Strål
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Technical Note

2012:52

Shear movement of near-field rock due to large earthquakes

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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 hantering av jordbävningars påverkan på sprickor i slutförvarets närområde. Frågor som berörs är uppkomst av skjuvrörelser och deras påverkan på slutförvaret, tillväxt av sprickor samt uppkomst av nya sprickor. Uppdraget går även ut på att titta på tillförlitligheten på utförda analyser.

Författarnas sammanfattning

Granskningsuppdraget fokuserar på möjliga skjuvrörelser på grund av stora jordbävningar och deras påverkan på strukturer i slutförvarets närområde. För detta ändamål genomfördes en generell granskning av några av SKB:s toppdokument.

I rapporterna dras en generellt enhetligt och till en stor del omfattande, bild av möjlig påverkan på slutförvarets integritet, i händelse av en osannolik jordbävning nära slutförvaret. För det mesta inkluderas relevanta referenser och data i rapporterna. Slutsatser dragna från relevant data är sunda och konsistenta.

Analyserna visar tydligt att för att en jordbävning ska påverka slutförvaret behöver den vara av betydande magnitud samt närliggande. Till det kommer att, för att en seismisk händelse ska påverka slutförvaret, behöver stora strukturer som korsar kapselpositioner ha förbisetts.

Denna granskning har identifierat två områden där fortsatta studier för att stärka förtroendet för detta koncept behövs. En bättre förståelse för spänningsfältet och dess modell för framtida utveckling behövs, och tillväxt av sprickor behöver tas i beaktande.

De utförda spänningsmätningarna i Forsmark lämnar utrymme för diskussion, och eftersom spänningsfältet är utgångspunkt för alla fortsatta geomekaniska analyser behövs en ny oberoende tolkning av spänningsfältet.
I alla analyser har tillväxt av sprickor ansetts inte vara en viktig mekanism. Det behövs en bättre förklaring av argumenten för att bortse från tillväxt av sprickor. Till det kommer, från en bredare syn på sprickmekanik, att det finns en del scenarier som kan leda till tillväxt av sprickor. Dessa scenarier är till stor del även dem beroende av modellen för spänningsfältet. Tillväxt av sprickor som leder in i deponeringshål med kapslar är ett ofördelaktigt scenario och kräver därför fortsatta studier.

Fortsättningsvis har mindre frågeställningar rörande antaganden om potentiell påverkan av jordbävningar på sprickor i slutförvaret blivit identifierade. Förutom förtydligande av detaljer i utförd analys, föreslås att många slutsatser dragna från simuleringar av seismisk påverkan på sprickor kontrolleras igen för att få ökat förtroende för SKB:s analyser.

Projektinformation

Kontaktperson på SSM: Lena Sonnerfelt
Diarienummer ramavtal: SSM2011-3630
Diarienummer avrop: SSM2012-109
Aktivitetsnummer: 3030007-4022

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. This assignment focuses on the handling by SKB on the impact of earthquakes on repository structures. Issues regarded are shear movements and their impact on the repository, growth of fractures and the initiation of fractures. The assignment includes assessment of the robustness of the analyses performed.

Summary by the authors

The review assignment concentrates on the possible impact of large earthquakes on the shear deformation of large fractures in the repository volume. For this purpose a general review of some of SKB's top-level reports was carried out.

The reports draw a generally consistent and to a considerable extend comprehensive picture of the potential impact on the repository integrity in case of the unlikely event of a large earthquake close to the repository. The reports mostly include the relevant references and data. The conclusions drawn from the incorporated data is sound and consistent.

The analysis clearly shows that an earthquake, which could potentially influence the performance of the repository needs, to be very close to the repository and needs to be of considerable magnitude. In addition, such a seismic event can only have an impact, if large fractures that intersect canister positions are overlooked.

This review identifies two main areas that require additional analysis to gain stronger confidence in the concept. The stress field and stress evolution model for the repository area needs to be better understood, and the growth of fractures should be considered.

