outcome of this was subsequently compared and integrated with an interdisciplinary approach in order to achieve a site-descriptive model. The site investigations have been progressively and systematically performed and a sequence of gradually more refined site models have

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[1] References to SKB reports are given by the type of report /TR, R and P/ followed by the number of the report /e.g. SKB TR-11-01, i.e. in this case the first SKBTR report for 2011/. The type of reports gives also the level of the report, cf. Fig. 1-4. To find the reference either the page in the report (e.g. SKB TR-11-01 PXX) is given or the figure or the table (e.g. SKB TR-11-01 Fig. XX/Table XX). SKB report are available at www.skb.se and go to publications. Other references are given by author/s and year. Cross-references have no external reference noted (e.g. Fig. XX).

been developed: version 0 (SKB R-02-32), version 1.1 (SKB R-04-15), version 1.2 (SKB R-05-18), stage 2.1 (SKB R-06-38), stage 2.2 (SKB R-07-45), stage 2.3 (SKB R-08-128, SKB R-08-64) and SDM-Site (SKB TR-08-05).

There is a large number of supporting reports (cf. references in reports listed above).

Site investigation approaches and applied techniques were documented in a series of SKB reports. Descriptions of applied methods are given in method descriptions (SKB MD) and performances are given in activity plans (SKB AP). As the site characterization proceeded investigation techniques were improved. A good example is the high-resolution ground magnetic measurements performed at a relative late stage of the site investigations (2006-2007; SKB R-07-62). The results of these had a great impact on the structure model of the local site volume.

The presentation of performed investigations is systematically described and the language is Standard English. However, the number of reports is, as pointed out above, large. The data are thereby successively filtered as the site investigation proceeds and it can therefore sometimes be hard to trace all data. By necessity, basic information is repeated while some data is only to be found in earlier reports while several times repeated data my lose their references. The search for data on SKB's homepage must be very specified unless not resulting in very large number of hits and to request primary data (see following section) need good information regarding what research has been performed or expectations regarding site characterization work.

Acquired site data are stored in the SKB data base SICADA (SIte ChAracterization DAtabase, mainly primary data) and models are stored in the SKB model data base SIMON (an Internet based data repository service; containing RVS / 3D models/ and GIS/ 2 D models -maps/). Data-freezes associated with each version/stage of the development of site descriptive models have been applied and secure that the data usage for each model is well defined and quality checked.

This review considers the following steps of the 11 steps (cf. Fig. 1-3) listed in the main SR – Site report (TR-11-01):

- Step 2a Description of site, initial state (TR-11-01 sections 4-1-4.4); section 2 in this review document.
- Step 2c Description of repository layout - with site adoption (TR11-01 section 5.2); section 3 in this review document.

The following SKB reports (or sections of reports if applicable) are included in this review assignment:

- SKB TR-10-52, Data report for the safety assessment SR-Site, Sections 2, 6.2, and 6.3
- SKB TR-10-48, Geosphere report, section 2, 4.1-4.4
- SKB TR-08-05, Site description of Forsmark at completion of the site investigation phase, sections 1-3, 5-6and 11.

In many cases information from other SKB reports (SKB TR, SKB R and SKB P-reports; references mainly given by report number, cf. Fig. 1-4) are also used to support the review as well as data obtained from SKB data bases SICADA (site data) and the SIMON (site models).

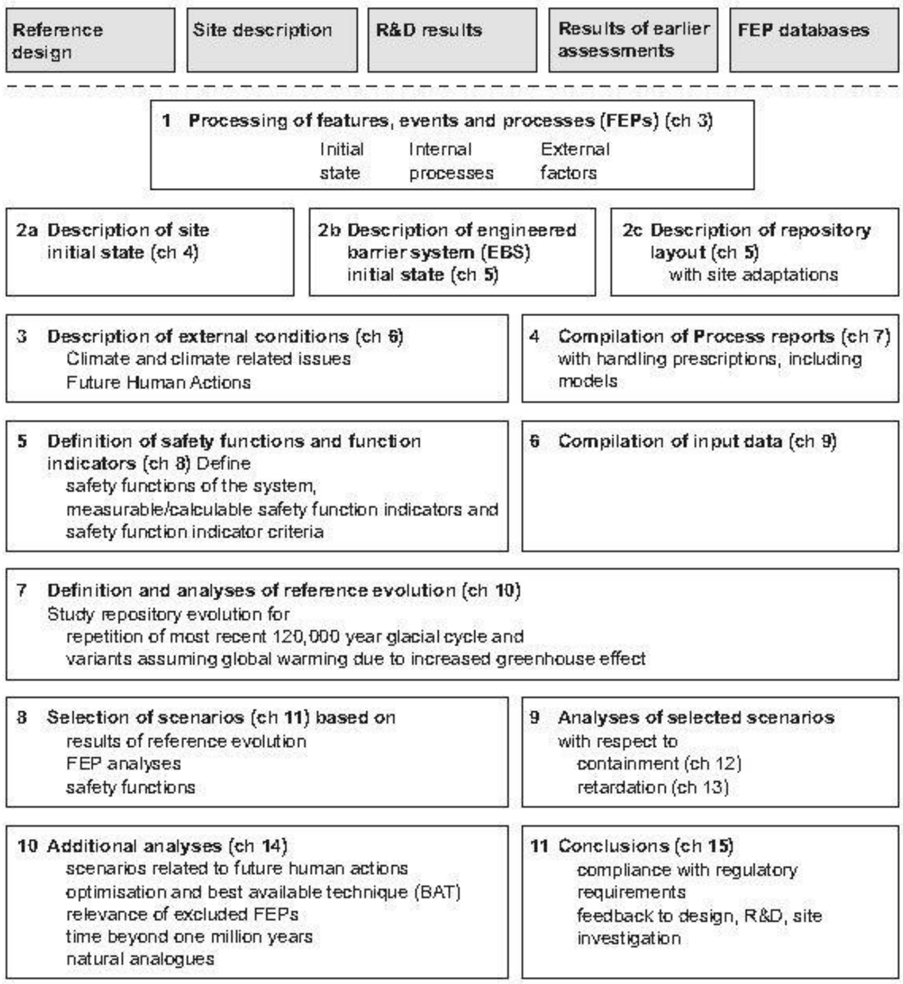


Figure 1.3: An outline of the eleven main steps of the SR-Site safety assessment. The boxes at the top above the dashed line are inputs to the assessment. The chapters in the main report where the steps are further documented are also indicated (TR-11-01 S-6: references given in the figure refer to report SKB TR-11-01).

The geological description of a site has to provide information about the existence of available space for the location of a repository (cf. step 2 C in Fig. 1.2) and to provide other disciplines with basic information (cf. Fig. 1.2). To do this a set of thematic sub-models have been developed to describe the site:

- Lithological model – rock domains; cf. section 2.6 below.
- Structure model – brittle deformation zones, cf. section 2.7.1 below
- Structure model – fracture domains, cf. section 2.7.3 below.

The first two types of sub-models are presented in two scales (R-06-38 P23-24): a regional scale block (165 km^2 large and having a vertical extension to -2 100 m a.s.l.) and a local scale block (16 km^2 large and having a vertical extension to 1 100 m a.s.l.). The local model is required to cover the volume within which the repository is expected to be placed, including accesses and the immediate environment.

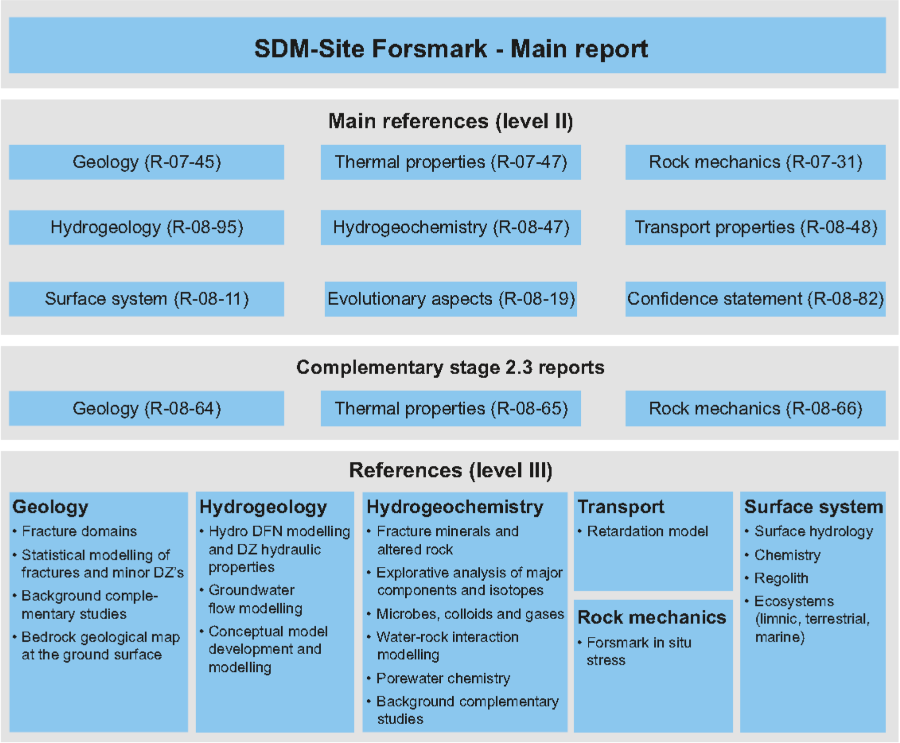


Figure 1-4: SDM site main report and background reports on different levels produced during modelling stages 2.2 and 2.3 (TR-08-05 Fig. 1-9).

The following, section of this review (Chapter 2) considers the description of the initial character of the Forsmark site and its geological and structural character. The second chapter is divided into subsections discussing various topics regarding the site description: geological setting (2.1), followed by a section describing how information about the geological evolution is presented (2.2). The following subsections are more focused on the Forsmark site itself, the local model volume, and comprise discussions of performed investigations (2.3), scales of geological models (2.4), homogeneity of acquired site data (2.5).Then follow reviews of the geological models (2.6) and structure models and fracture minerals (2.7).In the last section of part 2 a review of the potential for mineral resources at Forsmark (2.8) is given. In the third part (Chapter 3), terminology (3.1) and geological concepts supporting layout criterion of a deep geological repository (3.2) are discussed. In the last part (Chapter 4) summary and conclusions are presented.

In addition to the description on the local scale (review here), a description is also devised for a much larger volume, the regional model, in order to place the local model in a larger context and to allow for a sensitivity analysis of, mainly, hydrogeological boundary conditions" (R-06-38 P23). The structure model describing fracture domains is only presented for parts of the local scale model. The regional scale model of the Forsmark area is only briefly discussed in section 2.2.

References to SKB reports are in this review not given in general descriptions of topics, i.e. in the introduction sections. At the end of each overview and review sections in Chapter 2 and at the end of Chapter 3 short comments on, for instance uncertainties, performance and complimentary works, are given.

2. Description of the site, initial state – Geological description

The geological character of an area reflects its evolution and the characterization of an area is an interactive process as new information is progressively obtained during the characterization process. This implies that the approach of characterizing an area may be modified as the investigation proceeds, i.e. data with higher resolution may be needed and added, complimentary investigations to be adopted or that some performed investigations did not contribute successfully.

2.1. General introduction – bedrock geology

Location

The Forsmark candidate area is located within the sub-Cambrian peneplain and is a coastal lowland area in the northern part of Uppland (cf. Fig. 2-1 and 2-2), eastern Sweden. The bedrock is composed of metamorphosed and foliated Precambrian rocks. The degree of exposed rock inside the candidate area is low and outcrops are unevenly distributed, e.g. there are few outcrops in the central part of the target area NW of the lake Bolundsfjärden. The proportion of wet land is relatively high (25 to 35% in some of the sub-catchments) and the candidate area contains parts covered by sea water and lakes (Fig. 2-7b). The proportion of water-covered areas (lakes+sea water) in the target area or local model area is not found to be presented.

Geological setting of the Forsmark area

The Forsmark target area is located in a WNW-trending tectonic domain of Proterozoic age, composed by metamorphosed and foliated rocks and is regarded as part of a shear belt with an internal anastomosing network of ductile to ductile-brittle shears that outline large-scale tectonic lenses composed of apparently less deformed rock (cf. Figs. 2-1 and 2-4). The belt has a length of more than 1 000km and, at Forsmark, a width of about 35 to 40km. The amount of displacement along the discrete shears is not known and shears/faults have experienced later a tectonic, brittle reworking. Hence the bedrock in juxtaposed lenses may not be fully similar regarding rock type distribution and structural pattern. The Forsmark candidate area is located in the north-western part of a large scale shear lens.

Target area – target volume

In the target area, the bedrock types of interest for a potential deep geological repository are metamorphosed plutonic rocks (granodiorites-granites) in the north-western synformal part of a sheath fold (a tube like structure; in this case closing upwards), located between two regional shear zones, the Singö deformation zone and the Eckarfjärden deformation zone, conforming the north-western tip of a regional shear lens (cf. Fig. 2.4a and 2-4c). The boundary of the granitoids forms a reference structure as it has a well-developed magnetic banding. The questions are:
a) the size of available volume for a repository (section 2.6, bedrock model) and
b) how it can be effectively used for a geological repository (section 2.7.1, structure models, in combination with Paragraph 3, layout criterion and strategies)?

Geological modelling

The rock types and their three-dimensional distribution are well described in deterministic models for rock domains (RFM /rock domain in Forsmark/, cf. section 2.6), which were outlined at a relatively early stage of the site characterization work. Later boreholes have confirmed the bedrock model and only minor adjustments have been made. The geological model forms the framework for the thermal, rock-mechanics, hydrogeological, hydrochemical and bedrock transport models.

A central assumption in the modelling of lithologies (rock domains, cf. section 2.6) is that rocks are extended parallel to the mineral lineation giving for example an aplitic granitic body in the north-eastern part of the fold a tubular form; dipping steeply south-eastwards in the synformal northern part of the sheath fold. On a larger scale, this involves that the geometry of the sheath fold (a fold that may form closed structures) enveloping the bedrock hosting the repository is controlled by the striation. This implies that a good control of the striation is important in the modelling the rock distribution in the Forsmark area.

The accumulated strain in the central granitoids is hard to assess as the rock may have been recrystallized synkinematically. However, the ductile deformation in the central granitoids increases outwards (achieves a magnetic banding, as a foliation) when approaching the regional ductile deformation zones at the borders of the candidate area. These ductile zones are the precursors of the NW to WNW trending Singö and Eckarfjärden brittle deformation zones bordering the Forsmark candidate area. Furthermore, the geological map indicates that the sheath fold is asymmetric and sheared along the Eckarfjärden deformation zone to the southwest. This is reflected by increased deformation (including also brittle deformation) in the western part of the target area (an inhomogeneity that may be considered in stochastic modelling of subordinate rock types and also fractures outside deformation zones).

The internal deformation in the granitoids is also revealed by the occurrence of minor lens-shaped bodies of amphibolites (meta-dolerites) lying concordant to the foliation and having their long axis parallel to the mineral lineation.

The high-resolution ground magnetic measurements, performed in the north-western part of the candidate area (i.e. the main part of the local model volume), show a more intricate pattern in the central granitoids than what is expressed in the geological map. The magnetic pattern reflects both primary inhomogeneities in the granitoids and the imprint of alteration and tectonic structures. The magnetic measurements may also reflect rock constituents not exposed in outcrops or found in boreholes. An example is a magnetic linear structure discordant to the foliation, having a more westerly trend, and interpreted as a basic dyke (no age suggested: youngest dolerites in the region are c. 1.4-1.2 Ga: 1Ga=10^9 years). The magnetic measurements also indicate low magnetic lineaments trending mainly NNE and out of five investigated lineaments one was found to represent late granitoids and pegmatites (see text below) while the other four are brittle deformation zones, i.e. the late granites have similar magnetic signature as brittle deformation zones (cf. text below).

In areas with rock sequences displaying sheath-folds, the character of the rock at depth may be hard to predict as infolded rocks also may have tubular geometry (c.f. the aplitic granite described above). Rock types located below the granitoids are not discussed. However, modelling of gravity data confirms that the granitoids extend to great depth.

The Site Descriptive Model (SDM) gives a confident description regarding the geometry and distribution of the dominant rock types in the area. Information about subordinate rock types is scarce in all SDM’s (stage 0 to 2.3). However, the occurrence of amphibolites, due to their thermal conductivity (low) may affect the layout of canister positions in the repository. Based on a stochastic model of rock types, to display the distribution of minor rock types, the variation in thermal properties in the bedrock is given in the SDM. It is also shown that there are sub-horizontal layers of, e.g. "pegmatites, pegmatitic granites and amphibolites" whereas the dominant dip of rock contacts is steep. In the boremap documents (SKB P-reports) the orientations of lithological contacts are generally not given.

Of interest are sub-dominant rocks, with exception for amphibolites, occurring as NNE/sub-vertical acid dyke-like bodies and small irregular intrusions discordant to the foliation; i.e. the latter post-date the peak of the ductile deformation. Such rocks, composed of low-magnetic fine- to medium-grained meta-granitoids, generally less than one metre wide in boreholes, are relatively evenly distributed and constitute about 5 to 9% of the bedrock in the central part of the local area, i.e. in the core of the fold. The origin of these rocks is not given. The reason for the interest is that they occur together with brittle deformation zones having the same orientation and magnetic signature. Furthermore, the dykes may contain/trap extensive fractures, long fractures (cf. section 3.2), affecting the location of canister positions in the repository.

Bedrock alteration

The most common type of alteration (section 2.6) in Forsmark is oxidation; red-staining of the rock and a reduced magnetic signature. The oxidation is commonly associated with brittle structures and hydrothermal processes. Another type of alteration, albitization, occurs particularly in the north-eastern part of the local area and has an affinity to the amphibolitic lenses/bodies and is apparently not related to brittle deformation zones. These two types of alterations are not related to depth. A third and conspicuous type of patchy alteration is the vuggy granites (epi-syenite), which are characterized by a high porosity, voids formed due to solution of quartz, and altered, often oxidized/red-stained rock. Alterations are recorded in the core log, but are not modelled in three dimensions.

Brittle deformation zones

The local and regional brittle deformation zones (ZFM; zones with lengths ≥ 1 km) are displayed in the local brittle deformation zone model (section 2.7.1). Regional brittle deformation zones (≥ 3 km) are mainly presented in a larger scale, regional model. A conceptual model describing the development and reactivation of brittle deformation zones has been developed and a synopsis regarding orientation of fractures and assemblages of fracture minerals associated to the different sets of brittle deformation zones have been presented (cf. sections 2.7.1 and 2.7.2).

From a structural point of view the local model volume can be described to consist of a set of subareas, each with a dominating set of brittle deformation zones. In the vicinity of the NW- to WNW-trending regional boundary zones that demarcate the local area, brittle deformation zones conforming to the regional zones are common.

Such deformation zones are not found in the more central part of the target area. In south-eastern parts and the north-western quadrant of the local model volume, brittle deformation zones with ENE-trends are dominant, while in the north-eastern quadrant of the local model NNE-trending structures (local and minor brittle deformation zones) are prominent.

Fracture domain model

A special type of structure model has been constructed, a fracture domain model (section 2.7.3), and the aim of this model is to give input data to stochastic modelling of fractures and minor brittle deformation zones (DFN models). Fracture domains (FFM) are only identified for rock domains in the central part the local model volume. The fracture domains describe brittle structures, fractures and minor brittle deformation zones, in the parts of rock domains that are not occupied by regional and local deformation zones. The enhanced density of sub-horizontal to gently inclined fractures in shallow parts of rock domains RFM29 and RFM45 (Fig. 2-9) is also considered in the subdivision of the rock into fracture domains. This implies that the potential repository volume is located in two fracture domains and that these domains do not extend to the ground surface.

Economic geology – mineral resources

The region where the Forsmark candidate area is located, is, from the point of view of economic geology (section 2.8), regarded as a part of an ore province, as the bedrock is partly composed of supra-crustal rocks, meta-volcanites, which have potential to be mineralized. Minor mineralizations are known from the meta-volcanites southwest of the candidate area. In the sea northwest of the Forsmark candidate area there is a larger body of meta-volcanites. It has not yet been explored. A local gravity maximum corresponds to a magnetic low at the north-western tip of the Forsmark lens (just outside the mapped area, 3 km northwest of the candidate area) may indicate a mineralization. The metamorphic plutonic rocks occupying the central part of the candidate area appears to be non-mineralized. The largest ore bodies in the region are located in Dannemora, mainly iron ore, approx. 28 km southwest of Forsmark.

2.2. Review, geological evolution

The report on the geological evolution (SKB R-08-19 Chapter 2) presents a verbal overview of the regional structural context for the Forsmark and Laxemar areas. Large parts of the text constitute summaries of results obtained by SKB during the investigations of the Forsmark and Laxemar areas (e.g. dating of rocks and fracture minerals). The Forsmark area is located in a tectonic domain formed during the Swecokarelian orogeny (Fig. 2-1; Tectonic domain 2), which is characterized by ductile, high strain belts striking WNW and anastomosing around tectonic lenses with lower strain (one containing the Forsmark area) . The structures displayed to be located at the eastern and western “ends” of Tectonic domain 2 (Fig. 2-1) are younger. Tectonic domain 2 is actually located along a regional structure that intersects, possibly transect, the Fennoscandian Shield, i.e. the regional WNW to NW trending structures in Forsmark form a part of a large scale structure that have a length exceeding 600 km (Figs. 2-2 and 2-3).