The stress measurements that have been performed at Forsmark leave room for discussion, and as the stress field is the starting point for any further geomechanical analysis, the stress field interpretation needs to be independently revisited.

In all analyses the growth of fractures has been assumed not to be an important mechanism. The reasons for excluding fracture growth from the analyses need some better explanation of the arguments. In addition, from a broader fracture mechanics point of view, there are some potential scenarios, that may lead to fracture growth. These scenarios depend very much on the stress field model also. The growth of fractures into the deposition holes containing the canisters might be one of the potential unfavourable scenarios and hence additional analysis is suggested. Furthermore, minor issues regarding assumptions about the analysis of the potential impact of earthquakes on fractures in the repository have been identified.

Besides clarification about details in the performed analysis, it is suggested to crosscheck several conclusions drawn from the simulation of the seismic impact on fractures in the repository by alternative approaches to gain additional confidence in SKB's analyses.

Project information

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1. Review principles and layout

The review assignment requests the review of SKB‘s approach to quantify fracture shear displacements in the near-field rock induced by large earthquakes. For this purpose the SKB reports, suggested to be relevant for the assignment, were reviewed for the following general aspects:

- *What are the boundary conditions assumed for the quantification of fracture displacements due to large earthquakes?*
- *Are the assumed boundary conditions reasonable and is the argumentation framework to reach these consistent?*
- *Are the assumed mechanisms and models for simulating the fracture displacements valid for the given set of conditions?*
- *Are the material properties used reasonable?*
- *Are the applied methods, i.e. both analytical and numerical, suitable for the tasks?*
- *Are the conclusions drawn consistent with the results from the analyses?*

The review process involved going through all chapters of all reports. Sections that appeared to be of importance for the review assignment got a thorough analysis, the other sections got a reading of the headers and introduction as well as reading of selected figures.

The report at hand is laid out such, that after explanation of the review principles and the summary of the reports that were included in the review process, the main findings of the review are presented with an integrated discussion.

In the text open issues and suggestions for additional analyses are highlighted by a box.

This is followed by a chapter that gives specific comments to the individual reports along with the formulation of open issues and suggestions for further analyses.

The appendices give a listing of potential questions to SKB and a listing of suggestions for additional consideration.

The main review work was carried out by Tobias Backers. Ove Stephansson served as a discussion partner to evaluate the review findings. Carina Grühser overlooked the quality assurance.

2. Reports included in the review

The following SKB reports and additional literature were included in the review process; the main reports were downloaded from skb.se 1st of March 2012, additional reports in the period 1st of March 2012 to 25th of June 2012.

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

short: SR-Site

The document is the main report of the SR-Site project, an assessment of long-term safety for a KBS-3 repository at Forsmark. The report supports SKB's licence application for a final repository for spent nuclear fuel at Forsmark.

The report summarises, with aim of giving a comprehensive understanding of the repository concept, the Forsmark site, the risk analysis and long term safety, and the underlying enormous amount of results from studies carried out over the past decades by SKB. The report concludes that SKB has demonstrated that the properties of the Forsmark site ensure the required long-term durability of the barriers of the KBS-3 concept repository.

The review concentrated on the chapters Summary, 1. Introduction, 4.1. Introduction to the Forsmark site, 4.2. The Forsmark area, 4.3. Rock domains and their associated thermal and rock mechanics properties, 4.4. Deformation zones, fracture domains and fractures, 4.5. Rock stress, 4.7. Integrated fracture domain, hydrogeological DFN and rock stress models, 8.3.4. Safety functions for containment: Geosphere, 8.4.5. Safety functions for retardation: Geosphere, 8.5. Factors affecting temporal evolution of safety function indicators, 10.1. Introduction to Analysis of a reference evolution for a repository at the Forsmark site, 10.4.4. The remaining part of the reference glacial cycle: Rock mechanics, 10.4.5. The remaining part of the reference glacial cycle: Canister failure due to rock shear movements, 12.8. Analysis of containment potential for the selected scenarios: Canister failure due to shear load, 14.3.3. Potential for shear failure, and 15.4.5. Canister shear movements.

2.2. SKB TR-10-52. Data report for the safety assessment SR-Site.

short: data report

The data report compiles, documents, and qualifies input data identified as essential for the long-term safety assessment of a KBS-3 repository, and is considered by SKB an important part of the reporting of the safety assessment project SR-Site. The input data concern the repository system, broadly defined as the deposited spent nuclear fuel, the engineered barriers surrounding it, the host rock, and the biosphere in the proximity of the repository. The input data also concern external influences acting on the system, in terms of climate related data. It is claimed that the data are provided for a selection of relevant conditions and are qualified through traceable standardised procedures.

In the review at hand the sections 6.2, 6.3 and 6.4 were considered; the sections regard the thermal properties, the discrete fracture network and the rock mechanical issues.

2.3. SKB TR-10-48. Geosphere process report for the safety assessment SR-Site.

short: geosphere report

The report compiles information on processes in the geosphere that SKB identified relevant for the long-term safety of a KBS-3 repository. In the course of the review process sections 1. Introduction, 4.3. Mechanical processes: Reactivation - displacement along existing discontinuities, 4.4. Mechanical processes: Fracturing, 4.5. Mechanical processes: Creep were analysed.

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

short: SDM

The report compiles the understanding of the Forsmark site at the completion of the surface-based investigation of the target repository volume. The site descriptive model integrates geological, thermal, rock mechanical, hydrological, hydrochemical, transport information and processes into a comprehensive model that forms the basis for the justification of the long-term safety.

The sections that appeared to be of importance to the review topic are section 1. Introduction, 3. Evolutionary aspects of the Forsmark site, 5.2.4. Bedrock geology: Ductile deformation, 5.2.5. Bedrock geology: Brittle deformation, 5.2.6. Bedrock geology: Character and kinematics of deformation zones, 7. Rock mechanics, 11.3. Current understanding of the site: Deformation zone, fracture domains and fractures, and 11.4. Current understanding of the site: Rock stress.

2.5. SKB TR-08-11. Effects of large earthquakes on a KBS-3 repository. Evaluation of modelling results and their implications for layout and design.

short: EQ report

The report presents the results from a numerical simulation campaign using mainly 3DEC aiming at understanding the response of target fractures in the vicinity of a large fault that hosts a large earthquake. From this analysis a critical length of target fractures is defined; when such a fracture intersects deposition holes, these should not be used for deposition. The report was reviewed completely.

2.6. SKB TR-10-21. Full perimeter intersection criteria. Definitions and implementations in SR-Site.

short: FPR

The report defines the criteria for omitting deposition holes in the presence of large fractures intersecting the full perimeter of the deposition hole. The report was evaluated mainly for information purposes to understand the concept.

Additional reports and papers that were consulted for a better understanding of details in the review process are

- *R-07-31. Rock mechanics Forsmark. Site descriptive modelling Forsmark stage 2.2*
- *R-11-14. Framework programme for detailed characterisation in connection with construction and operation of a final repository for spent nuclear fuel.*
- *R-07-26. Quantifying in situ stress magnitudes and orientations for Forsmark. Forsmark stage 2.2.*
- *R-05-35. Evaluation of the state of stress at the Forsmark site. Preliminary site investigation Forsmark area - version 1.2.*
- *Damjanac B., Fairhurst C. 2010. Evidence for a Long-Term Strength Threshold in Crystalline Rock. Rock Mech Rock Eng, 43: 513–531.*

A more comprehensive review of background reports should be considered relevant, but this was not carried out in this initial scoping review.