Regional comparison

A difference between the described early deformation (during the Precambrian, ≥ 540 Ma ago) in Forsmark and south-western Finland is that well defined

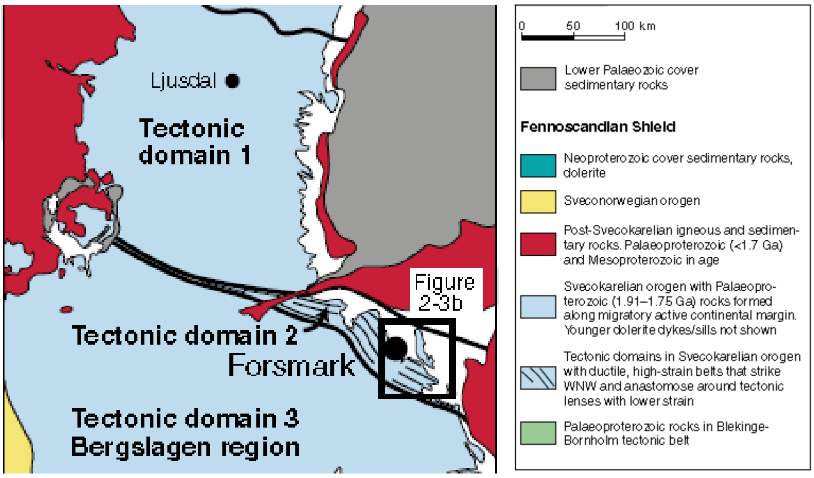


Figure 2-1: Regional geological setting of the Forsmark (modified from SKB R-08-19 Fig. 2-3).

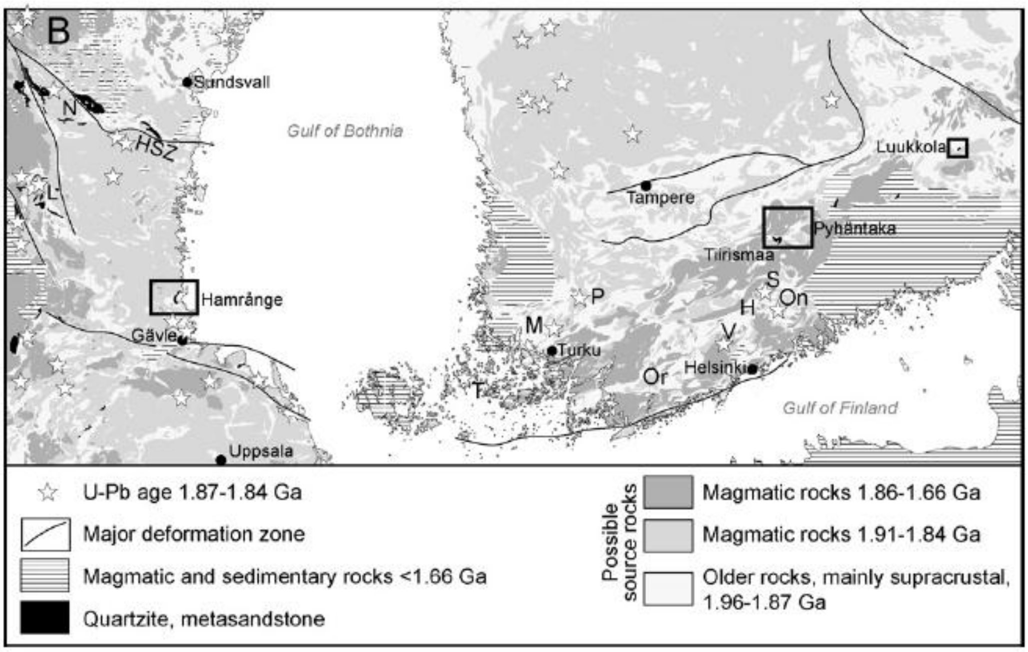


Figure 2-2: Bedrock map of south-central Sweden and Southern Finland, modified from Koistinen et al. (2001). Stars denote locations of 1.87–1.84 Ga U–Pb ages of plutonic rocks, from Nironen (2003), Hermansson et al. (2006), Bergman and Söderman (2005), Bergman et al. (2005) and the Geological Survey of Sweden age database. Localities referred to in the text: H: Hyvinkää, L: Los, M: Masku, N: Naggen, Or: Orijärvi, On: Onkimaa, P: Pöytyä, S: Soukkio, T: Torsholma, V: Veikkola (from Bergman et al.
2008 – references are given in Bergman et al. 2008).

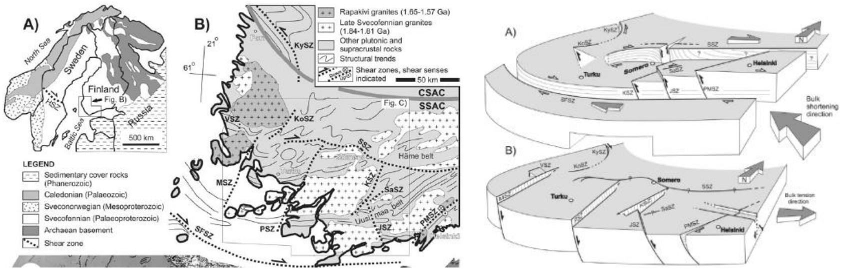
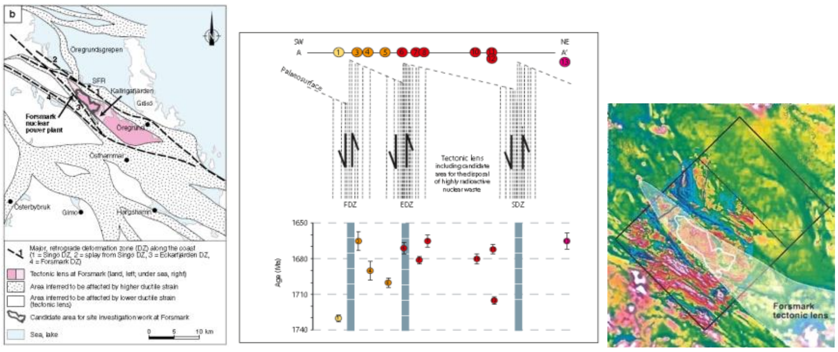


Figure 2-3: Schematic block diagram model for the evolution of the shear zones in SW Finland. To the left; A. An overview of the geological units in the Fennoscandian Shield. HSZ – Hassela Shear Zone (Fig 2-2). B. Shear zones described in the block diagram to the right.
To the right; A. The contractional stage at ~1.83–1.79 Ga. SE–NW contraction leads to a transpressional regime along the E–W trending Southern Svecofennian Arc Complex. Tectonic strain was partitioned into the major strike-slip shear zones at the margins and into steep reverse dip-slip shear zones between the strike-slip zones. B. The extensional stages at ~1.79–1.77 Ga, 1.64–1.55 Ga and/or 1.26 Ga. The MSZ, VSZ and PSZ were formed and the other SZs were reactivated. Lines on the shear planes illustrate mylonitic lineations. The block south to the SFSZ is omitted for clarity. (From Vaisänen and Skyttä 2007).



a. b. c.

Figure 2-4: Characteristics of areas affected by high ductile strain, location of NW to WNW trending regional zones (a.SKB R-08-19 Fig. 2-3), displacement along regional WNW to NW trending regional deformation zones (R-08-19 Fig. 2-22) and the magnetic signature related to deformation in the bedrock (TR-08-05, part of Fig. 5-1).

deformation stages controlled by extension tectonics are indicated in Finland but not in Forsmark (Fig. 2-3). In the Forsmark area the described periods of tectonic deformation are characterized by bulk crustal shortening (i.e., compression cf. SKB R-07-45 Figs. 5-3 to 5-5). Another difference is that the NE to ENE trending deformation zones in Forsmark are smaller. Still, the length of NE and ENE structures appear in both Forsmark and SW Finland to be restricted by WNW to EW trending zones, i.e. zones conform to the southern boundary of Tectonic domain 2. However, indications of extension tectonics in the Forsmark area have been found in a paleostress field reconstruction study (Saintot 2011) and are not included in the structure evolution model. What is emphasised here is that the description of the geological evolution should include relevant areas such as south-western Finland.

Ductile deformation at Forsmark

“Tectonic lenses, in which the bedrock is less affected by ductile deformation, are enclosed in between ductile high strain belts. The candidate area is located in the north-westernmost part of one of these tectonic lenses. This lens extends from northwest of the Forsmark nuclear power plant south-eastwards to the area around Öregrund” (TR-11-01 P17; cf. Fig. 2.4). Within a structure domain like Tectonic domain 2, lenses may occur on different scales and there is a possibility that the Forsmark lens closes south of the south-eastern tip of the candidate area (cf. Fig. 2-4a and c). Such smaller scale lenses will have higher symmetry than the larger scale Forsmark lens. Ductile deformation is found along both the northwestern and south-eastern borders of the candidate area (R-07-45 Appendix A13- P10, 14, 15 and 21). However, ductile shear are sparsely found in boreholes inside the lens and such zones are generally thin.

Plastic deformation such as folding and refolding is typical for the Tectonic domain 2 and the Forsmark lens contain in its central part a deformed “closed” fold (a sheath fold/tube fold – the fold display a closed structure on the geological map).

Ductile-brittle deformation at Forsmark

Major regional structures in the Forsmark area are the WNW to NW trending ductile to shear zones, e.g. the Singö, Eckarfjärden and Forsmark deformation zones (Fig. 2-4a) are mostly well described (the Eckarfjärden deformation zone is not investigated by any cored borehole) and located inside the areas with higher ductile strain. It is indicated that the zones are indicated to be curved, listric, as the paleoground surface is tilted (Fig. 2-4b). This character of the shear zones gives that reactivations associated with oblique displacement along the fault will cause tilting of the ground surface. The ground surface approximately coincides with an early formed denudation surface, the even and flat sub-Cambrian peneplain formed more than 540 Ma ago, and thus the period during which the distortion may have taken place is extensive.

Brittle deformation at Forsmark

It is indicated that “faulting with a conspicuous dip-slip sense of movement also occurred after 1.67 Ga ago along the steeply dipping ENE and NNE fracture zones inside the target volume” (R-08-19 P64), i.e. inside the north-western wedge of the Forsmark lens. Such block displacement must also encounter, be related to, dip-slip or oblique slip along other zones, e.g. the WNW to NW trending zones.

Study of fracture mineral indicates that a brittle regime prevailed in the bedrock at medium to lower temperatures, i.e. below ~400°C. The first generation of fracture minerals is given a relatively wide time period spanning from 1.8 to 1.1 Ga ago (R-08-12 P103), which is even from a geological viewpoint a large period.

Late deformation in the region around Forsmark

Comparing the regional interpretation of airborne magnetic measurements and the topographical map (Fig. 2-5) for the Uppsala County it is obvious that the main topographical breaks and low-magnetic anomalies coincide and represent deformation zones, faults. Notable is the systematic tilting of blocks displayed on the topographical map and the geometry of the blocks. What is special for the characterization/ identification of structures in the Forsmark area is that both the magnetic measurements and the topographical data indicate that structures trending approximately NS approach the Forsmark area from the south. Some of the northerly trending faults may transect the Forsmark lens, at least along Kallrigafjärden located southeast of the candidate area (cf. Fig. 2-4c). The Forsmark lens is possibly also cut by the structures that align the western boundary of the Gräsö block (the largest topographical break, > 30 m vertical displacement of the mean ground surface, within a radius of 10 km from the Forsmark site). The trough along the western side of Gräsö is locally deeper than – 40 m a.s.l.

However, it is pointed out that "On the basis of geomorphological data, dip-slip disturbance and eastward or northward tilting of the sub-Cambrian unconformity are apparent along faults that strike NNE-SSW, NNW-SSE or WNW-ESE in northern Uppland, where Forsmark is located. In particular, dip-slip displacement of the sub-Cambrian unconformity along the Forsmark deformation zone, with uplift and northward tilting of the bedrock block to the north of this zone, has been inferred. The consistent sense of kinematics and sense of block tilt inferred from both the 40Ar/39Ar biotite and the geomorphological data across the Forsmark zone suggest that at least some dip-slip displacement along this zone occurred after the establishment of the sub-Cambrian unconformity during the latest part of the Proterozoic and/or the Phanerozoic" (R-08-19 P64).

To get a better understanding of different generations of regional deformation zones in northern Uppland and adjacent sea areas a block model comparable with that presented for south-western Finland should be produced (cf. Fig. 2-3). Of special interest is to consider faults related to late block faulting as such fault are most probably the structures that control the present circulation of the groundwater in the bedrock and having the greatest potential to reactivate. Before this is done it is difficult to answer whether or not the regional Forsmark area has an appropriate size to reveal structures that may contribute to the characterization of the Forsmark site.

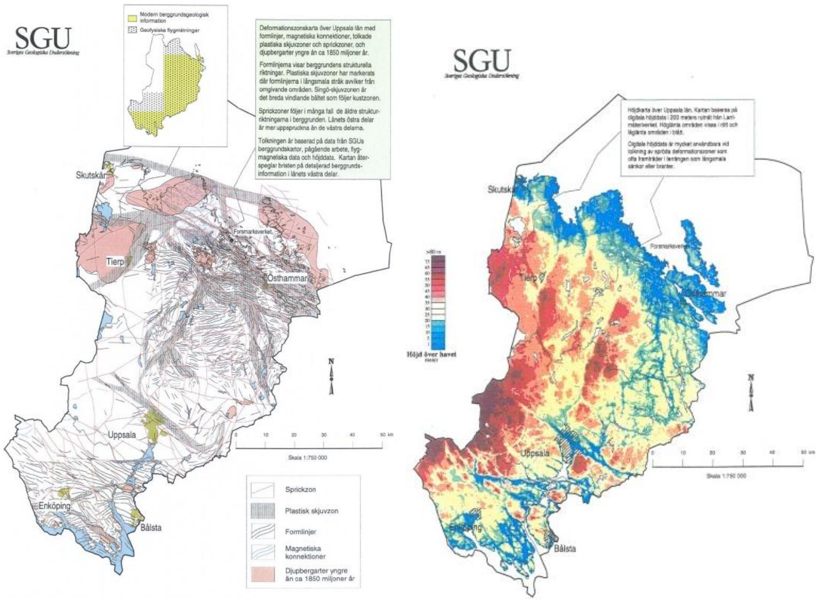


Figure 2-5: Interpretation of structures in the bedrock based on air-borne magnetic measurements (a;SKB R-98-32 Fig. 13) and the topographical elevation model (b.SKB R-98-32 Fig. 12), county of Uppsala.

It is not found in the site reports descriptions of how events or processes that have taken place in the regional surroundings of the site have affected the character of the Forsmark area, for example:

1. The intrusion of rapakivi granites, e.g. in Åland, about 1.5-1.6 Ga ago. Thus the distance from the centre of the Åland intrusion is in the order of two times the diameter of the intrusion (diameter c. 45-50 km and distance of about 75 km from the rim of the intrusion)
2. The Siljan impact, c. 377 Ma ago (Raimold et al. 2004), diameter c. 65 to75 km and at a distance of c. 170 km from Forsmark – the impact is located across the western part of Tectonic domain 2. Can be compared to a major earthquake in the vicinity of the site.
3. Late large scale block faulting of Tertiary age (Flodén 1980; <65 Ma ago) in the western part of the ENE-WSW trending basement culmination across Åland representing a late Cretaceous high (Lidmar-Bergström 1996) – the formation of the Åland deep between Åland and Uppland, c. -90 to - 280 m a.s.l. deep, by descending and tilting of large scale blocks with the sub-Cambrian peneplain preserved as top surface (cf. Söderberg 1993).

However, the two fundamental types of geological process that have impact on the late geological evolution (Tertiary to present, last 65 Ma) are:

- The active continental margins and related regional stress field within the continental plates.
- Compensation for the removal of the Palaeozoic sedimentary cover and loading and unloading cycles in connection to glaciations.

The study of fracture minerals gives indications of reactivation of shallow gently inclined fractures during the Quaternary. Fractures have been opened and presumably connected. However, there is no information about displacement. The search for Post Glacial Faults (PGF) in the Forsmark area and northern Uppland has not found any indications of late faulting or large late earthquakes (Lagerbäck and Sund 2008), i.e. displacement in Quaternary sediments indicating post glacial faulting. One of the most pronounced faults in the vicinity of the Forsmark area, the Forsmark deformation zone, has been investigated by a cored borehole (R-08-64). Even though this fault has a well-marked topographical expression northwest of the Forsmark village no indication of displacement of Quaternary triggered by moderately strong earthquakes was found at Kallrigafjärden, southeast of the candidate area (P-04-123).

The Swedish National Seismic Net (www.snsn.geofys.uu) has now been in operation for ten years and has so far only recorded minor earthquakes. Such earthquakes are enhanced, e.g. in the sea area northwest of Forsmark in Gävlebukten. There are indications of repeated seismic activity along zones. There is also a record of somewhat older earthquake data (Helsinki Catalog of earthquakes in Northern Europe since 1375) containing minor seismic events along WNW structures in the vicinity of Forsmark.

Comments on the description of the geological evolution

The description of the geological evolution of the Forsmark site is deficient in the description from the Palaeozoic to present day. However, the geological processes during this period left weaker indication as events presumably were of much smaller magnitude in a cold cratonic environment compared to the Precambrian period.

However, there are notable processes that are recordable and one of them is displayed by the distortion of the sub-Cambrian peneplain.

Information on late deformation are compiled elsewhere (e.g. distortion of sedimentary rock sequences in the Baltic Sea, denudation/weathering and uplift) and are more used to describe different geological periods (succession in sedimentary sequences) than presenting maps showing how structures are related and distributed.

Maps or block models are needed to describe different generation of deformation in the regional area surrounding the Forsmark site. One good example of thematic presentation of structure data is the report on “early Holocene faulting and paleoseimicity in northern Sweden” Lagerbäck and Sundh, 2008) with a generous presentation of figures and maps. These maps are of high value for the safety assessment as they indicate possible geometries of faults and faulting, i.e. how irregular active fault can be when formed by a combination of partial reactivation of faults and linkage of existing faults and what to measure as trace length of faults.

2.3. Overview, performed investigations

The documentation of the bedrock in the candidate area is based on: 1. Remote studies, 2. Field studies and measurements and 3. Surface based borehole investigations. The remote studies (1) comprise mainly structural analysis of helicopter-borne geophysical measurements and topographical data (elevation data, aerial photos). Field studies (2) involve geological mapping and geophysical surveys (detailed ground geophysical measurements performed at a late stage of the site characterization to compliment the helicopter borne geophysics, and gravity measurements, reflection and refraction seismic surveys). Detailed fracture mapping was conducted on cleaned rock surfaces at drill sites and along trenches. Surface-based borehole investigations (3) cover core logging, borehole geophysics, including TV-log/BIPS, borehole radar and vertical seismic profiling/VSP/.

The nature is regarded to have a high value in the Forsmark area and there are restrictions in possible drill site locations. Therefore, several boreholes, generally divergent, were drilled from some of the available drill sites. A total of 23 cored boreholes were drilled inside the candidate area and 21 of these are located in the target area. Percussion drill holes (38) were drilled either to support the cored boreholes or to investigate specific targets, e.g. structures related to lineaments.

The surroundings of the candidate area were more extensively investigated in order to establish the regional setting of the candidate area (documentation of the character of the regional area) and investigated by helicopter-borne geophysical measurements. Two cored boreholes were drilled to investigate regional deformation zones outsides the candidate area; the Singö deformation zone to the northeast (close) and the Forsmark deformation zone (at a distance) to the southwest of the candidate area. However, in the regional Eckarfjälden deformation zone, constituting the western border zone of the candidate area and located between the Forsmark deformation zone and the Forsmark candidate area, only two percussion boreholes were drilled.

The local model area covers the north-western part of the candidate area and the NW- to WNW-trending regional Eckarfjärden and Singö deformation zones constitute the eastern and western boundaries, respectively. It does not include the south-eastern part of the so called target area. There are 20 cored boreholes in the local model volume.

Comments on performed investigations

It is obvious how the high-resolution ground magnetic measurements (11 km^2, performed 2006-2007 /R-07-62/, appeared late in the site investigation) have contributed to the mapping of deformation zones (cf. SKB R-08-64 Appendix Table A-1). However, it is not clear if the high-resolution ground magnetic measurements have been used to update the distribution of rock types and rock alteration in the central parts of the local model area (rock domains RFM29 and 45).

Have structural relations in outcrops mimicking the relation between local scale structures (≥ 1 km) and larger scale (≥3 km) been noted and addressed in the three-dimension modelling performance?

The acquired data are extensive and the reporting of the site investigations is voluminous. The investigation techniques applied are of high quality. However, to evaluate the accuracy of the preformed interpretation of data made by SKB and the usage of all data recorder tests (for example alternative modelling) must be performed and further more detailed reviews should be done. Uniformity in data distribution is treated below. However, it can be noted here that the regional northwest-trending Eckarfjärden deformation zone, outlining the southwestern tectonic boundary of the Forsmark site is not investigated by any cored borehole.

2.4. Overview, scales of geological models

“The candidate area for site investigations at Forsmark is situated within the north-westernmost part of a tectonic lens (cf. Figs.2-4a and 2-4c). This lens extends along the Uppland coast from northwest of the nuclear power plant south-eastwards to Öregrund and it is approximately 25 km long. The candidate area is approximately 6 km long and the north-western part of the candidate area has been selected as the *target area* for continued site investigations during the complete site investigation phase” (SKB R-05-18 P5).

To describe the character of the Forsmark area/site several scales are used:

1. Regional model volume (SKB R-06-38 P23-14: 165 km^2 large, depth -2 200 m a.s.l)
2. Local model volume (SKB R-06-38 P24-25: 16 km^2 large, depth -1 100 m a.s.l.).
3. A central area containing the proposed location of the repository (the near-field, target volume) containing mainly granitic and to granodioritic rocks (rock domains RFM29 and RFM45, see text below; SKBTR-08-05 and SKB R-08-113).

The geological models are deterministic models. The types of models are:

A. Bedrock models – rock domains (generalized lithological model, cf. Fig. 2-9 the local model) – same resolution in regional and local model volumes.

B. Models of deformation zones – different resolution in regional and local models (Figs. 2-12 and 2-13, the local model)
C. Fracture domain model (only as a local volume model, Fig. 2-14) – used as input data to stochastic modelling of fractures, DFN, located outside modelled regional and local brittle deformation zones in the central part of the local model volume, cf. SKB R-07-45 and SKB R-07-46). The fracture domain model covers the near-field of the planned repository.

The models of deformation zones are three:

1. Regional model; surface trace length of deformation zones ≥ 3km.
2. Local model; surface trace length of deformation zones ≥ 1km.
3. Modelled minor deformation zones, MDZ, in the local area; surface trace length of deformation zones ≤ 1 km. Used together with the local model in the layout of the repository.

A detailed description of the bedrock geological map at the ground surface describing distribution of different lithologies (rock types) and gently inclined brittle deformation zones and steeply dipping regional brittle deformation zones (>3 km trace at the surface) is given (SKB R-08-128).

“Local models for the geometry of rock domains and deterministic deformation zones, with a higher resolution, are presented for the first time” in a report from 2006 (SKB R-06-38 P5). These models were further developed in 2007 (SKB R-07-45 P5 and Appendix 15) and added was also a description of minor deformation zones (SKB R-07-45 Appendix 16). A synthesis of the characters of different sets of brittle deformation zones was presented in 2008 (SKB TR-08-05 P144-153) and described are:

- Sets of brittle deformation zones.
- Orientation of fracture sets within the different sets of brittle deformation zones.
- Fracture minerals in different sets of brittle deformation zones.

The site description at completion of the site investigation phase is focused on the local scale description and also considers the minor deformation zones (MDZ) at repository depth (SKB TR-08 AP.4).

Comments on applied scales

The different scales of describing the character of the bedrock at Forsmark are mainly found appropriate. The exception is the description of structural relationships, including internal pattern, of structures belonging to different sets. There are detailed fracture maps presented for cleaned outcrops (cf. SKB R-05-18 Fig. 5-31), but the structure interpretation of the fracture data is missing. Sketches displaying character of zones are missing.

The dispersion of boreholes in the area at repository depth do not allow modelling of geometries of subordinate rock types within rock domains RFM29 and RFM45, i.e. in the near-field of the repository. However, detailed mapping and modelling of rock types and tectonic structures will be performed during the construction of the repository (SKB R-11-14). The outcome of a late borehole in the northern part of the Forsmark site (SKB R 08-64 Fig. 4-8) display that there is a greater spread in the orientation of deformation zones than postulated and that there are also indicated intercepts of possible zones that are not included in the model (see text below, section 3.7). It is a plausible assumption that the density of deformation zones can be estimated but their locations can be uncertain.

2.5. Overview, base data – uniformity in data distribution

Exposed rock – outcrops

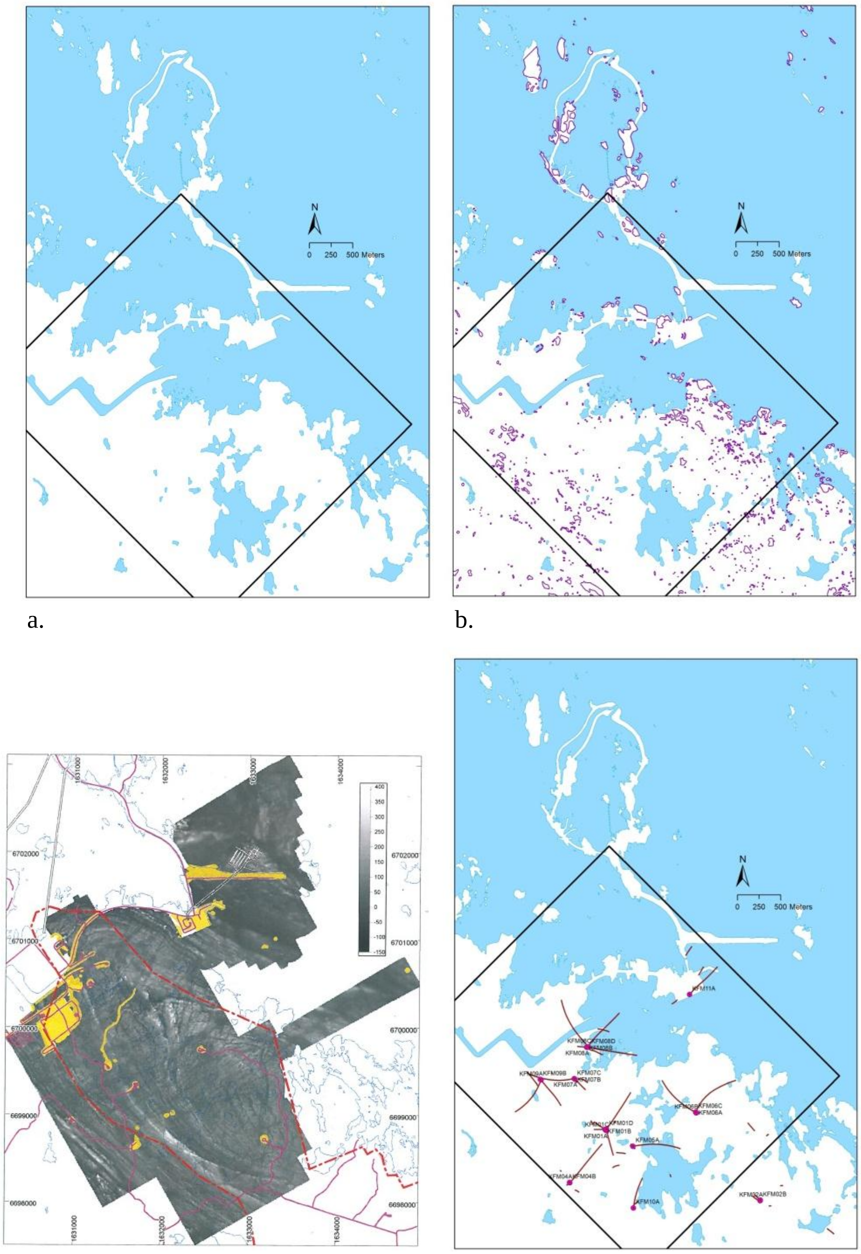
The percentage of water-covered areas inside the local model area (Fig. 2-6a) is not found in the reports by SKB. The proportion of wetland is relatively high (25 to 35 % in some catchments). The degree of exposed rock in the land area of the local model area is low (5%, while 13% in the regional model area; SKB R-05-18 P100) and outcrops are unevenly distributed (Fig. 2-6b), e.g. there are few outcrops in the central part of the local model area NW of lake Bolundsfjärden. For example, at drill site 1 (Fig. 2-6d) the depth to bedrock is generally between 4 to 8 m. The maximum measured depth to the bedrock in the Forsmark area is 17 m. Despite the variation in depth to the bedrock head, the upper surface of the overburden, is “quite flat” (SKB R-06-18 P101). In other words, the degree of exposed rock is more enhanced outside the central parts of the local model area than in its central parts, i.e. outside the area of the potential repository.

Elevation data

Topographical information used is elevation data:

- Land areas inside the local model volume and main parts of regional model volume (SKB P-02-02) grid 10 m.
- Regional land areas outside the regional model volume (Lantmäteriet, GSD (Geografiska Sverigedata) - Terrain Elevation Databank, elevation data bank 50+) grid 50m.
- Sea areas between Forsmark and Gräsö (SKB P-05-101), inside the local and regional model volume – measurements performed by SKB.

The resolution in the elevation data covering land area and sea area in the local and regional model volumes are not identical, but the difference may have minor importance for the geological interpretation as SKB states that there is a low correlation between brittle deformation zones in the bedrock and the topography in the Forsmark area (R-06-38 P120).



a. b.

c. d.

Figure 2-6: Data acquisition in the Forsmark area (the square represent the local model area): a. Water covered areas (SKB GIS database) – direct observation of the bedrock not possible, b. distribution of outcrops (SKB GIS database), c. ground magnetic representation of the bedrock (42 % of measurements are made from boat; line separation 10 m and point separation 2-5 m (R-07-62 Fig. 3-7), and d. cored boreholes and their surface projections (SKB GIS database; two boreholes are not displaced: KFM03 and KFM12 located southeast and southwest of the map area. Short traces are percussion boreholes).

Ground geophysics and seismics

The most notable amongst the geophysics measurements (cf. SKB TR-08-05 Fig. 5-17 Coverage of airborne and ground geophysical measurements) are the high-resolution magnetic ground measurements (Fig. 2-6c) that well display the pattern of moderate to steeply dipping structures in the bedrock and the complimenting reflection seismics (cf. SKB TR-08-5 Fig. 5-20) indicating moderately to gently dipping structures. However, the bedrock surface intersections of brittle deformation zones are generally covered by soil and only a few has been exposed in trenches.

The outcome of performed refraction seismic surveys (profiles given in SKB TR-08-05 Fig. 5-22) is that "there is only a moderate correlation between low velocity anomalies and lineaments defined by magnetic minima or modelled deformation zones" (TR-08-05 P132).

The structure interpretation of the detailed magnetic measurements (Fig. 2-7) forms base data for modelling of structures in three dimensions, evaluation of structure homogeneity and structural relations (pattern) within the area.

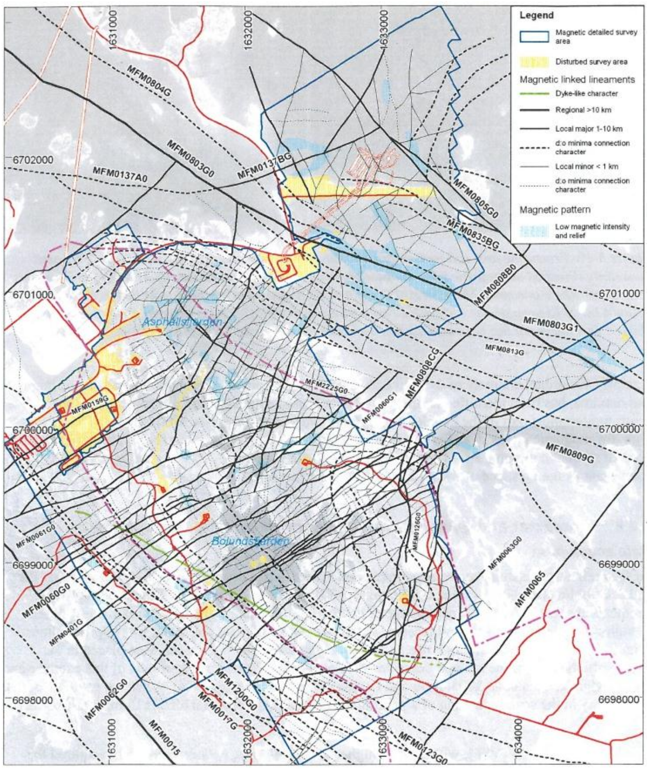


Figure 2-7: Low magnetic lineaments inferred from the integration of high-resolution ground magnetic and airborne helicopter data (TR-08-05 Fig. 5-18).

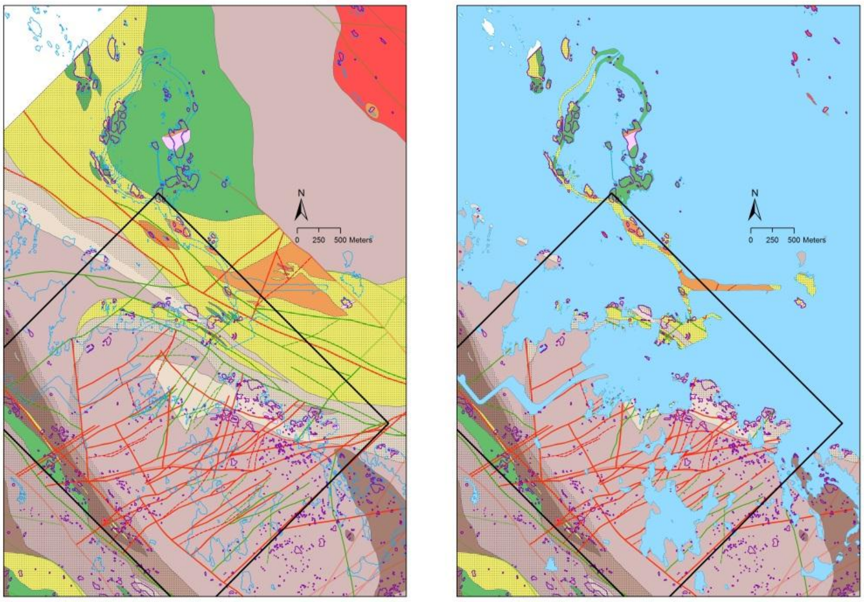


Figure 2-8: a. Geological map of the Forsmark area (SKB GIS data - displaying lithologies and deformation zones /all zones – also zones with surface traces less than 1 km long/; cf. Bedrock geology modelling stage 2.3 (R-08-128) for legend, and b. same model as Fig. 28-a displayed with sea area and lakes masking the bedrock geology.

Subsurface data acquisition - Borehole investigations

The borehole programme (Fig. 2-6d) in the Forsmark area has to some extent been steered by restrictions (proclaimed by the county administration in Uppsala) because of natural value of the sites proposed for drilling (cf. section 2.3). 21 cored boreholes have been drilled from 8 drill sites inside the local model volume From additional four drill sites outside the local model volume 5 borehole have been drilled; four southeast of the local model volume and one southwest (targeting the regional Forsmark deformation zone). No cored boreholes investigate the Eckarfjärden deformation zone bordering the western side of the candidate area.

Uncertainties – data acquisition

The ground surface is generally the only surface where data could be sampled. The detailed magnetic measurements are of good quality and display bedrock features where the bedrock is covered by soil or water (fresh water and sea water). Outcrops are more common within the local model area along contacts of rock domains. In some cases brittle deformation zones indicated on maps are drawn across outcrops. However, descriptions of the characters of such zones are not found in reports.

One of the main uncertainties (1 out of 3) is the location of acquired data, especially the borehole data. Many of the cored boreholes deviate clockwise from the planned direction. This sort of divergence is commonly depending on the drilling performance. How much the divergence affects the planned outcome of the borehole investigation is not known to the reviewer.

The second main uncertainty in the geological description of the Forsmark site (as for most areas) is the step from two-dimensional (the geological and structure maps; cf. Figs. 2-7 and 2-8) to three-dimensional modelling (Figs. 2-9, 2-12, 2-13 and 2-14). Drilling boreholes in different directions from a drill site is an investigation technique not earlier applied, an investigation of volumes more than specific targets; a technique that favours cross-hole interpretations. However, the separations of the endpoints of boreholes are in most cases more than 500 m at repository depth.

There is not presented any analysis of locations of rock volumes within which sets of structures, especially those that that are extensive (e.g. ≥ 1 km), can occur without being intersected by a borehole – a combination of blind volumes and sampling bias. Each set of deformation zones will have their own blind volumes. For example, structures trending NE to ENE may, if they exist, cross the central part of the local model area without being intersected by a borehole. If existent, such zone(s) may affect the central parts of the planned repository.

The sea and lakes cover a large part of the local model area and also the central area below where the repository is planned to be located. This may not affect the characterization of the repository as much as the modelling of structures during the construction of the access ramp (Fig. 2-8).

The borehole configuration and the reflection seismics may catch the gently inclined to sub-horizontal local zones in the area. The third main uncertainty considers detection of minor or thin local sub-horizontal deformation zones at deeper levels. If they exist they may have effects on the layout of the repository and may cause problems during the construction of the underground facility, the repository.

2.6. Review, geological models – rock domains

The spatial distribution of rocks in the Forsmark area (Fig. 2-9) is displayed by using a rock domain model. The model displays also the ductile deformation as the geometry of rock domains is mainly a result of such deformation.

The concept of rock domains and rock units needs clarification. Rock types (petrographically determined) are mapped in outcrops and drill cores.. Within an area the bedrock is generally composed of some dominant rock types accompanied by sets of subdominant rock types (e.g. dykes or layers/bands). Furthermore, the bedrock may locally be affected by deformation and alteration processes. The modelling of the bedrock geology may need simplification depending on scale of modelling, how rock types are distributed, how superimposed deformation have distorted the character of the rock, and the relation between rock types.

To simplify the description of the distribution of different categories of rock types in the regional and local models a concept dividing the bedrock into rock domains (cf. SKB R-05-18; Table 5-20 and Appendix 1) has been applied. Rock domains (SKB R-03-07 P9) are defined as the “combination of the composition, grain size, homogeneity, and style and inferred degree of ductile deformation of various rock units” (unit, see below). A modified regional model and a local model are presented in the Forsmark modelling stage 2.1 (R-06-38 P113). In that model, rock domains RFM29 and RFM45 are inferred while other rock domains are the same as in the previous model.

“A *unit* is the smallest, undivided volume in a 3D geological model. Depending on its properties and intended use, the following qualifiers may be applied: rock unit (lithological unit) and structure unit (e.g. within a deformation zone) in bedrock models” (R-03-07 P12). In practice, for example the interpretation of borehole data (cf. SKB R-07-15 Appendix 2), the subdivision of mapped rocks into rock units is primarily based on the lithological homogeneity and character of overprinting deformation (SKB MD 810.003) and each borehole is considered separately.

The lithological model, represented by the rock domain model (Fig. 2-9), indicates that the central part of the local area contains relatively uniform types of metamorphosed rocks (granitoids to granodioritoids) occupying a volume of such size that it may host a repository for spent nuclear fuel.

The difference between rock domains RFM29 and 45 is that rock domain RFM45 has a more granitic composition, a specific type of alteration (albitization) and is more fine-grained then rock in RFM29. The large-scale fold is, as mentioned before interpreted as a part of a sheath/tube fold.

General notes on the rock domain model are:

1. “The candidate area is located in the north-westernmost part of one of these tectonic lenses” (TR-11-01 P17). Boreholes at the margin of the candidate area display “strong ductile deformation” in some parts of their extensions (upper part, when drilled towards the rock domain RFM29, KFM04A, and lower parts of cored boreholes when borehole drilled towards the margin of the rock domain, KFM 06C, 07A, 9A; cf.SKB R-07-15 Appendix 4). That is, the ductile deformation outlining the lens may extend into rock domain RFM29 and be located inside the repository area.
2. The distribution of different types of rock domains in the Forsmark area is asymmetric across the axial plane of the central fold structure (Fig. 2-9).
3. The structural relation between rock domains RFM29, 32, 44, 45 and 34 (cf. Fig. 2-9) is of interest for the understanding of the central fold structure. Do rock domains RFM29 and RFM34 represent the same layer or two separate layers? The same question rephrased: Is rock domain 32 infolded (a folded-fold) into rock domain RFM29?
4. Rock domain RFM045 is surrounded by rock domain RFM29 in the target volume and has a constricted rod-like geometry that plunges moderately to steeply to the southeast, close to the mineral stretching lineation in this part of the Forsmark site.
5. Felsic rock (meta-volcanic rock, cf. main rock type in rock domain RFM21 and 31, occur also in rock domains RFM18 and 32;SKB TR-08-05 Fig. 5-24 andSKB R-08-128 Fig. 4-2) are found at the rim of rock domain RFM45. The felsic rock has a potential to be mineralized (sulphides and iron oxides, cf. Stephens et al. 2009).
6. Rock domain RFM32, the eastern limb and the crest of the central fold, contains to a large extent the dominant rock type in rock domain 45 and has a superimposed strong ductile deformation.
7. The western limb of the fold (rock domain RFM44) is sheared out against a regional NW trending deformation zone located along the western side of the candidate area. Rock domain RFM44 is a southward structural continuation of rock domain RFM32, the western limb of the central fold structure, and is characterized by strong plastic deformation. This may indicate that rocks in rock domain RFM44 react to ductile deformation in a different way than rocks in rock domain RFM29 did (cf. item 3 above) during the shearing off of the western limb.

8. The internal deformation in the granitoids is, however, revealed for instance by the occurrence of lens formed bodies of amphibolites (meta-dolerites – the Herräng dolorites?) lying concordant to the foliation having the long axis parallel to the mineral lineation.
9. The dominant rock type in rock domain RFM29 (TR-08-05 P395) is a medium-grained metagranite (74% of the domain volume). Subordinate rock types are pegmatitic granite or pegmatite (13%), fine- to medium-grained metagranitoid (5%), and amphibolite and other minor mafic to intermediate rocks (5%).
10. In rock domain RFM45 aplitic metagranite and medium-grained metagranite, the latter similar to the dominant rock type in domain RFM29, are the dominant rock types (67%). To variable extent, both rock types show the alteration referred to as albitization. Subordinate rock types include pegmatite and pegmatitic granite (14%), fine- to mediumgrained metagranitoid (9%) and amphibolite and other minor mafic to intermediate rocks (7%).
11. With the exception of amphibolite that contains little or no quartz, the dominant and the subordinate rock types in rock domains RFM29 and 45 have high quartz content (c. 20–50%).
12. The amphibolites (meta-basite) occur dominantly as bands thinner than one metre (R-07-45 Appendix 5; not including boreholes KFM02B and 8D) and there are some sparse thicker layers of basic rocks (a few 17 to 40 m wide layers located in the rim of the central fold and about 20 layers that have a range in width from 1.5 to about 5 m). The amphibolites generally conform to the foliation and ductile and ductile-brittle shears (R-07-45 Appendix 6). However, some subhorizontal amphibolites are found (indicating folds?). No data on the separation between amphibolites are found to be presented. The amphibolites are modelled stochastically (cf.SKB TR-08-05 Fig. 11-7) as they have distinct lower thermal conductivity than other rock types in the area and thereby may affect the layout.
13. Subordinate rock types in rock domains RFM29 and 45 are similar and they generally occur distributed in the rock as minor segments. However, the relation between more acid sub-ordinate rocks and the foliation is less well described. This hold especially for the fine- to medium-grained granites, which have similar magnetic properties as brittle deformation zones, occurring discordant to the tectonic foliation and the banded magnetic anomaly pattern in the bedrock (R-07-45 P107, cf. Figs. 2-6 and 2-7). Are these late granitic dykes deformed in the western part of rock domain RFM29? The fine-grained granitic dykes may also trap fractures by refraction, fractures extending along the dykes.
14. There is no three-dimensional model describing alteration of the bedrock. Some notes on alteration are given below.