3. Main comments to the reviewed reports and discussion of the review findings

In general, the work summarised in the technical reports (TR), which can be ranked as ‚top-level‘, is impressive and seems to address most, if not all aspects of relevance related to the review topic. However, the level of detail in the summaries of the underlying work is not optimal to gain a comprehensive understanding of the methodology used, the data basis and arguments leading to the conclusions. It is mostly essential to look up the indicated references to gain more information on the background, the argumentational framework and the validity of the conclusions drawn. Further, the reports contain some repetitions within themselves. This is not only true for the SR-Site report, which is the main document in the series summarising mostly the conclusions only, but also for all the reviewed technical reports.

In general the presentation of information and data appears to be of good quality. The given reference to the latest scientific findings is in general adequate, but in some areas misses some scientific findings that are of relevance and should be at least discussed in the general context. The conclusions drawn are sound and based on all presented information and data.

During the review of SKB‘s approach to quantify fracture shear displacements in the near-field rock induced by large earthquakes three main fields that require to be addressed in detail have been identified. These are

- *the in situ stress field,*
- *the assumption that no fracture extension takes place, and*
- *simplifications made in the simulation of the impact of large earthquakes on the (shear) displacement of fractures in the repository volume.*

These are discussed in the following. Additional comments, particularly related to induced seismicity, are given at the end.

3.1. In situ stress field

One of the most important aspects in each geomechanical analysis is the appropriate understanding of the stress field, i.e. the in situ stresses including the pore pressure with their spacial and temporal variation. The stresses define the mechanical performance of the rock, the behaviour of fractures and fracture networks, hence the rock mass, and therefore the hydraulic behaviour of the system also. Any geomechanical or geohydraulic model used is generally bound directly or indirectly to the assumptions about the stress field. Hence, the determination of the in situ stress field, the pore pressure and their evolution over time is a necessary prerequisite for the analysis of the long term safety of a repository for radioactive waste.

Any inaccuracies in the initial stress field, which is the starting point for any further analysis, will inevitably influence the majority of the mechanical interpretations of the repository performance, including safety during construction, spalling during the thermal phase, fracturing during periods of increased fluid pressures during and at the end of glaciations, and the impact of earthquakes on the existing fractures.

Figure 1 summarises the SKB‘s current understanding of the stress field at the Forsmark site. The depicted data (maximum horizontal stress, minimum horizontal stress and vertical stress, all assumed to be principal stresses) consists to a large percentage of overcoring measurement results for the depth interval 0-500m and a stress model based on hydraulic and HTPF data at -500m, i.e. 500m below ground surface. The direction of the principal stresses is generally consistent between the presented data. The vertical stress is calculated from the density of the rock.

The regression lines presented in Figure 1 (red) are based on the overcoring measurements only. Omitting some data that is assumed to be of low confidence, the regression shows a two slope fit for the minimum horizontal stress and a three slope fit for the maximum horizontal stress. Consistently for both the maximum and minimum horizontal stress, the first change in slope is at the change from FFM02 to FFM01 at about -150 m. This change in stress gradient could be interpreted to be bound to the change in fracture intensities in the two fracture domains. However, the second change in slope at about -400 m is not explained in any of the reviewed reports, nor is it obvious from the presented data. The change in slope is only plotted for the maximum horizontal stress, but the gradient change should be also in the minimum horizontal stress. This is not the case. It would be possible to plot a linear regression to the maximum horizontal stress in the interval -150 m to -500 m; the resulting deviation from the data would be about the same as is evident in the minimum horizontal stress.

The hydraulic data is not used in SKB‘s modelling of the stress field for Forsmark. The arguments brought forward to exclude the data are given in the SDM page 216:

- *it is suspected that the hydraulic measurements do not measure the correct minimum horizontal stress, but rather the vertical stress (reference to R-07-26), and*
- *the results do not indicate that a thrust regime is prevailing, and this does not agree with the evaluated state of stress in the Fennoscandian shield (reference to Stephansson et al 1991).*