The main types of alteration are oxidation (related to deformation zones) and albitization (related to the occurrence of amphibolites, common in rock domain RFM45). A conspicuous type of alteration is selective dissolution of quartz (so called vuggy granite, another name is episyenite) associated with strong oxidation of the rock. As the name vuggy granite (cf. section 2.7.2) indicates, the voids formed after the removal of quartz are generally not filled with any mineral.

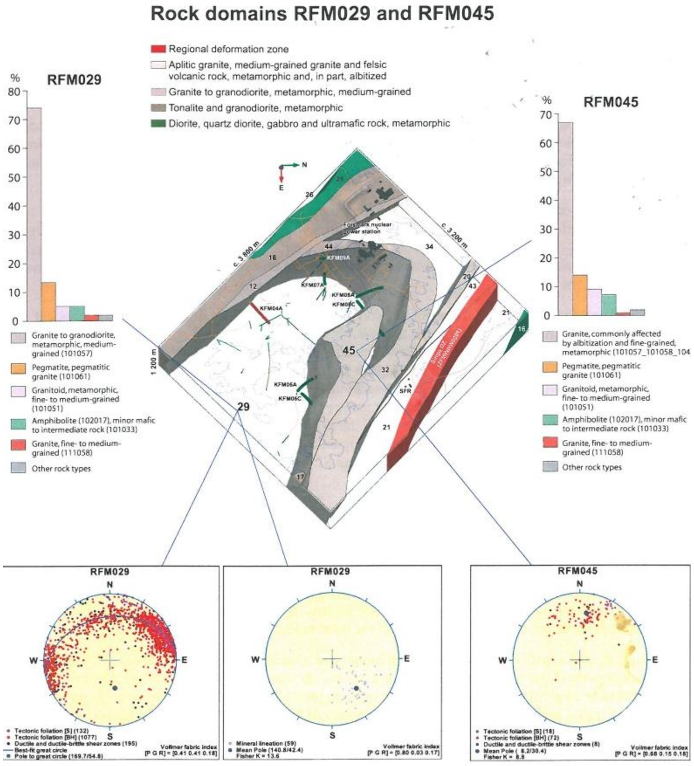


Figure 2-9: Rock domains (numbered) included in the three dimensional local model, stage 2.2. The model is viewed to the west towards SFR and the nuclear power station from a position above the local model volume and approximately 2 km to the southeast of the SFR repository. The target volume consists of domains RFM29 and RFM045 in the hinge of the major synform (TR-08-05 Fig. 5-25).

"Based on the stable isotopic composition in calcite precipitated in voids in the vuggy rock, it can be concluded that the development of the vuggy rock is, at least, older than generation 2 minerals" (R-08-102 P29), i.e. a sequence of hydrothermal fracture minerals (T ~ 150–280°C) dominated by adularia, albite, prehnite, laumontite, calcite, chlorite and hematite. $_{40}$Ar/$_{39}$Ar ages from adularia indicate a major influence of early Sveconorwegian tectonothermal activity at 1.1 to 1.0 Ga ago. Generation 2 minerals are particularly common along steep, ENE-WSW to NNE-SSW and NNW-SSE fractures (R-08-102 P46) and a high proportion of such fractures are generally sealed (fracture log, SICADA data) while so is not the case for the vuggy granites.

Other types of rock alterations listed in the borehole log (SICADA, rock alteration) are, for example, chloritization, epidotization, laumontitization, sassuritization, carbonitization, silification, argillization, seritisation and albitization. Of special interest, regarding influence of regional zones on the host rock, is to investigate distributions of alterations that can be related to formation or reactivation of regional zones, e.g. the NW to WNW zones located northeast and southwest of rock domain RFM29. This issue is related to determination of respect distance and is further discussed in the next section (structure models) and is a topic to be developed further.

The bedrock has a geophysical signature that is reflected in the detailed magnetic measurements (R-07-62), which show a more intricate pattern in the central granitoids than the geological map does. The magnetic pattern reflects both primary inhomogenities in the granitoids and the imprint of alteration and tectonic structures. The detailed magnetic map may also reflect rock constituents not exposed in outcrops or missed by boreholes. An example is a magnetic linear structure discordant to the foliation (R-07-62 Fig. 4-2), having a more westerly trend than the foliation, and interpreted as basic dyke (no age suggested: youngest dolerites in the region are c. 1.4-1.2 Ga) unnoticed by all boreholes. An evaluation of the detailed magnetic measurements supported by petrophysical data can support interpretation of the internal structure in the granitoids. In sheath-folded rocks sequences, the character of the rock at depth can be hard to predict as infolded rock may have tubular geometry (cf. the aplitic granite above, RFM45).

Comments on the geological models – rock domain

The use of rock units and rock domains as generalization and classification of the bedrock on different scales has been constructive and indicate that there is, regarding rock type only, a larger relatively homogeneous rock volume at suitable depths that can host a repository. However, on a repository scale keeping this subdivision may not be appropriate. The mapping of rock types should meet the needs for a proper layout of the repository (cf. SKB R-11-14). Mainly the thermal property of certain rock types will be of importance, i.e. the location, width and separation of amphibolitic layers have to be determined.

Other rock types that will be of interest are late granitic, appearing as dykes cutting the foliation and parallel to at least minor NNE to NE trending deformation zones and may host extensive brittle structures (long fractures – cf. Paragraph 3).

The border of the Forsmark lens should be determined. Even though the rock overprinted by ductile deformation may at least partly have similar mechanical properties as less effected rock the location of a repository should not be within a deformation zone (cf. SKB R-98-20 P44). The border of the ductile deformation should be determined even though the deformation does not have sharp boundaries.

Rock domain RFM45 has a rod-like appearance and its shape is not fully congruent with the form of the sheath fold, which appear to be a more open structure (cone like), i.e. rock domain RFM45 may widen up with increasing depth. However, this will not affect the repository. On the other hand, the sheath folding may import into the local model volume rock types that are not found inside the fold at surface.

The understanding of the vuggy granites could be complemented. The fact that they are open is undisputable. However, the interpretation that they are associated with deformation zones and predate the second generation of fracture minerals (G2) appears to be a contradiction as a high proportion of G2 fractures are sealed. On the other hand, the patchy appearance of the vuggy granites (SKB R-07-45 P58-64 including Tables 3-7 to 3-9) makes them hard to model in three dimensions. What can be said about the vuggy granites is that they form groundwater reservoirs, locally conduits for flowing groundwater and they should be avoided regarding layout of canisters.

2.7. Review, structure models

The site description contains two structure models:

1. Brittle deformation zone model (Figs. 2-12 and 2-13).
2. Fracture domain model (Fig. 2-14).

The brittle deformation zone model is a deterministic model and the local brittle deformation zone model should contain structures (local and regional zones) with surface traces greater or equal to 1 km. Minor deformation zones (MDZ), with surface traces lesser than 1 km, are also modelled when identified. Information about the MDZs is stored separately. Shorter structures (surface traces < 1 km) could be incorporated in the local model if they represent structures related to the more extensive structures, e.g. form splays and structures outlining lenses along local or regional zones (SKB R-07-45 Appendix 15). However, the local structure model contains some MDZ (surface trace < 1 km) not obviously related to any larger structure (R-07-45 Appendix 15).

"To support the stochastic modelling of fractures (DFN) outside brittle deformation zones a need was recognized to divide the Forsmark area into fracture domains (R-07-15), to describe the fracture population in the near-field of the planned repository. Fracture domains and deterministically modelled deformation zones are mutually exclusive volumes, whereas rock domains contain both fracture domains and deterministically modelled deformation zones" (SKB TR-08-05 P404). The orientation of fractures in the fracture domains is similar to that in the adjacent fracture zones (SKB TR-08-05 P404). However, one major inconvenience in the Forsmark area is that the upper part of the rock differs in fracture characteristics (the relative occurrence of open fractures and the density of gently inclined fractures) compared to deeper part of the rock. Four fracture domains are described in the central part of the local model volume (section 2.7.3).

Conceptual structure model – Forsmark area

The SKB conceptual model of the relation between ductile, ductile-brittle deformation zones (Singö, Eckarfjärden and Forsmark Deformation Zones) and deformation zones in the Forsmark site, located between the Singö and Eckarfjärden Deformation Zones, is given in Figure 2-10. There is only one structure (approximately oriented NS/vertical), located in the Forsmark local model volume and outside the main areas with strong ductile deformation having a ductile precursor. This zone is located in the upper part of the sketches and it coincides with the strongly sheared western limb of the fold in the central part of the Forsmark local model and therefore labelled as a fracture zone ("The term fracture zone is used to denote a brittle deformation zone without any specification whether there has or has not been a shear sense of movement along the zone. A fracture zone that shows a shear sense of movement is referred to as a fault zone"/SKB P-06-212 P13/).

The conceptual structure model does not contain structures that overprint the regional deformation zones (the Singö, Eckarfjärden and Forsmark deformation zones). However, such structures occur, e.g. the NE trending Kallrigafjärden Deformation Zone southeast of the candidate area. West of this zone gently inclined zones dipping south-eastward are most common.

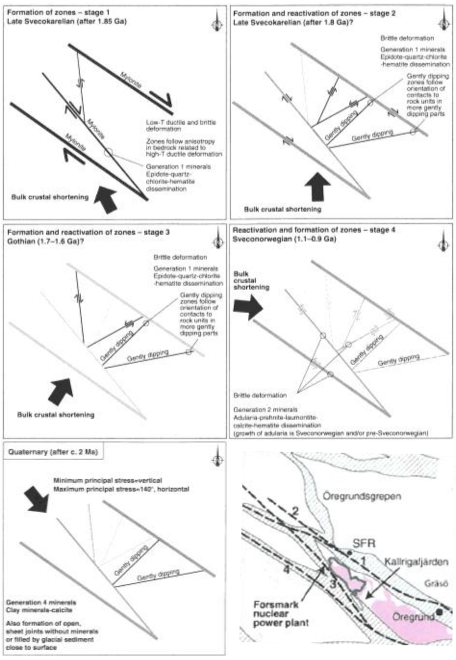


Figure 2-10: Two-dimension sketches illustrating the regional scale dynamics during the formation and reactivation of different sets at Forsmark site (TR-05-08 Figs. 5-25 and 5-36). Lower left figure (modified fromSKB R-07-45 Fig. 1-3) gives the relation between regional structures in the conceptual structure model (the 5 first sketches). Hatched areas represent parts of the bedrock that are strongly affected by ductile deformation, and 1= Singö Deformation Zone (DZ) /the upper WNW trending zone in the sketches/, 2 = a splay from the Singö DZ, 3=Eckarfjärden DZ /the NW transect in the sketches/, and 4= Forsmark DZ /the lower WNW trending zone in the previous sketches describing the conceptual structure model/.

Modelling of brittle deformation zones

"An important modelling prerequisite /R-03-07/ is that the resolution of the modelled objects should be the same throughout the model volume, at any particular modelling scale. For this reason, it is essential to define, for each model, the size of the smallest object to be modelled deterministically. The choice of this limit is guided by the intended use of the model, at a particular scale, and the data density within the model volume. These features are balanced against the efforts required to fill the volume homogeneously with modelled objects" (SKB TR-08-05 P132).

In the SKB modelling an important requisite, as stated above, is that the resolution in the presented models should be uniform. The modelled object could be heterogeneous, but the ability to identify a structure of a certain minimum size should be the same in the whole modelled volume. This implies according to SKB that modelled structures should have a minimum size.

However, it is not fully apparent how this uniform minimum size would be obtained or tested for the whole model volume. SKB decided, based on considerations regarding the continuity between the deterministically modelled brittle deformation zones (cf. Fig. 2-12) and the stochastic geological DFN model, that the limit for structures included in the block model was set to be related to the surface trace length of structures; corresponding to a minimum length of 1000 m (SKB TR-08-05 P132). That is, the deterministic models will describe structures of a certain order of magnitude (in this case 1000 m: the radius (r) of the area of an equivalent disc-shaped fracture is 564 m) while smaller structures will be treated in the stochastic models. However, there is, as far as what is found in reports, no structural argument for choosing 1000 m, based on, for instance length distribution of different sets of magnetic lineaments.

Modelling of zones is based mainly on structure interpretation of surface data (magnetic lineament interpretation, mapping traces of possible moderate to steeply dipping zones), borehole data (geological single hole interpretation, SHI – extended geological single hole interpretation, ESHI; SICADA data and SKB P-reports) and reflection seismics (especially indicating gently dipping zones). Regarding the lineament interpretation based on high resolution ground magnetic "where all structure are concordant it is generally impossible to distinguish magnetic minima connections that are simply related to lithological contacts from those that are related to deformation zones" (TR-08-05 P126) within rock domains RFM29 and RFM45. This holds for areas in the vicinity of the regional WNW to NW trending deformation zones bordering the Forsmark area.

Where the magnetic lineament are excavated within these rock domains it is found (4 out of the 5 investigated cases) that the lineaments represent steeply dipping brittle deformation zones or (1 out of 5 cases) represent a swarm of dykes of late granites and pegmatites (TR-08-05 P401), which indicates that the main part of the low magnetic anomalies represent deformation zones. However, the statistical base for this statement is vague and measurements in boreholes could give a more representative sample.

The detailed magnetic measurements (R-07-62) are mainly used to refine the lineament interpretation of the area (previously based on helicopter- borne magnetic measurements) and updating the deterministic model of brittle deformation zones in the previous SDM. The refinement of the lineament interpretation is quantified (SKB R-08-64 APP. Table A-1). The adjustment of the length of structures in the local model considered about 82% of all structures in the magnetically measured area (most commonly structures were extended but some were also shortened). New lineaments/zones were also added. Most of the brittle deformation zones have their surface traces adjusted and slightly less than 40% of the deformation zones have also their terminations adjusted.

The performed adjustments of trace lengths and terminations affect the hydraulic model of the area and possibly also the rock mechanical and stochastic fracture models, respectively. The detailed magnetic measurements illustrate the importance of high resolution data. However, the detailed magnetic measurements do not cover the whole local model volume and only minor parts of regional NW-WNW trending brittle deformation zones bordering the candidate area. The latter implies that the magnetic data give limited information about the relation between local structures and regional structures. Detailed topographical data (10m grid) were found to have limited use in mapping deformation within the site area. The reason for this is not found to be explained by SKB. It could be due to the flat top-surface of the overburden covering most parts of the bedrock surface?). However, the regional topographical map indicates large-scale block faulting (cf. section 2.2 Late deformation in the region around Forsmark and main part of Uppland).

Modelling of steeply dipping brittle deformation zones

The modelling of steeply inclined brittle deformation zones (TR-05-08 P142) was based on:
1. "The decision to match a particular low magnetic lineament with a particular borehole determines the dip of the zone. The dip of medium confidence zones (see

below) is estimated by comparison with the dip of high confidence zones in the same set or sub-set."

2. "The along-strike termination of steeply dipping or vertical zones is determined by the truncation pattern of the corresponding lineaments, and follows the conceptual model for the site".
3. "Apart from two minor zones that have been modelled deterministically, the orientation of a zone is not determined by the orientation of fractures inside the zone".

The first item in the modelling performance is based on the assumption that structures related to parallel lineament/sets of lineaments have similar dip, i.e. that there exists a unique orientation(-s) for structures related to certain trend of the structures. "A high confidence of existence is applied to all zones that have been confirmed directly by geological data from a borehole or tunnel, or from the surface. In general, indirect data (e.g. low magnetic lineament, seismic reflector) are also present. It is important to emphasize again that the majority of high confidence zones are based on a single borehole intersection along a cored borehole. By contrast, a medium confidence zone generally lacks direct confirmatory data and the zone has been identified solely by the occurrence of a low magnetic lineament or a seismic reflector"(R-07-45 P150). This implies that a structure intersected by two or more holes may subsequently steer the interpretation of structures intersected by single boreholes. In an area with regular and dense lineament pattern such performance can cause a systematic error in the interpretation.

This is indicated in the late borehole KFM08D where the postulated locations of zones in the upper part of the borehole fits well with what is found in the borehole (the three upper zones). However, for structures intersecting the borehole at deeper levels postulated intersections of zones were not fully appropriate; one zone agree, the orientation of three zones has to be modified, one zone at the bottom of the bore hole was reinterpreted to be another zone, and an additional zone intersects the borehole and three new indications of zone intersections were found (R-08-64 Fig. 4-8). In short, the assumed regular inclination of zones with similar trends must be reconsidered as zones are indicated to have a spread in orientation.

In the local model volume the detected steeply inclined to sub-vertical zones (48 zones; SKB R-07-45 Appendix 15) range in width (mean 26 m, median 15 m, range 2 to 200 m, and standard deviation 30 m). However, when the WNW to NW trending brittle deformation zones bordering the central part of the local model volume are excluded the remaining zones (34) are somewhat thinner (mean 19 m, median 15 m, range 2 to 45 m, standard deviation 12 m).

Modelling of gently dipping brittle deformation zones

All but one of the modelled gently inclined deformation zones are detected by reflection seismic measurements. The gently inclined zones are preferentially located in the south-eastern part of the target area, have a dominant dip direction towards SE, and have open fractures. It is shown that gently inclined fractures are common in all parts of the bedrock and gently inclined seismic reflectors are indicated at depth below the repository level (below – 600 m a.s.l.), though located outside and away from the repository area. The geometry of the gently inclined zones is apparently affected by NE to ENE/vertical brittle deformation zones.

The gently dipping zones are assumed to terminate against the nearest, significantly steeply dipping deformation zone, both along their strike and in the down-dip direction. Some gently dipping zones have also been truncated against other gently dipping zones and this has resulted in a splay-like relationship between these structures.

In the local model volume the detected gently inclined to sub-horizontal zones (12;SKB R-07-35 Appendix 15) range in width (mean 21 m, median 19 m, range 6 to 44 m, and standard deviation 12 m). No gently inclined minor deformation zone is found. An important question regarding the location of a repository for nuclear waste at Forsmark is whether or not thin extensive fractures or brittle deformation zones occur at Forsmark at repository depth. A strategy for detecting such structures at early stages of the construction of the underground facilities is needed (cf. SKB R-11-14 P50).

Displacements along faults

The high-resolution ground magnetic and helicopter data covering the Forsmark area (SKB TR-08-05 Fig. 5-18, cf. Figs. 2-6c and 2-7 in this technical note) display very few indications of displacement of structures. However, most NE and ENE trending magnetic lineament stops against NW to WNW trending magnetic lineaments.

In the kinematic analyses of deformation zones (focused on intersections of modelled structures in boreholes) the relative displacement along faults were studied in detail (Saintot et al. 2011). However, there is general lack of data on absolute displacement along fault planes.

The studies of the character and kinematics of deformation zones both along boreholes and at the surface confirmed SKBs “conceptual model for the formation and reactivation of deformation zones at Forsmark site that was used in the 3-D modelling work” (Saintot et al. 2011). The study indicated also that “it is not possible to reject fully the influence of reactivation during even younger Phanerozoic tectonic events” and “revealed some evidence for extensional regimes”. The study was not performed as a support to the actual modelling performance.

Synthesis of sets of brittle deformation

The deterministic structure model has successively been developed (cf. SKB R-05-18, SKB R-06-38, SKB R-07-45 and SKB R-08-64). A synthesis describing the characteristics of sets of zones is presented in SKB TR-08-05 (Figs. 2.12 and 2.13). In previous site descriptions all zones were described separately.

Uncertainties and gaps

The uncertainty in modelling increases with depth and therefore it is questionable to use the surface trace length as the only guiding parameter regarding the size of zones. Lineaments (1D information) and reflection seismic measurements (3D information) form together with borehole data (~0D, point data) the base for the identification and modelling of brittle deformation zones. This implies that the uncertainty in the modelling of moderately to vertical deformation zones was strongly dependent on the number of boreholes intersecting the zones as fracture orientation was not used to indicate the orientation of zones. Of all structures included in the local block model 85% outcrop (have a surface trace length); all steeply dipping structures (a modelling prerequisite – are correlated with a magnetic lineaments) outcrop while some of the gently inclined brittle deformation zones do not outcrop. There is also one moderately inclined brittle deformation zone that does not outcrop.

Missing is an analysis of the decision (SKB R-03-07) that the resolution of modelled objects should be the same throughout the modelling volume and that the local structure model should include only brittle deformation zones that are at least 1 km large (or at least have a surface trace, corresponding lineament, longer than 1km; SKB R-07-45 AP.16) would give a homogeneous representation of structures (cf. SKB TR-08-05 P132). If such structures exist they should have a high potential to be detected. Such an evaluation should consider the borehole configuration (location and orientation of boreholes), the map of magnetic lineaments and the orientation of sets of brittle deformation zones detected in the local area (cf. section 2.5). The analysis should also consider the possibility to have a smaller limit for the size of brittle deformation zones to be described deterministically.

2.7.1. Structure model – brittle deformation zones

The local structure model of the Forsmark site contains sixty brittle deformation zones that 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 vertical or steeply dipping brittle deformation zones trending NNW or E-W are also found. The number of sets of brittle deformation zones is thereby seven. However, the sets with only a few zones are not included in the synthesis regarding character of brittle deformation zones (TR-08-05 Figs. 5-29 and 5-30).

“In general, the zones in the target volume can be characterised as having a transition zone that contains a higher frequency of sealed and open fractures and more hydrothermal alteration than the host rock outside the zone, but also segments that resemble the unaffected host rock. Fault cores, recognised in 55% of all the zones studied in drill cores in the area, are predominantly composed of a sealed fracture network in combination with rock alteration and, locally, cohesive breccia or cataclasite. Fault gouge has not been recognised along the fracture zones” (TR-08-05 P402, cf. Fig. 2-11). Note that SKB fault cores (cf. Fig. 2-11) are not identical with the common use of the term (cf. Caine et al. 1996).

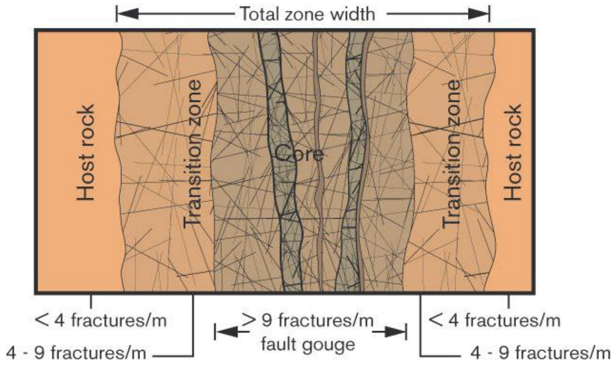


Figure 2-11: Brittle deformation zone; host rock – transition zone – core—transition zone—host rock. (FromSKB R-03-07 P10 and modified inSKB P-06-212 P13). Note that the transition zone is now denoted “damage zone” (TR-08-11 Figs. 1-7 and 1-8).

The uncertainty in the structure modelling generally decreases with decreasing distance between assumed borehole intersection and correlated magnetic lineament and decreases also with increasing number of boreholes intersecting the structure. Several of the local deformation zones are intersected by a single borehole. The model may also contain deformation zones well indicated by the detailed magnetic measurements without being intersected by any borehole. However, the structure model should also contain descriptions of the terminations of zones. Zones may terminate against other zones or have blind terminations. Blind terminations are relatively frequent in the south-eastern part of the local model area regarding ENE trending zones. The lack of displaced zones is conspicuous in the local deformation zone model.

Character of brittle deformation zones

The visualization of the deterministic three-dimensional model displaying brittle

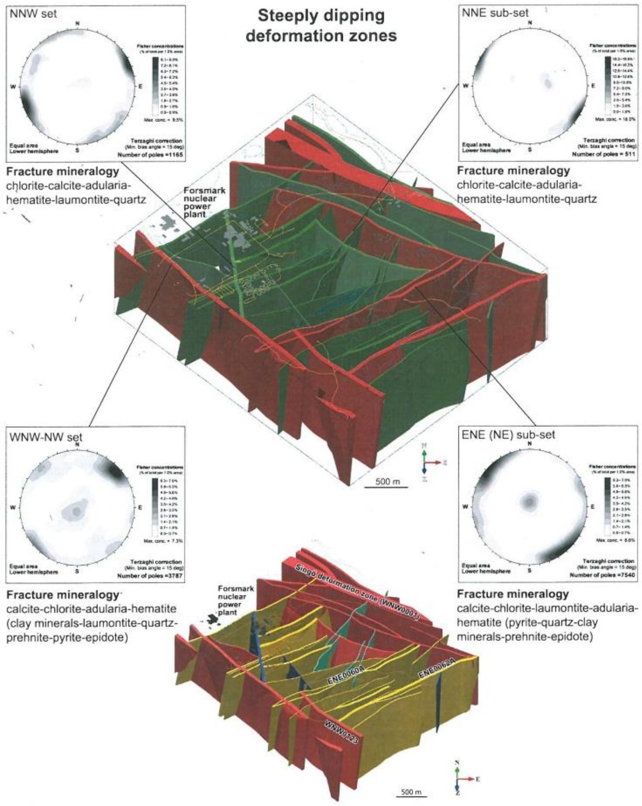


Figure 2-12: Vertical or steeply dipping deformation zones included in the three dimensional local model, stage 2.2. In the upper model figure (viewed to the north), zones marked in red have a trace length at the ground surface longer than 3,000 m and zones marked in green are between 1,000 and 3,000 m in trace length. The orientation of fractures inside the different sets or sub-sets of vertical or steeply dipping deformation zones, which are included in the local model (stage 2.2), are plotted as poles to planes in stereographic projections (equal-area, lower hemisphere) and contoured. A Terzaghi correction has been applied in these plots. The fracture mineralogy along each set or sub-set is also shown and the order of mineral presentation reflects the order of abundance (based on Figure 5-18 and Appendix 17 in /Stephens et al. 2007/). The zones in each orientation set or sub-set are distinguished in the lower model figure (viewed to the north). In this figure, red = WNW to NW set, yellow = ENE (NE) sub-set, green = NNE sub-set and blue = NNW set (TR-08-05 Fig. 5-29).

deformation zones is divided into two parts to avoid that structures cover each other. Thereby the description of the model is also divided in two parts: steeply dipping and gently dipping to sub-horizontal brittle deformation zones. Starting with the description of the steeply dipping zones.

Characteristics for the structure model describing steeply dipping local deformation zones (Fig. 2-12) are:

1. NW to WNW/subvertical oriented brittle deformation zones are located along the NE and SW sides of the candidate area. Such zones are not found in the central parts of rock domain RFM29 and RFM45.
2. The NS/sub-vertical brittle deformation zone in the north-western part of the model is located along the strongly deformed western limb of the large scale fold in the local area (cf. Figs. 2-8a and 2-9).
3. Extensive ENE zones transect the south-eastern part of the local area. These zones generally terminate, inside or outside the local area, against ductile-brittle, NW to WNW trending deformation zones. However, they may cross some NW to WNW trending brittle deformation zones before they stop.
4. Most of the ENE to NE trending deformation zones in the central and north-western part of the local area also terminate against zones located in rock strongly affected by ductile deformation (e.g. the western fold limb inside the local area of zones of ductile deformation along the north-eastern and south-western borders of the candidate area).
5. The size of the zones in rock domains RFM29 and RFM45 appear to be restricted by structures conforming to the ductile deformation zones at the border of the candidate area.
6. The dominant set of fractures inside deformation zones more or less conform to the orientation of the zones.
7. It is not clearly expressed whether the presented fractures in the different sets of zones (Fig. 2-12) containing all mapped fractures in the zones (the actual character of the zones comprising also fractures not related to zones; fracture overprinted by the zone and fracture overprinting the zone) or only fractures related to the zones (structural genetic description).
8. The relation between fracture sets in zones and fracture sets in the country rock is barely described (except from that they are generally parallel).
9. In the model (digital format, SKBs model database SIMON; three-dimensional model produced by SKBs CAD tool RVS /Rock Visualisations System) the relation between structures at surface (how they terminate against other) are not fully kept at depths (structures separate from each other or cross each other) and all parts of structures (e.g. the gently dipping brittle deformation zone ZFM02A) are not represented in the RVS model.

The configuration of steeply dipping brittle deformation zones may form connections across rock domains RFM29 and RFM45, i.e. may be able to transmit differential movement into the local area and also form conduits for circulating groundwater. This implies that potential of displacement along local brittle deformation zones may not be entirely related to their lengths.

Twenty-eight minor deformation zones (surface trace length shorter than 1 km; all located in the candidate area and 26 in the local model area) are found in the local model volume and none of them is gently inclined. Twelve MDZs are assumed to reach repository depth (c. – 500 m a.s.l.).

Where brittle deformation zones intersect each other the deformation of the rock may be locally affected, for example enhanced when zones are crossing each other. In the digital version of the model of brittle deformation zones the intersection of zones are displayed (cf. Fig. 2-13). However, it is not found that the zone to zone intersections are described whilst they are displayed in models (Fig. 2-13).

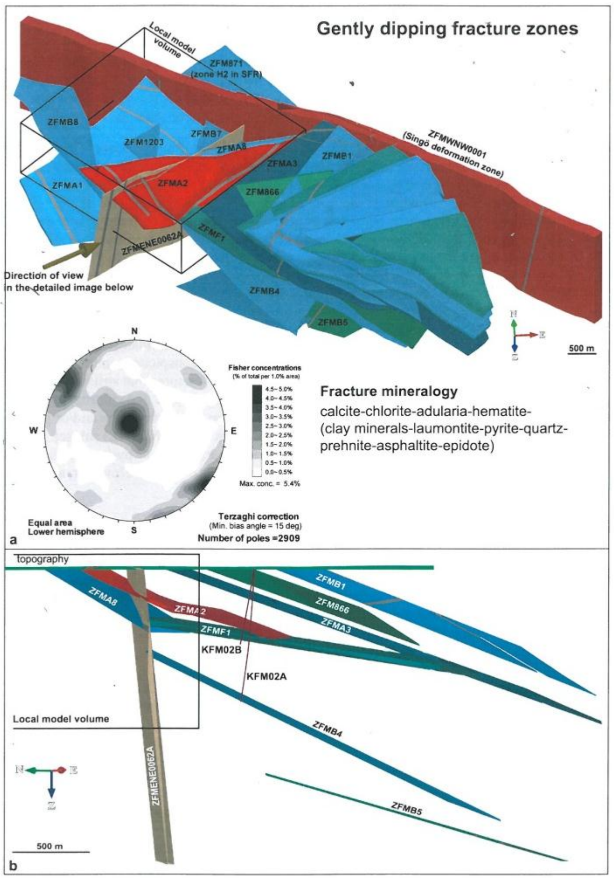


Figure 2-13: a) Gently dipping deformation zones on both sides of the Singö zone (WNW0001) extracted from the three dimensional regional model for deformation zones. The orientation of fractures inside the gently dipping deformation zones, which are included in the local model (stage 2.2), are plotted as poles to planes in a stereographic projection (equal-area, lower hemisphere) and contoured. In order to limit the bias that is related to the orientation of boreholes, a Terzaghi correction has been applied in this plot. The fracture mineralogy in the gently dipping zones is also shown and the order of mineral presentation reflects the order of abundance (based on Figure 5-18 and Appendix 17 in SKB R-07-45). 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 (SKB TR08-05 Fig. 5-30). The grey bands displayed on zones are the intersections where the gently inclined zones are intersected by other zones, mainly steeply dipping ones.

Comments on the models of gently inclined brittle deformation zones (Fig. 2-13):

1. All except one of the gently inclined zones are detected by reflection seismics.
2. Gently inclined zones are preferentially located in the southern part of the local area. Zone ZFMA2 is the best investigated zone – intersected by 8 cored boreholes and 6 percussion holes. Other gently inclined zones are

intersected by 0 to 3 boreholes; most common are 1 to 2 borehole intersections. The smallest detected gently inclined brittle deformation zone, having a trace length at surface of 881 m, is intersected by 3 boreholes. All of these boreholes are drilled from the same drill site and the borehole intersections are shallow, i.e. the distances between the boreholes are relatively small (ZFM 1203 detected in boreholes KFM07A,B,C; SKB R-07-45 AP. 15-191).

3. The geometrical relation between gently dipping zones and steeply dipping local deformation zones is uncertain (supported by reflection seimics?), cf. the relations displayed in Figure 2-13. The structural relation between gently inclined brittle deformation zones and regional brittle NW to WNW trending deformation is neither fully understood.

Minor gently dipping brittle deformation zones may either not occur at deeper levels in the central part of the local model area or they cannot be detected by the used seismic instruments.

Size of brittle deformation zones in the local model area

In the conceptual structure model of the Forsmark area (Fig. 2-10) regional ductile-brittle WNW and NW trending zones in the rim zones of the Forsmark tectonic lens restrict the extension of deformation zones inside the lens. The maximum possible horizontal dimension for the dominating sets of brittle deformations zones, trending ENE to NE, in the Forsmark local model volume is greatest in its easternmost part and decreases north-westwards and in the north-western parts of the local model volume. The ENE to NE trending zones could therefore not achieve straight horizontal lengths greater the 3 km, while the vertical extension of these zones or how they are linked to other zones are not known (3.5 km is considered to be the minimum length for a fault generation a M5 earthquake, SKB R-04-17 P51). However, if the demarcating structures are represented by the Singö and Eckarfjärden deformation zones then it is geometrically possible to have NE and ENE trending zones longer than 3.5 km and thereby may host strike-slip M5 earthquakes. The special interest for the existence of extensive structures (>3.5 km) is related to one of the criteria for the layout of a repository for nuclear waste stating that a “respect distance” of 100 m should be assigned to such zones, i.e. affects the available volume for the repository. “The respect distance is the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to anticipated seismic effects on canister integrity” (SKB R-04-17 P8).

Termination of brittle deformation zones

The geometry of modelled brittle zones in Forsmark is strongly influenced by the structure pattern outlined on the magnetic lineament map (SKB R-08-64 Fig.2-2 AND Table A-1). Included in the model are braiding patterns, minor branches enveloping lenses along the trace of associated larger structures, than structure offshoots like splays. Furthermore, the central part of the local model volume does not contain displaced structures even though such alternative interpretations could be possible.

In the local map displaying linked low magnetic lineaments in the Forsmark candidate area most lineaments terminate against other lineaments (cf. Fig. 2-7). The local minor lineaments have a higher proportion of blind terminations compared to more extensive lineaments. This interpretation could be related to the resolution in the magnetic base data. However, in the geological model a higher proportion of structures with blind terminations are displayed even though the structures can be linked to local minor lineaments. It is not fully clear how blind terminations of structures in the local model are treated in, e.g., the hydraulic and rock mechanical modelling and layout of the potential repository.

The conceptual structure model (Fig. 2-10) together with the detailed magnetic ground measurements (Figs. 2-6c and 2-7) are used to locate the termination of structures; generally lower order structures against higher order structures. However, the conceptual structure model does not consider situations where higher order structures appear to terminate against lower order structures (e.g. zone ZFMWNW 0123 stops against ZFMENE0060A and ZFMNW0123 points towards deposition tunnels in the planned repository area, cf. SKB TR-11-14 Fig. 5-6 and Figs 3-1 and 3-3).

Many NE and ENE trending deformation zones terminate outside the area covered by the high-resolution ground magnetic measurements and it can therefore be hard to judge how they terminate (based on the helicopter-borne magnetic measurements with lower resolution). Furthermore, data regarding termination of brittle deformation zone on outcrop scale is missing.

Fractures in brittle deformation zones

Fractures in the presented five sets of brittle deformation zones (Figs. 2-12 and 2-13) conform to the orientation of the zones, i.e. the zones and its fractures are to a great extent sub-parallel to parallel. However, it is not clear from the description if fractures strongly oblique to the extension of zones are related to the zones, predates the zones or overprint the zones. It is not fully clear what type of fractures (open, partly open or sealed or all fractures) is plotted. Anyway, the result is interesting and can be used to check the constructed model (there are modelled brittle deformation zones mainly composed of fractures strongly oblique to the orientation of the zone) and refine the applied approach for zone identification.

In the description of the structures there is a lack of illustration or analyses of geometrical patterns (outcrop scale) that may mimic the appearance of larger scale structures and the relation between sets of structures.

Structures at repository depth

In the local model all modelled structures (46) at repository depths (-400 to -600 m a.s.l) are brittle deformation zones (TR-08-05 Appendix 4) and one NNW trending zone, located along the western limb of the central fold (cf. Fig. 2-9), has a ductile precursor. Out of the 46 modelled zones five are gently inclined local zones and remaining 41 zones are brittle deformation zones that are steeply dipping (3 regional zones /length >3km/, 25 local zones /1≤lenght≤3km/ and 15 minor deformation zones /length <1km/).

All inferred structures are investigated by boreholes; 70% are investigated by single boreholes (one by a percussion borehole and others by cored boreholes) and 15% are investigated by three or more cored boreholes. About 35% of the structures are investigated by boreholes at repository depths and the same amount of deformation zones are investigated below repository depth. One fourth of these brittle deformation zones are also investigated at higher levels, i.e. 25% of all inferred structures in the local model volume that extend below repository depths are only intersected by single boreholes at depths greater than -500m a.s.l. On the other hand, three structures only investigated by single boreholes at shallow levels (above –

200m a.s.l.) are extended to repository depths. Furthermore, about 50% of all indicated intersections of structures in boreholes (ESHI DZ) at the potential repository level are not included in the deterministic model.

For slightly more than 50% of all modelled local structures reaching depths greater than - 400 m a.s.l. in the local model, the trace lengths are more than 2 times the distance from the surface to the interpreted borehole intersection/-s. Structures that are intersected by a single borehole, having the borehole intersection located deeper than – 400m a.s.l., and having surface traces shorter than the down-dip extensions constitute about 15% of all modelled structures. There is also a structure, having a trace length shorter than 400m and only found at a shallow level in a single borehole, which is extended to repository depth. This implies that there is no obvious correlation between trace lengths of structures and their vertical extension.

Complementary work, updating of models and uncertainties

The description of brittle deformation zones within the different versions of the structure models needs to be updated (e.g. information from late boreholes; for example, compare Table 4-7 in SKB R-08-64 and Appendix 4 inSKB TR-08-05).

The tables in SKBs database SICADA regarding SHI and ESHI (p_eshi-KFMXXY) should be updated and revised (the ESHI files contain columns with extensive descriptive text sections, reports. To facilitate compilation/use of data these text sections should be given as parameters/properties in separate columns.

Data on brittle deformation zones (e.g.SKB R-07-45 Appendices 16 and 17 andSKB TR-08-05 Appendix 4) should be stored in a data base (some information exist in tabular format in the SKB GIS model data base).

The number of zone to zone intersection within a volume will be maximum N*(N-1)/2 number of intersection linear possible channels. For example, the maximum number of zone to zone intersection of the 46 deformations zones intersecting the target volume at -400 to – 600m elevation (TR-08-05 Appendix 4) is 1058. The number of zone to zone intersection for modelled brittle deformation zones in the near-field of the potential repository is much less. Still, the zone to zone intersections are linear structures (or tubes) having a potential to form hydraulic conduits and therefore should be described.

Modelling of geological features, for example brittle deformation zones, contain several steps with related uncertainties starting from:

- Data acquisition with related sampling biases.
- Applied sorting and classification of data.
- Applied conceptual assumption regarding identification of the character of a brittle deformation zone (representing an anomaly).
- Identify location of brittle zones within sets of acquired data.
- Performance of three-dimensional modelling of brittle deformation zones (including premises for interpolation and extrapolation of interpreted observation).

The progressive process of interpretation of data and geological modelling is a learning process and the outcome is that, parallel to the deterministic modelling of zones; a conceptual structure model is developed. This model summarizes the genetic framework for the occurrence of brittle deformation zones.

However, the conceptual structure model should only be used as a guideline and should be interactively updated as new information about structural relationships are gained, e.g. regional structures may stop against local structures without being faulted (cf. zones ZFMWNW0123 and ZFMENE0060A, SKB TR-08-05 Fig. 5-42). Otherwise, errors in the conceptual structure model may introduce systematic errors in, for instance the three-dimensional deterministic model.

2.7.2. Fracture minerals

The fracture minerals in the Forsmark area indicate a decline in temperature in the rock associated with elevation synchronous with erosion. Timing for the onset of brittle deformation by studying the decrease of the temperature in the bedrock reflected by the fracture minerals has been performed. The brittle regime mainly starts below c. 400°C. Four generations of fracture minerals (G1 to G4) are identified (R-08-102) in the Forsmark area.

“The abundance of different fracture minerals in all fractures (open and sealed) in Forsmark shows a large variation and the relative abundance can be summarised as follows: calcite and chlorite/corrensite >> laumontite > quartz, adularia, albite, clay minerals > prehnite, epidote > hematite and pyrite (R-08-102 P19).

The generation of fracture minerals (R-08-102 P45-46) are:

- Generation 1 (T> 200°C, 1.8 to 1.1 Ga old, in WNW to NW/steeply dipping and gently inclined to sub-horizontal fractures): epidote, quartz and chlorite, brittle-ductile cataclasites are sealed with these minerals and associated with red staining/oxidation of the wall rock.
- Generation 2 (T ~ 150 to 180°C, about 1.1. to 1.0 Ga old, in steeply dipping fracture with trending ENE, NNE, and NNW): dominated by adularia, albite, prehnite, laumontite, calcite, chlorite and hematite, and associated with red staining/oxidation of the wall rock.
- Generation 3 (T ~ 150 to 190°C, Palaeozoic, no specific fracture orientations given): calcite, quartz, pyrite, corrensite, asphaltite and open fractures with no fill.
- Generation 4 (< 50°, precipitation of minerals has most likely occurred during a long period of time after the Palaeozoic, prominently in gently inclined to sub-horizontal fractures and occur also in different sets of steeply dipping fractures): chlorite/clay and calcite occur predominantly in hydraulically conductive fractures and brittle deformation zones, including also open fractures without any visible fracture minerals.

It is also inferred that most of the hydraulically conductive fractures are ancient structures, though some sheet joints occurring at shallow levels could be Quaternary in age.

Two period/types of dissolutions/erosion of minerals are recognized:
1. The first period predates the precipitation of G2 minerals and is associated with the formation of vuggy granites within the actual bedrock (dissolution of quartz in granitoids, cf. section 2.6).
2. The second type concerns dissolution of G2 fracture minerals (effecting laumontite and calcite) during a period predating the precipitation of G3 fracture minerals. The cause and timing of this event is unknown.

Fractures without any visible fracture fill, notable frequent, are considered to belong to the G4 generation of fractures.

The occurrence of the four generations of fracture mineral in the context of the structure evolution has also been described (cf. Fig. 2-10), i.e. formation and reactivation of deformation zones (SKB R-06-38 Figs. 3-4 to 3-6) and the accumulated assemblages of fracture minerals associated with different sets of zones (SKB TR-08-05 Fig. 5-36; Fig. 2-12 in this review). In the latter case 6 to 11 different fracture minerals are associated with the different sets of zones.

However, the core logging system (Boremap; SKB MD 2005) has only four positions for notation of fracture minerals (cf. SICADA files: p_fract_crush-KFMXXY.xls and p_fract_core-KFMXXY.xls). If more fracture minerals are identified it could be noted in the column for comments, but data in that table are not simple to find during an automatic extraction of data from SICADA.

The notation of hematite as a fracture mineral in the synthesis of fracture set characteristics (Fig. 2-12) does presumably refer to what is noted as oxidized walls in the database SICADA and in the description of generations of fracture minerals. Hematite as a fracture mineral is relatively uncommon.

Future reactivation of structures

Reactivation of deformation zones and fractures are treated in sections above presenting the conceptual structure model of the area and the fracture minerals. However, regarding prediction of future reactivation and consequent change in character of fractures and brittle deformation zones it is stated (TR-08-05) that “it is not the task of the site description to present any predictions of the future evolution of site conditions. This is completed within safety assessment based on the understanding of the current conditions and of the past evolution as compiled in the site description. It is also not the task of the site descriptive modelling to evaluate the impact on current site conditions of the excavation or the operation of a repository at the site. This is carried out within the framework of repository engineering and as part of the environmental impact assessment, but again based on input from the site description”(cf. SKB TR-11-01 Table 7-6 P235).

Uncertainties and complementary studies

There are some uncertainties regarding the identification of fracture mineral (cf.SKB R-08-102) and they are:

- Prehnite is easily mistaken for epidote and vice versa, both noted to occur about 2 to 3 % of all fractures – prehnite is slightly more common of the two.
- Identification of minerals, e.g. hematite stained adularia was in early boreholes mapped as hematite - adularia is therefore not recognizes in the following boreholes in the local model volume: KFM01A, 1B, 4A, and 5A.
- Corrensite (mix-layered mineral: clay and chlorite) is not recorded in the core log, while described in reports.
- Clay minerals are not fully recorded; noted occurrence of clay mineral can be regarded as an absolute minimum.
- Oxidized wall (red staining) is presented in the core log as a fracture mineral.

The association of fracture minerals in different sets of deformation zones (Figs. 2-10, and 2-12) together with the typical fracture minerals in the four fracture generations (G1 to G4) can be used to study how deformation/reactivation of brittle deformation zones is steered and the potential for reactivation of zones. It could be further elaborated how and where fracturing has taken place during reactivation of deformation zones, reopening of existing fractures or formation of new fractures along existing zones or both. This may also support the characterization of brittle structures and thereby also the location of thin extensive brittle structures, so called large fractures (affect the layout of a repository, structures that shall not intersect a deposition hole, cf. part 3 of this review).

It could also be tested if there is some spatial relation of different sets of fracture minerals along local zones terminating against or crossing WNW to NW brittle deformation zones located at the border of the site, i.e. in the rock strongly affected by plastic deformations.

Of special interest is the distribution of open fractures without visible fracture minerals at repository depth within the near-field of the potential repository area and in the vicinity of regional WNW to NW trending brittle deformation zones. The latter may indicate late distortion along the regional zones (cf. the concept respect distance, part 3 of this report).

2.7.3. Structure model – fracture domains

Fractures outside deterministic modelled brittle deformation zones (i.e. fractures and minor deformation zones, SKB R-07-46 P3) are characterized and described in the Site Descriptive Model by stochastic modelling (geological DFN; Discrete Fracture Network). The preferential aim is to model brittle structures (fractures and also minor deformation zones, the latter are < 1km or having a radius smaller than 564m) is to describe such structures in the near-field of the repository area. The aim of the DFN models is “to facilitate hydrologic and geomechanical modelling in support of safety assessments, and to provide engineering data related to fracturing for repository design and construction” SKB R-07-46 P8).

Fracture domains (FFM) inside the local model volume are:

- The parts of rock domains that are not affected by deformation zones (SKB R-07-45 P5).
- Fracture domains and deterministically modelled deformation zones are mutually exclusive volumes, whereas rock domains contain both fracture domains and deterministically modelled deformation zones (TR-08-05 P404).

However, these two statements are not fully congruent as it not entirely clear what is the meaning of the concept “not affected by deformation zones” (cf. SKB R-07-15 Appendix 4).

In borehole sections where the rock is assigned to be “affected by DZ, the overall fracture frequency is enhanced relative to the rock mass as a whole, but the sections “affected by deformation zone” are not considered to be physically part of the deformation zone volume (SKB R-07-45 P194). Noted are 21 sections with a length of 4 to 151m along cored boreholes in the candidate area and a total borehole length of 915m, i.e. 7% investigated boreholes (cf. SKB R-07-15 Appendix 4). Adding the concept “affected by deformation zone” to the nomenclature of deformed rock implies that the term “brittle deformation zone” becomes vague in character. Sections in the rock that is affected by deformation zones are actually a part of the zones. For example, Kim et al. (2004) incorporate such deformation in the fault damage zone. Using a statistical approach to outline the damage zone (cf. SKB R-03-07 Fig. 2-1 and SKB TR-08-11 Figs. 1-7 and 1-8) or genetic interpretation during mapping exposed deformation zones (Kim et al. 2004) may give different results.

The relative proportion of potential intersections of brittle deformation zones in boreholes (SICADA, DZ in p_eshi-KFXXY.xls files) that are engaged to locate brittle deformation zones above and below the level – 300m a.s.l., are similar, 24 % (SICADA data).

Note that rock domains are mainly assigned by similarity in rock types and also by the degree and style of ductile deformation in the rock. However, only in the central parts of the local model volume rock domains, i.e. rock domains RFM29 and RFM45, have been divided into sub-volumes regarding fracture domains (FFMXX). The reason for this is the enhanced density of gently inclined to sub-horizontal fractures dipping mainly SE in the shallow part of the bedrock.

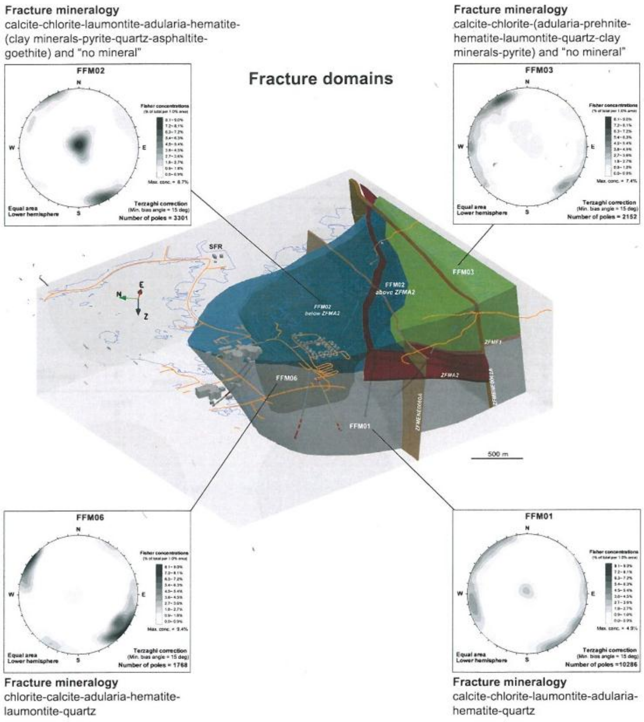


Figure 2-14: Three-dimensional model for fracture domains and fracture orientations within the fracture domains (TR-08-05 Fig. 3-34).

The potential repository volume, located below the shallow volume with enhanced density of gently inclined fractures, is located in two fracture domains:

- Fracture domain FFM01 (deeper part of rock domain RFM29).
- Fracture domain FFM06 (deeper part of rock domain RFM45).

None of these rock domains extend to the surface and that has implications on the ability to characterize fracture sets in these domains, especially the length distribution of fractures.

The gently inclined to sub-horizontal fractures in the upper part of rock domains RFM29 and RFM45 are inhomogeneously distributed and fractures are inferred to represent sheet joints and tectonic fractures. The volume outlined by such fractures increases in depth south-eastwards and the relation between these fractures and the gently inclined brittle deformations zones, most common in this part of the candidate area, need to be further described. It is not obvious whether or not the gently dipping fractures are frequent in rock domains adjacent to rock domains RFM29 and 45.

The shallow wedge-shaped volume with enhanced density of gently inclined and sub-horizontal fractures in rock domain RFM29 and RFM45 are divided into two rock domains:

- Fracture domain FFM02, the shallow parts of rock domains RFM29 and 45.
- Fracture domain FFM03 located southeast of fracture domain FFM02 and coincides with the upper part of rock domain RFM45.

The characters of fracture domains FFM01, FFM02, FFM03 and FFM06 are addressed in DFN models (R-07-46, while adjacent fracture domains (FFM 12, 44 and 32) are not DFN modelled due to scarcity of data.

This implies that in the D2 layout of the planned repository some main tunnels and the main part of the transport tunnels will be located at the borders or outside the stochastically modelled rock volumes (SKB R-08-113 Fig. 3-20). How far out from the deposition holes does the near-field of the repository extend?

In the deterministic modelling it is inferred that structures outcropping in the area, indicated by the high-resolution ground magnetic measurements, may be correlated with structures found in boreholes, i.e. the processes causing the fracturing in fracture domains FFM02 and 03 have not displaced the location of brittle deformation zones in the local model volume. What is not considered in the SKB modelling of zones is that moderately to steeply inclined zones found in boreholes at deeper levels may stop at or below the gently dipping to sub-horizontal deformation zones.

Rock domain RFM29 and thereby also the related fracture domain FFM01 are the largest domains in the area. If, for instance FFM01 is modelled as a single unit it should have a degree of the homogeneity which is related to borehole data. However, if the structure pattern at depth is reflected by the structure pattern displayed in the high-resolution ground magnetic measurements it is apparent that the fracture domain FFM01 may have a low degree of homogeneity. Especially if the reverse of the statement “the orientation of fractures in the domains is similar to that in the adjacent fracture zones” (TR-08-05) holds. That is, that fractures in the vicinity of brittle deformation zones is similar to the orientation of the zones.

An alternative subdivision of the bedrock hosting the potential repository, which appears not be structural uniform, can be performed to support the layout of the repository and be based on structural patterns:

1. Steeply dipping ENE trending zones forming braided networks of zones in the south-eastern part of the area between zones ZFM061 and ZFM062 (ENE zones are relatively evenly distributed in the central part of the model area).
2. The high density of NE trending structures in the north-eastern part of the target volume, mainly minor deformation zones (MDZ).
3. The zone of shearing along the western boundary of the lens and associated with the shearing out of the western limb of the central fold (Fig. 2-9). This structure may interfere with the two previously described structure patterns (item 1-2).

The three sets deformation zones may outline at least four fracture sub-domains in the near-field of the repository. Note that this sub-division of the rock into fracture domains eliminate fracture domain FFM06 as the location of NE trending MDZs in that part of the bedrock may not be controlled by rock domain RFM45. However, the number of boreholes in the area may not be sufficient to promote a DFN modelling of four subareas. However, the discussion indicates structural inhomogeneity in the near-field of the repository volume.

“Deformation zones and minor deformation zones identified in boreholes are complete and correct” is one of the DFN modelling assumptions (R-07-45 P192). As an assumption it stands alone, but as a statement it is uncertain as a relative high percent of all detected potential zone intersections in boreholes are not engaged in the structure model (cf. text above).

However, some minor deformation zones have been treated twice; both in the DFN and in the deterministic modelling work (SKB R-08-113 P16).

Uncertainties

The inhomogeneity in spatial distribution of different sets of structures in the rock volumes occupied by rock domains RFM 29 and RFM45 described above may represent properties (specifically, fracture intensity and fracture location) that “will require either additional subdivision or conditional simulation” (SKB R-07-45 P193) of fracture domains. However, so far “the geological DFN is parameterised only for domains in which sufficient three-dimensional information was available: FFM01, FFM02, FFM03, and FFM06” (SKB TR-10-52 P241). The question is then if an additional subdivision of fracture domains can be made based on available data. Detailed information about the characteristics of fractures will be obtained by fracture mapping of pilot boreholes, tunnels and shafts within the repository area. However, additional boreholes may be needed if the suitability of the rock volume planned to host the repository should be evaluated in more detail before the excavation at repository level starts.

A sensitivity test, a test of representatively of performed modelling (cf. section 2.7.1), considering the brittle deformation zone model, and thereby also the fracture domain model, would be to use the distribution of length of brittle deformation zones (magnetic lineaments associated with deformation zones) to determine the cut- off for structures that should be considered in the deterministic and stochastic models, respectively. A simpler version of the test could be to use fixed values for the cut-off, for example 0.75 and 1.25 km. The question can also be expressed weather or not the cut-off for local deformation zones mask essential deformation zones. However, these zones will, if not considered in the deterministic model, be considered in the stochastic DFN models.

The volume outlined by horizontal to gently inclined fractures increases with depth south-eastwards and the relation between these fractures and the gently inclined brittle deformations zones, most common in this part of the candidate area, need to be further elaborated.

2.8. Review, economic geology – natural resources

The Forsmark area is located within an “ore province” (SGU Ba 29), or what is now denoted a “mineral resource province” (Stephens et al. 2009), that is generally called Bergslagen. “The Bergslagen region forms one of Sweden’s important provinces for the exploitation of mineral deposits. During the 18th and 19th centuries, iron ore from over 3 000 workings in this area provided much of Sweden´s wealth, and the region is historically the most prosperous mining district in the country” (Stephens et al. 2009).

An ore province is a well-defined area containing ore deposits of a particular kind while a metallogenic province need not contain economic mineral deposits although it should contain particular mineral assemblages, i.e. one or more specific types of mineralization. The closest mine relative the Forsmark area is the Dannemora mine (iron ore, reopened early 2012) located less than 30 km southwest of Forsmark. In the regional Forsmark area there are some minor mineralizations and some of them claimed exploration permits (Figs. 2-15 and 2-16).

However, the selected target area for a potential repository is located within plutonic rocks, mainly granites and granodiorites (rock domains RFM29 and RFM45, Fig. 2-9), lacking minerals of economic interest. Potential for iron oxide mineralisation and possibly base metals (SKB R-04-18) are recognised both to the north and south of the target area (SKB R-08-128 Fig. 4-1), and associated mainly to felsic to intermediate meta-volcanic rocks outside. Mineralizations north of the target area are not known since the bedrock is covered by the sea.

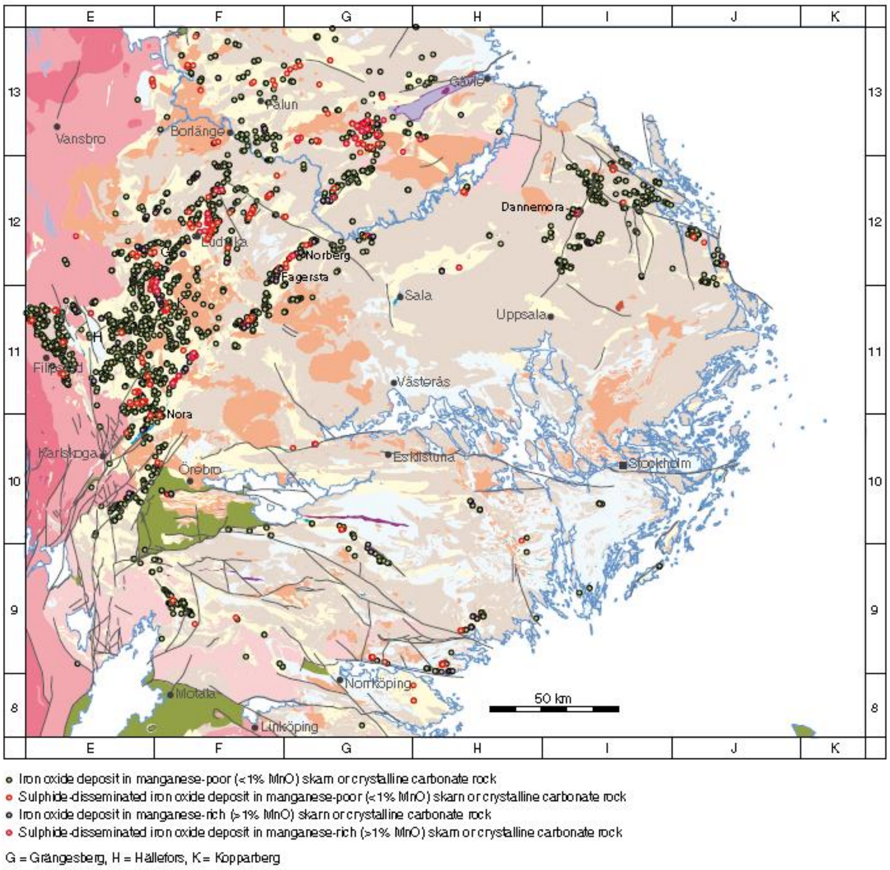


Figure 2-15: "Distribution of iron oxide deposits hosted by manganese-poor or manganese-rich skarn and crystalline carbonate rock in the Bergslagen region. Similar deposits with conspicuous sulphide dissemination are also shown. The deposits are presented on a simplified bedrock geological map of the region. The location of place names referred to in the sections that address the iron oxide deposits hosted by manganese-poor or manganese-rich skarn and crystalline carbonate rock is also shown" (Stephens et al. 2009). The Dannemora mine reopened in 2012.

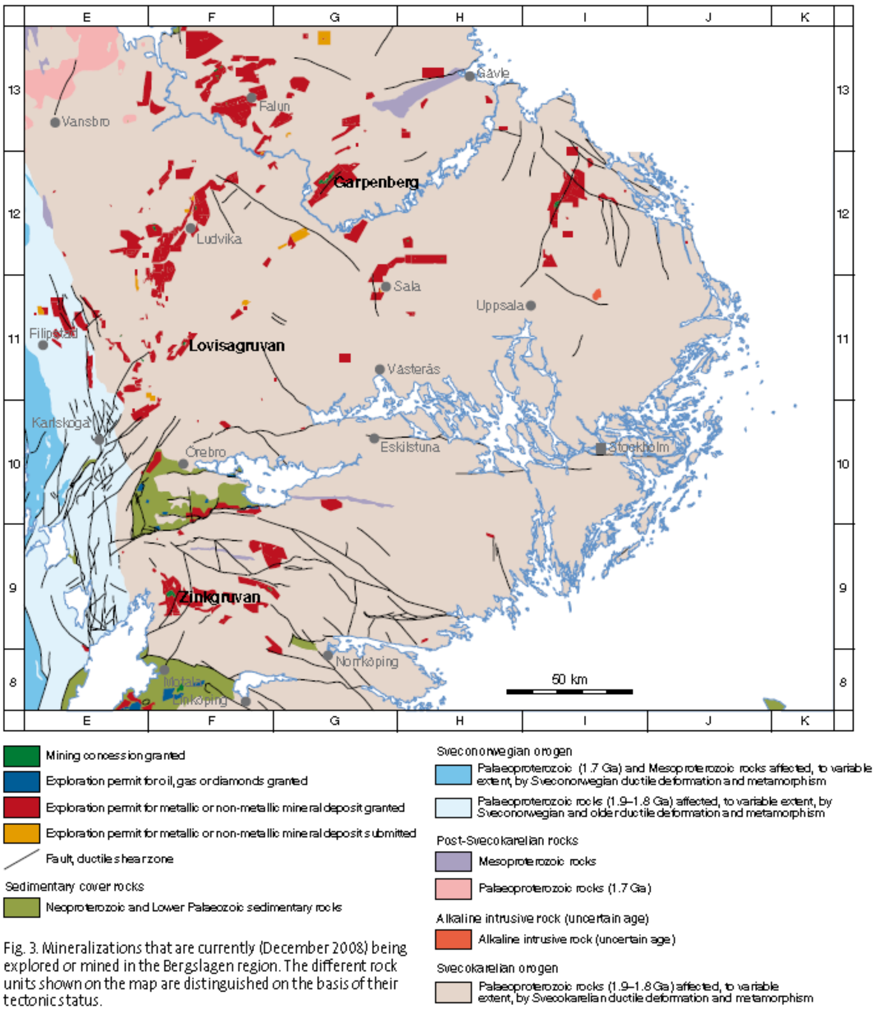


Fig. 3. Mineralizations that are currently (December 2008) being explored or mined in the Bergslagen region. The different rock units shown on the map are distinguished on the basis of their tectonic status.

Figure 2-16: Exploration permits, natural resources in the Bergslagen region (Stephens et al. 2009).

Complementary investigation

Despite the lack of mineral of economic interest in the Forsmark granitoids the radioactive waste in a deep geological disposal will form a physical anomaly. How such an anomaly will differ from natural mineralizations in the Bergslagen mineral resource province is not clear. Therefore a geophysical simulation is needed to evaluate the risk of future human intrusion related to mineral prospecting.

3. Geological concepts to support the layout criterion and strategies

A robust performance in the geological classification of rock structures is basic and important to ensure a uniform evaluation of the long-term safety throughout the construction of a deep geological repository for spent nuclear fuel located in the Precambrian crystalline rock at depths of about -500 m. a.s.l.

Of primary importance is to have a well-established nomenclature, which facilitates communication and also gives instructive clarifications and support to a uniform adoption of the terminology, i.e. how to identify and classify objects.

The discipline of terminology (http://www.websters-online-dictionary.org/definitions/terminology 2012-05-28) is based on its own theoretical principles and consists primarily of the following aspects:

- Analysing the concepts and concept structures used in a field or domain of activity.
- Identifying the terms assigned to the concepts in the case of bilingual or multilingual terminology, establishing correspondences between terms in the various languages.
- Compiling the terminology, on paper or in databases.
- Managing terminology databases.
- Creating new terms, when required.

In this section the terminology used SKB to describe structural features in the bedrock is treated and how the features affect the layout of a deep geologic repository. However, the precise definition of the terms is up to SKB to present as they will be the users of the terminology. Furthermore, SKB has to document how the terminology shall be applied and SKB has to control uniform time-independent usage of the terms. If there is a need to change the nomenclature the change should be manifested and distributed throughout the organisation.

3.1. Terminology

Applied geological terminology related to geological features that may affect the long-term safety should be strict. Without going into details the terms are:

- **Brittle deformation zones** (c.f. text below; now three characters of deformed rock are associated: core zone, damage zone /previously called transition zone/ and rock “affected by deformation zones”) – to locate borders of zones (external and internal) and lengths of zones (as single structures or as connected to other sub-parallel zones).
- **Large fractures** (SKB R-11-14 P17; cf. discriminating fractures, SKB R-06-54 P5 and Figs. 5-1 and 5-2,and SKB TR-10-21 Fig. 3-1 to 3.4) – length/size of the structure (as single plane, or as connected trace of fractures or part of a network of fractures?).
- **Rock type** (subdivision of the bedrock into rock types. The rock domain concept is not applicable on the detailed layout of canister positions due to different thermal conductivity in some subordinate rock types, amphibolites and fine- to medium-grained metagranitoids; SKB TR-11-01 P112).

The term for describing deformation zones formed within a brittle deformation regime was appointed to be *brittle deformation zones* (SKB R-03-07 Fig. 2-1). However, the term was briefly presented in a principle sketch without any tools to measure, for example, the density of fracture within the different parts of the brittle deformation zone or how to define internal and external borders of a brittle deformation zone (cf. Fig. 2-11). The latter is pointed out as brittle deformation zones in many cases are inhomogeneous structures. With time the term *fracture zone* was reintroduced and "is used to denote a brittle deformation zone without any specification whether there has or has not been a shear sense of movement along the zone" (SKB P-06-212 P13). The term fracture zone is for example frequently used in one SR-site report (SKB TR-11-01) while omitted in another (SKB TR-10-48).

A brittle deformation zone may contain a less deformed "transition zone" and the "core zone". It is noted that in 2010 (SKB TR-08-11 Figs. 1-5, 1-7 and 1-8) the term "transition zone" was changed to "damage zone" which is commonly used in the international nomenclature. The term damage zone was not described in more detail than that it is located outside the core of a fracture zone, i.e. constitute a part of the brittle deformation zone. The term 'brittle deformation zone' was not used in the report (SKB TR-08-11), while the used term in the report is the more general term "deformation zone".

The term "affected by deformation zone" appears relatively late in the site description (SKB R-07-45). "The geological work during stage 2.2 has involved the development of deterministic models for rock domains (RFM) and deformation zones (ZFM), the identification and deterministic modelling of fracture domains (FFM) inside the candidate volume, i.e. the parts of rock domains that *are not affected by deformation zones* (italic made by the reviewer), and the development of statistical models for fractures and minor deformation zones" (SKBR-07-45 P5). However, as described in a previous section of this review (2.7.3) the borehole sections where the rock is assigned to be "affected by DZ, the overall fracture frequency is enhanced relative to the rock mass as a whole, but the sections "affected by deformation zone" are not considered to be physically part of the deformation zone volume (SKB R-07-45 P194). Parts of the fracture domains (FFMXX) are noted to be affected by deformation zones (SKB R-07-45; mainly fracture domain FFM01 but also fracture domains FFM04 and 06). Rock noted as affected by deformation zones are generally located in areas in boreholes where the separation of indicated brittle deformation zones (DZ in ESHI) are small and locally also found bordering a single indication of an intersection of a brittle deformation zone (large distance along the borehole to next brittle deformation zone). As also noted previously (2.7.3), the usage of the concept "affected by deformation zones" is confusing and it affects the stringency in the terminology denoting brittle deformation zones. If the rock is affected by a deformation zone, that part of the rock should be included in the deformation zone. A reason for the usage of the term "affected by deformation zones" may go back to the definition of the term brittle deformation zone (>4 fracture/m for the transition zone, a static definition) and the lack of principles/tools how to determine the location of the border of a brittle deformation zone.

The concept ductile deformation zone (cf. previous items) is of special interest to locate the borders of the "Forsmark lens" which is enveloped by rock strongly affected by ductile deformation and could be closely located to the near-field of the repository volume. However, in the central part ductile deformations zones are scarcely found.

Large fractures may constitute single fracture planes of thin brittle deformation zones (if large fracture also consider ductile shear zones is not fully obvious) along which shear that could harm a canister can take place. Such fractures are not allowed to intersect a canister position (cf. SKB TR-10-21). Determination of the location of large fractures are to be performed in deposition tunnel and deposition hole scale (R-11-14 Chapter 4).

Comments

The SKB definition of "brittle deformation zone" is more or less restricted to a figure (Fig. 2-11; SKB R-03-07 Fig. 2-1) and need to be complimented by text together with a presentation how the definition should be applied. For example, present principles for locating external and internal boundaries of brittle deformation zones.

3.2. Layout and the character of the bedrock

To relate the SKB applied nomenclature of brittle deformation zones to the SR-Site context and the D2 layout of a geological repository at Forsmark (SKB R-08-113) some remarks are made here:

1. For all brittle deformation zones with surface trace lengths larger than 3 km (cf. Figs. 2-12 and 3.-1), regional brittle deformation zones, the following conditions hold (SKB TR-08-11):
    - All brittle deformation zones have respect distances, i.e. deposition holes are not permitted within 100m from the outer boundary of the deformation zone (i.e. 100m is the respect distance counted from the outer part of the damage zone).
    - Fault planes (fractures) located within the damage zone of brittle deformation zones count as potential slip planes.

    Transport tunnels are allowed to cross regional brittle deformation zones and go along regional brittle deformation zones, inside their respect distance (cf. SKB R-8-113 Figs. 2-5 and 3-23). In the layout of the potential repository at Forsmark one regional deformation zone (ZFMENE60A, Figs. 3.1 to 3.3) will split up the repository volume in two parts; the northwest part containing the main part of the repository and the ramp and central area and the part south-eastern of zone ZFMENE060A. Zone ZFMENE60A will be passed two times by the transports tunnel circumscribing the repository. It may also be cut by a pair of tunnels forming short-cuts (if constructed) between central parts of the south-eastern and central main tunnel (Fig. 3-3b). Detailed tunnel mapping of the location and character of zone ZFMENE60A will determine the location of the position of the respect distance to the zone which is essential for the layout of deposition tunnels (Fig. 3-3).

2. Displacement along regional deformation zone may have effect on fractures and deformation zones located outside their respect distance, i.e. inside the repository volume. The following parameters are to be adhered (SKB TR-08-11 P21):
    - The canister damage threshold for shear along a plane (e.g. a fracture intersecting the deposition hole) is 0.05m (previously 0.1 m).

- The critical fracture radius (the minimum size of the fractures that determine whether intersected canister positions should be accepted or rejected, cf. large fracture /SKB R-11-14 P17/) for fractures that may slip 0.05m will vary with distance from the slip plane along the earthquake fault (cf. SKB TR-08-11 Fig. 1-8).
- The critical radius of "suitably-oriented" fractures, located outside the respect distance of brittle deformation zones, is about 150m during temperate conditions (SKB TR-08-11 P167).

Fractures that have a radius greater than the critical radius, i.e. not accepted to intersect a canister position, are local brittle deformation zones and large fractures and these are treated below.

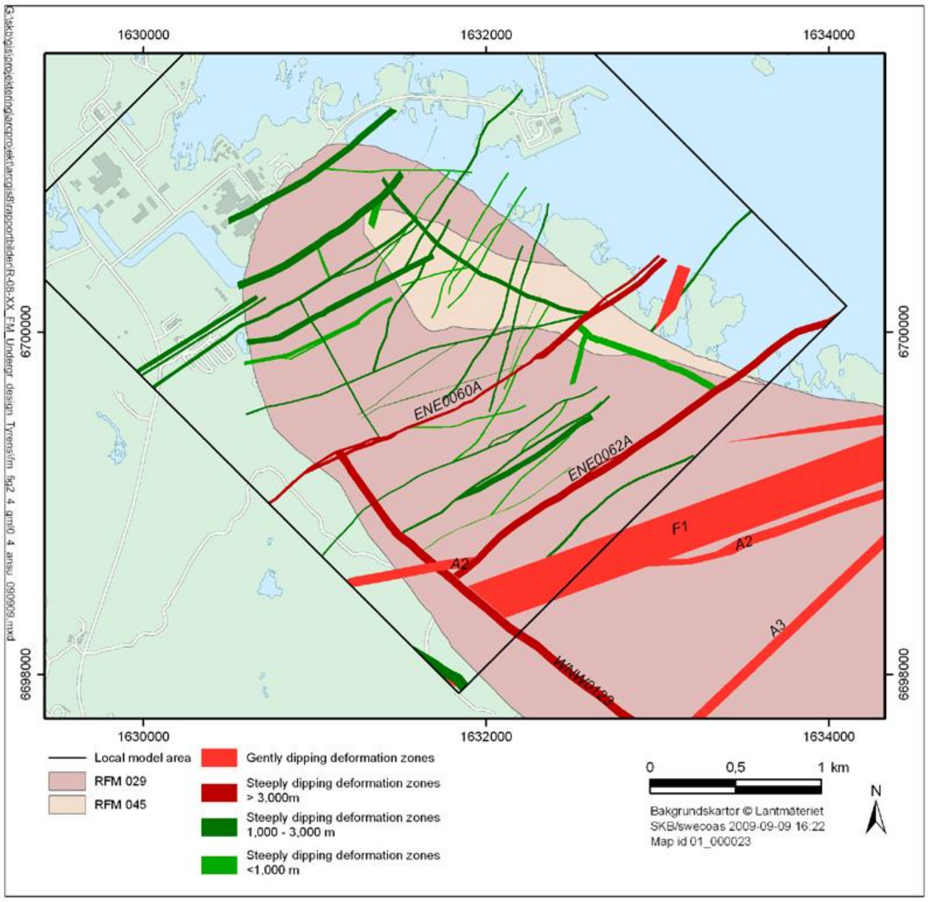


Figure 3-1: *Deformation zones at the depth of 470m (RHB 70) (from SKB R-08-113 Fig.2-4).*

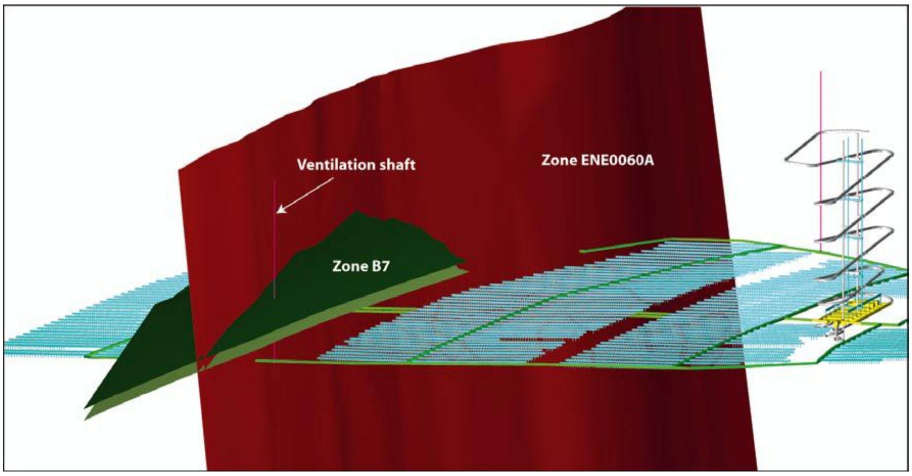
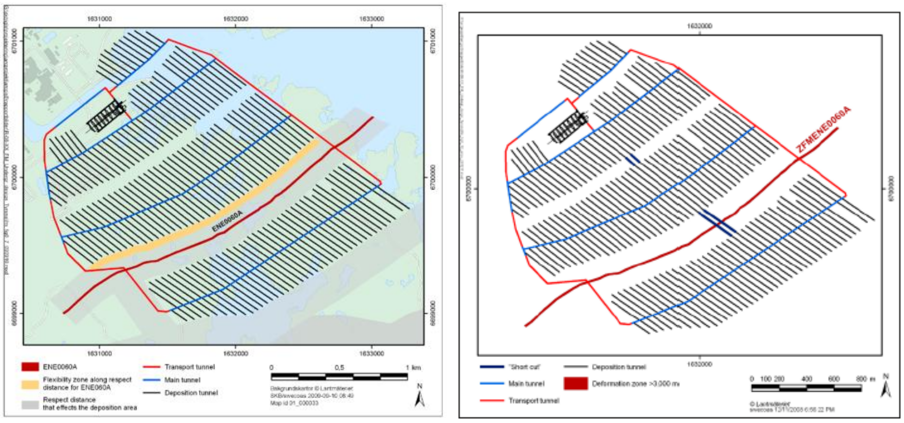


Figure 3-2: Illustration showing the intersection between eastern ventilation shaft (SA01) and B7 at a depth of 310m (RHB 70). Underground facilities at -470 m (RHB 70). View from northeast (SKB R-08-113 Fig. 3-19). Note the transport tunnels parallel to the deposition tunnels and crossing the central part of the repository area (cf. Fig. 3-3b).



a. b.

Figure 3-3: a. Flexibility zone of deposition tunnels due to uncertainty of position of zone ENE0060A. Section at 470 m depth (RHB 70) (SKB R-08-113 Fig. 3-20), and b. Position of temporary transport tunnels (“short cut”) at 470 m depth (R-08-116 Fig.4-9).

3. Local brittle deformation zones, 1 to 3 km in size, may intersect deposition tunnels but not deposition holes (cf. SKB R-08-113) and are allowed to coincide, go along, main tunnels (SKB R-08-113 Fig. 3-23) and cross transport tunnels.

   As the local deformation zones can be located close to deposition holes it is important to have clear criteria and methodology to determine the width of zones and to have principles to characterize and describe the zones (basis for three-dimensional modelling, generalization and synthesis – a part of a learning process to recognize zones and the transparency in location and accepting deposition holes). Local brittle deformation zones are displayed in the local model volume together with regional brittle deformation zones. The location of local and regional brittle deformation zones will be interactively updated during the construction of the repository and the scale of modelling will mainly vary from tunnel scale (including deposition holes) via deposition area scale to local scale (SKB R-11-14 P26).

Critical for the layout is extension of sub-horizontal to gently dipping brittle deformation at repository level. Such zones have not been indicated.

4. Minor deformation zones (MDZ) are zones inside the local model volume that are shorter than 1 km. In the layout these structures are treated as local deformation zones (SKB R-08-113 Fig. 2-4; cf. previous section), i.e. they are not allowed to intersect deposition holes.

   "In SR-Site it is assumed that fractures, or rather minor deformation zones, with a radius larger than 250m and with efficient transmissivity larger than 10^{-6} m^2/s, will be detected by the detailed investigations so that potential deposition positions intersecting such fractures would be avoided. Such fractures would have the potential of an inflow in the order of 25 L/min. Furthermore, they would also be easy to recognize by local geophysics and other tools applied within the detailed investigation programme. The size limit of 250m is the same as that applied when assessing critical deposition positions regarding shear movements" (SKB TR-11-01 P158). This statement has to be validated further during an early state of the construction of the repository (cf. SKB R-11-14). However, if it is correct then the critical "large fractures" to be identified are those that are sealed, tight or have low transmissivity. The method to detect, describe and model minor deformation zones, as well as other types of brittle deformation zones, will be re-examined during an early stage of the underground construction work (R-11-14) and the minor deformation zones will be mapped in detailed during construction of the repository volume and shafts.

   Occurrence of minor gently dipping to sub-horizontal brittle deformation zones at repository level will affect the utilization of the planned repository volume. Existence of such zones should be investigated during the construction of the ramp (access tunnel) and the central area. Though, it should be considered to construct all transport and main tunnels before starting the construction of deposition tunnels. The main argument is that early construction of transport and main tunnels will support an evaluation of the overall suitability of the site before starting the production stage, i.e. depositing canisters.

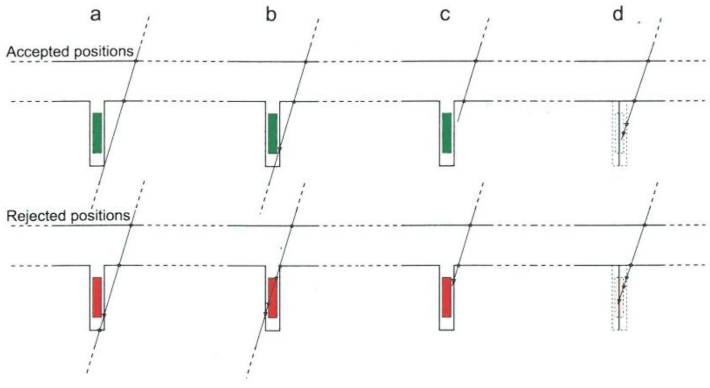


Figure 3-4: Acceptance end rejection of canister positions; Effect on acceptance when using different FPC a–d. Top row illustrate accepted positions whereas the bottom row illustrates positions that would be rejected under the FPC criteria (SKB TR-10-21 Fig. 6-1). The EFPC criteria are applied when a discriminating fracture intersect four of more canister positions (cf. SKB TR-10-21 Figs. 3-3 and P13).

5. Remaining critical tectonic structures affecting the layout of the repository are the large fractures, i.e. structure that may be represented by a single fracture plane or a thinner brittle deformation zones extending for more than 300m (radius ≥150m, SKB TR-08-11 P167, cf. SKB TR-10-21 P7).

   Large fractures are not allowed to intersect deposition positions in accordance with the Extended Full Perimeter Intersection Criterion (EFPC; cf. SKB TR-10-21 P12-13). This criterion requires that a canister position must not be intersected by a fracture that also fully intersects the deposition tunnel perimeter (so called discriminating fracture or large fractures, Fig. 3-4). Furthermore, canister positions that are intersected by fractures that also intersect four or more adjacent positions are rejected (cf. SKB TR-11-01 P22). "EFPC criterion is a tool to identify such large fractures, but can be replaced or complemented by other tools if these are shown to yield a comparable or lower risk"(TR-11-01P47).

   The large fractures will be mapped, characterised and modelled continuously during the detailed investigation of deposition tunnels and deposition holes (including pilot, probe holes and injection holes: SKB R-11-14). Approaches to detect large fractures (geological mapping and geophysical investigations) will be tested and documented before the excavation of the repository volume starts.

   Documentation of transport tunnels circumscribing the repository area and main tunnels in the repository area are planned to be performed as in the ramp (R-11-14 P47). However, the transport tunnels will give information about structures close to regional structures demarcating the available repository volume and rock volumes close to deposition tunnels. The grade of investigations in the transport tunnels should be considered to be upgraded to the deposition tunnel standard. This should also be the case for the lower part of the access tunnel, shafts and central area in order to investigate occurrence of thin gently to sub-horizontal brittle deformation zones/large fractures. Key parameters that can be used to indicate fracture length are (SKB R-06-39 P134):

   - Fracture apertures.
   - Shear displacement.
   - Deformation zone (fracture) thickness.
   - Conductivity.

   However, it is also stated that none of these indicators listed above are by themselves sufficient for assessing the sizes of these features. "For any site, a study must be made to establish the appropriate "tool box" of methods suitable for detecting deformation zones and these methods need to be tested and calibrated" (SKB R-06-39 P135). Such a toolbox should contain also geophysical investigation that could remotely detect structures, for instance borehole radar (saline water is a problem to solve) and seismic investigations.

   In a study by Joutsen (2012) using geological data from pilot holes to predict full perimeter tunnel intersections, some additional fracture characteristics are added:

   - Occurrence of fracture sets with recognized distribution of large fractures.
   - Undulating and/or slickensided fracture surface profile.
   - Existence of the addition of certain fracture mineral to the common fracture mineral assemblage.
   - Fracture alteration.
   - Fracture filling is thicker than general.

To locate and characterize large fractures and the deformation zones in the near-field of a repository the development of detailed mapping performances and modelling procedures supported by hydrogeological data and geophysical investigations are necessary to develop and be tested well before the actual characterization of deposition tunnels and deposition holes starts.

However, tests of using borehole radar (SKB R-07-56 P145-159, Döse and Gustafsson 2011), ground penetration radar in tunnels (Heikkinen and Kantia 2011) and seismic investigations (Sireni et al. 2011, Cosma et al. 2011) indicate that the three investigation methods could be further developed (considering limitations including sampling bias, performance/data processing and interpretation) as the geological outcome of the results are in many case not fully clear. However, together with borehole and tunnel mapping the three methods may constitute important support in detailed three-dimensional modelling of deformation zones and fractures on tunnel-scale.

6. Some local brittle deformation zones have blind terminations inside the local model volume (Fig. 3-1) and some extend west of the local model volume. There is also a regional brittle deformation zone (zone ZFMWNW0123A in the south-western part of the local model volume; Fig. 3-1) that is displayed to terminate against a lower order zone. The latter case has been discussed above in this review as its north-westward extension point into the western part of the repository area.

7. Ensure that the temperature of the repository, canister positions, is below 100°C with a sufficient margin. This criterion is related to the thermal conductivity of rock types, for example the occurrence of basic rocks (amphibolites), and the separation of canister position. Amphibolites occur mainly as bands and lenses located in the foliation and could be missed by pilot boreholes where planned deposition tunnels are sub-parallel to the foliation.

In the repository the loss of positions of deposition holes “could range between 10 to 25% depending on which DFN model is used, but it is also stated that the actual loss of positions is judged much smaller, since prospects are good of finding more efficient means of identifying fractures that are too large” (SKB TR-11-01 P153). The relative lengths of indicated zone intersections in boreholes (DZ in ESHI, SICADA data) are of the same magnitude.

Comments

The review of the detailed investigations planned to be performed during the construction and how the outcome may affect the layout of the repository have to be reviewed in more detail, e.g. borehole investigations (possible needs for investigations outside the rock volumes planned to be excavated), tunnel mapping performance (resolution in relation to different categories of mapping and description of terminology – what will be mapped), programme for geophysical investigations (incl. seismics and radar) and modelling on different scales. The order of constructing the repository may influence uniformity in the acquisition of data, the quality of recorded data and thereby also the characterization of the repository volume.

There is a need for a library /data base containing definitions of terms and it should be used to illustrate and ensure uniform usage of the used terminology. At present, modifications and introductions of terminology are given in reports and thereby all participants in the investigation teams may not be aware of their existence. The usage of a data base for this purpose makes the terminology easy to retrieve.

Many terms used to describe objects include some type of measures and the process to obtain such measures should be given, for example how to identify a brittle deformation zone and how to describe it.

There is a need for a database describing the character of each modelled structure and set of structures – a part of a learning process (cf. the observation method will be applied - prediction and outcome). Such a database could also describe the internal pattern in deformation zones and how structures are related to each other (e.g. terminations).

Develop a modelling approach that ensure that structural relations are analogues throughout the modelled volume, i.e. relations found by mapping of outcrops and tunnels should steer the modelled relations between structures outside the exposed areas (cf. Figs. 2-12 and 3-1).

The framework outline for the detailed investigation during the construction of a deep repository is good and it outlines the intentions for further development. As pointed out in the previous section, information gained in transport tunnels circumscribing the repository volume is essential for locating structures that may emanate from the regional structure northeast and southwest of the candidate area into the near-field of the repository.

4. Summary and conclusions

The geological part of performed site investigation in the Forsmark area is structured and well presented in a series of reports describing the development of the understanding of the site. The successively achieved knowledge are summarized for each of the stages of the investigation programme and presented in the site descriptive reports. These main reports are based on a sequence of supporting reports. For each investigation stage there was a data freeze, a date when all primary data should have been stored in databases and quality checked before used as input data in the site description for the investigation stage.

The model describing the distribution of rock types in the Forsmark area indicate that there is a large volume composed of granitic to grandioric rock (granitoids) large enough to host a repository in the central part (core) of a large-scale fold enveloped on both sides by regional WNW to NW trending deformation zones. The two main WNW to NW trending brittle deformation zones, The Singö and Eckarfjärden deformation zones, form a large-scale wedge structure closing north-westwards.

The presented rock type model contains two steps of generalizations. Such a performance (filtering) can be used to classify the bedrock into units that can be modelled on larger scale (site scale and regional scale) in order to get a good understanding of the geological setting of the site. However, there are inhomogeneities represented by basic rocks (amphibolites), with lower thermal conductivity, in the granitoids that may affect the layout of the repository (increased separation of canister positions may be needed). There are also a set of younger granitic dykes cutting across the pervasive foliation in the granitoids. These dykes, oriented NNE/subvertical, are sub-parallel to a set of minor and local deformation zones and they may contain extensive fractures trapped inside the dykes. By this the granitic dykes may indirectly affect the layout as large fractures are not allowed to intersect canister positions.

The future three-dimensional modelling of rock types in the Forsmark area should have such resolution that at least the occurrence of the amphibolites can be documented and so also the occurrence of late granitic dykes. The latter have similar magnetic signature as brittle deformation zones, i.e. they are low-magnetic.

A conceptual structure model for the development and evolution of brittle deformation zones is presented. The model gives the relation between structures of different orders. By relating formation of fracture minerals and alteration along fractures and brittle deformation zones the timing of deformation can be determined in broad figures. The deformation in the deformation zones is revealed by the internal character of the deformation, the type of fracture minerals and the order the fracture minerals have precipitated. It is found that the WNW to NW trending brittle deformation zones are mainly located in rock affected by penetrative ductile deformation outside the target area consisting of granitoids. The brittle deformation zones inside the granitoids are oblique to the WNW to NW trending border zones and it is found that each set of zones are mainly composed of fractures parallel to the orientation of the zone and that fracturing in the county rock, outside a zone, is also dominated by fractures parallel to the considered zones. The assemblies of fracture minerals found within the different sets of brittle deformation zones include up to 11 minerals, which may indicate that all sets of brittle deformation zones have been active during a long time span or reactivated several times.

However, the distribution of fractures with genetically related mineral assemblages can display whether fractures are reactivated, for example associated with existing brittle deformation zones, form independently of existing zones, or both. Findings regarding the relation between orientation of brittle deformation zones and their associated fracture can be used to test, for example, the presented three-dimensional model describing the occurrence and relation between local and regional brittle deformation zones. One investigation that is performed is kinetic analysis of relative displacement along faults and it confirmed the structural relation presented in the three-dimensional local fracture zone model and postulated in the conceptual structure model are correct. However, there is a need for updating the description of structures in the brittle deformation zone model and the actual three-dimensional model (especially the termination of zones but also the location of zones).

Notable regarding the local model describing brittle deformation zones is that the modelled steeply dipping brittle deformation zones (mean and median widths are about 18 and 15m, respectively) are generally somewhat thinner than gently inclined brittle deformation zones (26 and 15m, respectively). However, the gently inclined to sub-horizontal zones are generally found at shallow depth in an environment with strongly enhanced gently dipping to horizontal fractures. The origin of these fractures is not fully understood (a mix of tectonic fractures and sheet jointing is postulated).

The local brittle deformation model is presented also as structure maps describing structures at repository depth. The importance of such maps should be considered as the uncertainty in the modelling of structure has a relatively high degree of uncertainty. The main uncertainty may not be related to the number/density of deformation zones as to the actual location of zones (cf. outcome from the test performed in borehole KFM08D) and their geometries (extension, form and termination). The location and structural relation of local and minor deformation zones will be mapped in detail during the construction of the repository. Such large areas as a repository has never been mapped in detail before and the outcome will give information about the possibility to correlate data over relative short distances (40m, the separation of deposition tunnels) and information about the natural variation in characteristics of brittle deformation zones along their extensions and the relation between zones (how to measure the length of a zone). However, the testing and development of the tunnel mapping system will be performed earlier during the construction of the access tunnel (the ramp, cf. Fig. 3-2) thereby some information about the character of zones will be obtained.

Fractures outside brittle deformation zones are stochastically modelled (DFN) and the selection of input data is based on fracture domain models. At repository depth two fracture domains are recognized in the granitoids planned to host the repository. The boundaries of the two domains follows the boundaries of the two dominant rock types occurring in the central part of the Forsmark site making the separation of the fracture domains simple. However, the high resolution ground magnetic map (the base data for mapping deformation zones at the surface) indicates that the structure system in the rock in the central part of the local model volume may not be related to the distribution of granites and granodiorites and an alternative sub-division of the bedrock into rock domains is possible. However, the density of subsurface data (boreholes) may not be high enough to support subdivision of the bedrock in, for example four fracture domains at levels below the shallow section with enhanced gently inclined to sub-horizontal fractures.

Critical for the layout of a repository could be the existence of gently inclined to sub-horizontal brittle deformation zones/large fractures at repository depth. The more extensive large fractures are, the greater their effect on the utilization of the repository volume will be. The potential of the existence of thin gently inclined to sub-horizontal brittle deformation zones should be evaluated before the excavation of the repository volume starts.

Borehole radar and/or seismic investigation would help the three-dimensional modelling of large fractures. However, both techniques have their limitations (e.g. environmental and method related) and their ability to distinguish large fractures should be elaborated further.

The importance of performing tunnel mapping with a uniformly high standard within all tunnels in the near-field the repository is stressed here. The reason for this is that the transport tunnels will provide essential information regarding structures in the rock volumes inside the respect distance of the WNW to NW trending zones bordering the repository area and are also of importance for modelling structures in deposition tunnels and deposition holes in the outer part of the repository. Furthermore, the geometry of the ENE trending structure (ZFMENE060A) with its associated respect distance will be crossed at, at least, two (possibly four) locations by transport tunnels.

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APPENDIX 1

Coverage of SKB reports

In Table 1:1 reviewed SKB reports and reviewed section are presented. . The full title of the reports is given below Table 1:1.

Table 1:1 Reviewed reports and the main sections reviewed therein.

Reviewed report	Reviewed sections	Comments
SKB TR-08-05	1-3, 5-6, 11, Appendix 4	
SKB TR-08-11	1, Appendix C	
SKB TR-10-21	1-3	
SKB TR-10-48	2, 4.1-4.4	
SKB TR-10-52	1-2, (6.2), 6.3	(thermal properties is outside the reviewers competence)
SKB TR-11-01	Summary, 1, 4.1-4.4. 5, 5.2	
SKB R-03-07	All	
SKB R-04-17	1, 2, 4-8, Appendix 3	
SKB R-06-39	All	
SKB R-07-15	1-5, 9, Appendix 2-9	
SKB R-07-45	All	
SKB R-07-62	All	
SKB R-08-19	1-2, 4	
SKB R-08-64	All	
SKB R-08-102	1-4, 6, 10	
SKB R-08-113	Mainly figures	+ Sorted part related to geology/zones
SKB R-08-116	Mainly figures	+ Sorted part related to geology/zones
SKB R-08-128	All	
SKB R-11-14	All	Should be revisited, investigations-drilling-excavations
P-06-212	All	+ other reports on kinematics, Forsmark.SKB P-07-101 and -111

SKB TR- reports, Swedish Nuclear Fuel and Waste Management Co (SKB)

SKB TR-08-05 SKB, 2008: Site description of Forsmark at completion of the site investigation phase SDM-Site Forsmark.

SKB TR-08-11 Fälth, B., Hökmark, H. and Munier, R., 2010: Effects of large earthquakes on a KBS-3 repository. Evaluation of modelling results and their implications for layout and design.

SKB TR-10-21 Munier, R., 2010: Full perimeter intersection criteria. Definitions and implementations in SR-Site.

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SKB TR-11-01 SKB, 2011: Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. Volume I.

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SKB R-07-45 Stephens, M. B., Fox, A., La Pointe, P., Simeonov, A., Isaksson, H., Hermanson, H., and Öhman, J., 2007: Geology Forsmark Site descriptive modelling Forsmark stage 2.2.

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SKB R-08-113 SKB, 2009: Underground design Forsmark, Layout D2. Layout and construction plan

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SKB R-08-128 Stephens, M .B., Bergman, T., Isaksson, H., and Petersson, J., 2008: Bedrock geology Forsmark Modelling stage 2.3. Description of the bedrock geological map at the ground surface.

SKB R-11-14 SKB, 2010: Framework programme for detailed characterisation in connection with construction and operation of a final repository for spent nuclear fuel.

R-reports, Swedish Nuclear Fuel and Waste Management Co (SKB)

SKB P-06-212 Nordgulen, Ø. and Saintot, A., 2006: Forsmark site investigation The character and kinematics of deformation zones (ductile shear zones, fault zones and fracture zones) at Forsmark – report from phase 1.

APPENDIX 2

Suggested needs for complementary information from SKB

1. The conceptual model presented in, e.g. SKB TR-08-05 Figs. 5-26 and 5-36 is focused on deformation related to the WNW trending major deformation system controlled by the WNW trending Singö and Forsmark deformation zones. The SKB structure model incorporates no structures overprinting the regional WNW zones.

   Maps or block models are needed to visualize how different generations of deformation in the regional area surrounding the Forsmark site interfere with structures in the Forsmark area.

   In the “geological evolution report” (R-08-19), structural events outside the Singö-Forsmark belt are described. However, it is not fully apparent how these events have affected the Forsmark area, for example:

   a. The displacement, faulting of the sub-Cambrian peneplain with reference to, e.g. Lidmar-Bergström 1994. Faulting associated with systematic tilting of large scale blocks in Uppland, the Gräsö fault north of Forsmark and the block faulting in Ålandshav east of Forsmark.

   b. The intrusion of the rapakivi granites (1.5 to 1.6 Ga), e.g. Åland.

   c. A comparison of the structure evolution of the Forsmark area with south-western Finland – extension and compression events (Väisänen, M. and Skyttä, P., 2007: Late Svecofennian shear zones in south-western Finland, GFF, 129:1, 55-64.)

   d. A description of the interference of ductile to brittle-ductile structures in northern Uppland and the Singö-Forsmark belt (interference between structures in Tectonic domain 3 and 4 in SKB R-08-19 Fig. 2-3).

   One good example of thematic presentation of structure data is the report on “early Holocene faulting and paleoseimicity in northern Sweden” Lagerbäck and Sundh, 2008) with a generous presentation of figures and maps. These maps are of high value for the safety assessment as they indicate possible geometries of faults and faulting.

   The most essential part of this issue is to locate structures along which late displacements have occurred.

2. An uncertainty in the geological description of a site is the step from two dimensions, e.g. the geological and structural maps, to three-dimensional modelling. Drilling of boreholes in different directions from a drill sites is

an investigation technique not earlier applied by SKB; implying an investigation of volumes more than specific targets, a technique that favours cross-hole interpretations. However, the separations of the endpoints of boreholes are in most cases more than 500 m at repository depth.

There is a deficiency in analysis of location of rock volumes within which sets of structures, especially those that are extensive (e.g. ≥ 1km) may occur without being intersected by any borehole – a combination of blind volumes and sampling bias. Each set of deformation zones will have their own blind volumes. For example, structures trending NE to ENE may, if they exist, cross the central part of the local model area without being intersected by any borehole.

The borehole configuration and the reflection seismic may catch the gently inclined to sub-horizontal zones in the area. The third main uncertainty considers detection of minor or thin local sub-horizontal deformation zones at deeper levels. If they exist they may have effect on the layout of the repository and may cause problem during the construction of the underground facility, the repository.

What is asked for are three-dimensional models visualizing rock volumes where local brittle deformation zones may be located without being intersected by boreholes. Such modelling have to be performed for each set of brittle deformation zones (7 sets) and the ground surface could be draped with the high-resolution ground magnetic measurements and the structural interpretation of the magnetic (e.g. SKB R-07-62 Fig. 3-7) measurements (SKB TR-08-05 Fig. 5-18).

3. Rocks that postdate the metamorphic peak and appear discordant relative to the regional foliation is of interest. Of special interest is a description of late low-magnetic granitic dykes parallel to steeply dipping NNE to NE trending brittle deformation zones (SKB R7-45 P111). In such environments the granitic dykes may contain large fractures or minor brittle deformation zones, being trapped inside the dykes. The question concerns the structural relation between the dykes and the surrounding brittle deformation zones and do the dykes contain fractures sub-parallel to the extension of the dykes? What are the dimensions and distribution of the granitic dykes according to borehole data?

4. "An important modelling prerequisite /R-03-07/ is that the resolution of the modelled objects should be the same throughout the model volume, at any particular modelling scale. For this reason, it is essential to define, for each model, the size of the smallest object to be modelled deterministically. The choice of this limit is guided by the intended use of the model, at a particular scale, and the data density within the model volume. These features are balanced against the efforts required to fill the volume homogeneously with modelled objects" (SKB TR-08-05 P132).

   In the local scale, three-dimensional deterministic structural models (e.g. SKB TR-08-05 Fig. 5-29), the minimum size of local structures is 1km. The applied prerequisite presented should be demonstrated that it obtains its purpose: to present a uniformly sampled model. The sampling may be an inhomogeneous sampling of an inhomogeneous object. Are essential and mappable structures missed by setting the limit for local structures to 1km? A related question is what should the model describe?

5. A synthesis for sets of brittle deformation zones in the Forsmark site is presented (SKB TR-08-05 section 5.5.4). Five major sets of deformation zones are found and the dominant fracture orientation inside the brittle deformation zones is parallel to the orientation of the zones.
   This information should be used to test zones included in the structural models (SKB R-07-45 Appendix 15 and 16,SKB R-08-64 section 4.4, 5.4 and 6.4. and SKB TR-08-05 Appendix 4) and reasons should be presented for, for instance, including zones that that mainly contain fractures that deviate from what is presented in the synthesis.

6. Update the description of the deterministic model describing deterministic brittle deformation zone models (cf. SKB R-07-45 Appendix 15 and 16, and SKB TR-08-05 Appendix 4) based on complementary data (borehole data from KFM08D, 11A and 12A).

   Update also the description of data on possible intersections between brittle deformation zones and boreholes (description of DZ in ESHI files; SICADA data base). Data in the ESHI files should be searchable; all parameters should have separate columns in the data files.

7. SKB should compile, if not already done, a main data file for each geological model where all descriptive parameters for each modelled element (e.g. a brittle deformation zone) are compiled. Such file or rather set of files may be very extensive. At least for reviewers/scientists not having direct connections to the SKB database SICADA, such a compilation of data will be important.

8. The SSM Review Group should be provided with updated rock domain, deterministic fracture zone (and hydrogeological ditto) and rock domain models in digital format (e.g. 3D pdf-files). Such models should also contain boreholes (cored and percussion drilled) and the D2 layout of the repository.

9. The association of fracture minerals in different sets of deformation zones (SKB TR-08-05 Figs. 5-29 and 5-30 section) together with typical fracture minerals in the four fracture generations (G1 to G4:SKB R-08-12 section 4) can be used to study how deformation/reactivation of brittle deformation zones is steered and the potential for reactivation of zones. One question is if reactivations are prone to the vicinity of regional WNW to NW trending brittle deformation zones. A related issue is the distribution of alteration in

the bedrock in relation to regional zones?

It could be further elaborated how and where fracturing has taken place during reactivation of deformation zones, re-opening existing fractures or formation of new fractures along existing zones or both. This may also support the characterization of brittle structures and thereby also the location of thin extensive brittle structures, so called large fractures (affect the layout of a repository, structures that shall not intersect a deposition hole, cf. part 3 of this review).

A special issue is the distribution of open fractures without fracture minerals or alteration of the fracture surfaces (SKB R-08-12 page section 4.4). This fracture characteristic is most common among sub-horizontal to gently dipping and occurs also along steep fractures. There is an on-going study of such fractures and what is the status of this work?

10. Despite the lack of minerals of economic interest in the Forsmark granitoids, the radioactive waste in a deep geological disposal will form a geophysical anomaly. How such an anomaly will differ from other mineralizations in the Bergslagen mineral resource province is not clear. Therefore a geophysical simulation is needed to evaluate the risk for future human intrusion related mineral prospecting?

11. There is a need for a library /data base containing definitions of terms and it should be well illustrated and ensure uniform usage of the used terminology. At present modifications and introductions of terminology are given in reports and thereby all participants in the investigation teams may not be aware of their existence/redefinition. The usage of a data base for this purpose makes the terminology easy to retrieve.

    The data base could also contain instructions how to measure different types of parameters and how to classify recorded data. For example, how to measure distributions of fractures in a brittle deformation zone and where to locate the borders (external and internal /between the damage zone and core zone/) of the zone.

12. The data base could also contain instructions how to measure different types of parameters and how to classify recorded data. For example, how to measure distributions of fractures in a brittle deformation zone and where to locate the borders (external and internal /between the damage zone and core zone/) of the zone.

13. High- resolution topographical data (2m grid, LIDAR data) covering the Forsmark area can be a compliment to the high resolution ground magnetic measurements. Of interest is to map the extension/prolongation of structures indicated by the magnetic measurements. Even though the bedrock head may have some relief the top surface of the overburden is very flat and thereby masking the bedrock relief. However, high-resolution elevation data is needed to map areas where the bedrock outcrop and the overburden is thin. Of special interest is to map long fractures. For instance, in Olkiluoto it is found that such fractures, initially not identified, are oriented NS/steep (Posiva W-R 2012-12). NS trending fractures are dominant on Åland. Do SKB have LIDAR data for Forsmark and, if this is

the case, how have they been used?

14. SKB database SICADA contains both recoded data and interpretations. All data are described by metadata. Some data files in SICADA may contain both recorded data and interpretations. For instance, the data files containing the characters of fractures in drill cores contain a column Joint_Alteration (an interpretation; each category is given by a number). On the other hand, noted alteration of fractures are given in the column Fracture_Alteration (fresh or slightly, moderately to highly altered, and included is also gouge/a fault rock, i.e. a fracture fill)/). The columns presenting the fracture minerals (Min) are four and they present minerals occurring in fractures and also notation of “Oxidized Walls” which is an alteration of the fracture walls.
    Alteration associated with a fracture may affect the fracture walls (the rock in the vicinity of the fracture), the fracture surface and the fracture fill (i.e minerals and other substances in the fracture). At present, this distinction regarding the alteration associated to fractures is not made. However, it may be of interest in the characterization of fractures that form conduits for circulation groundwater.

15. Data extracted from SICADA are quality controlled. However, it is found that some geophysical borehole data from Forsmark are distorted and have no sense. This was apparent when plotting the data. Furthermore, borehole radar data files (interpretation of orientation of reflectors) in SICADA contain a mix of two types of radar measurements even though the two types should be presented in separate file. Both deviancies are reported to SKB.

APPENDIX 3

Suggested review topics for SSM

The suggested topics for further review concerns mainly classification and interpretation of borehole information as this information represent continuous section though the bedrock and the data are structured and available in treatable format. The proposed plan for further investigation has the following objective: based on fracture scale, perform an alternative classification of boremap data (SICADA data) and locate and characterize intersections of brittle deformation zones in boreholes. The different steps (milestones) are:

1. A tool is needed for handling data. The principles for the process presented below are tested within a SSM study (Tirén S.A. 2011“Identification of brittle deformation zones and weakness zones”) and the processed fracture data are visualized together with supplementary borehole information (core loss, sections of crushed rock, shear zone, fault rock, alteration and PFL):

   a. The first step will be to develop a procedure for sorting and classify borehole data on fracture scale regarding separations of fractures (true separation for fracture sets – separation along the borehole for all fractures).

   b. The procedure should have capability to sort fractures related to any chosen fracture attribute/character. The main attributes used for sorting the base data will be orientation, sealed/partly open/open, alteration, aperture and kinematic indicators (e.g. slicken sided). All fractures will maintain their original attributes noted during mapping. By studying only open or open and altered fractures, weaker parts of the rock will be indicated, e.g. weakness zones within brittle deformation zones will be determined.

   c. The classification of fractures based on separation will be flexible and statistically tested. The separation will be classified by using at least two classes of separations, e.g. 10 and 20 cm.

   d. The next step is to define how many fractures are needed to form a cluster, i.e. a succession of fractures with mutual separations less than 10 or 20 cm. At this step the thinnest deformation zone will be indicated.

   e. However, a fracture zone is generally inhomogeneous and to locate the brittle deformation zones an interactive process is applied to identify clusters of fractures. It is found that the interactive process stops by itself if stringent rules (based on statistics) for the process are postulated.

   A last comment is that the presented procedure is very sensitive and can be used to describe the internal distribution of fractures in zones.

2. The tool will be applied on borehole data in order to:

   A. Characterize the general fracturing in boreholes.

   B. By using the synthesis describing fracture sets in brittle deformation zones (SKB R-08-05 section 5.5.4), i.e. that fractures in zones are mainly parallel to the zone, zones of different sets can be located. Brittle deformation zones with widths from, e.g. a few centimetres to tens of metres can be indicated.

   C. It is found that by applying the presented method to sort and classify fracture data and locate brittle deformation zones, relations between gently inclined and steeply dipping brittle deformation zone can be developed. Zone to zone intersections can be studied.

   D. By sorting according to both orientation and index minerals for the different generations of fracture minerals, reactivation of brittle deformation zones and fractures outside zones can be studied.

3. The outcome of item 2 regarding location of gently inclined to sub-horizontal brittle zones can be modelled in boreholes drilled from one or two drill sites with three or more boreholes. This is a test of the possible extension of thin gently inclined to sub-horizontal brittle deformation zones.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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