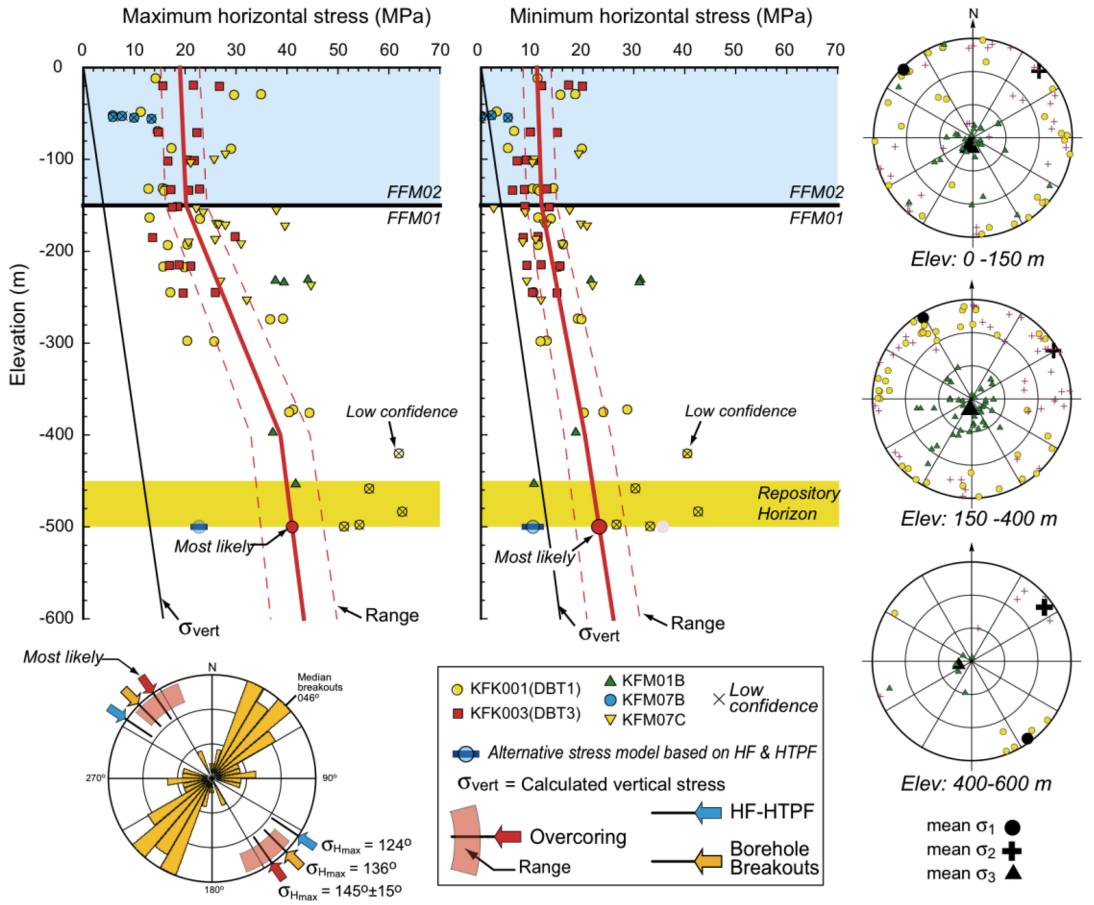

Figure 1. SKB's in situ stress field model for fracture domains FFM01 and FFM02 with measurements data (from SKB TR-10-52 page 293, Figure 6-48).

R-07-26 reports that the hydraulic fracturing experiments carried out gave minimum horizontal stresses less than the vertical stress calculated from the rock column. This suggests a strike-slip regime, which contradicts the general trend assumed for the Forsmark area. However, the target area is in a compartment surrounded by large fault zones and additional singular faults, hence local variation of stresses cannot be excluded.

Also, the argument that the hydraulic data contradicts the overcoring measurements does not hold for the following reasons:

- *Some of the data points from overcoring are considered to be of low confidence. These are in particular the very high stress magnitudes measured in DBT1 at about -450 m to -500 m. Therefore, there is only one overcoring measurement below -400 m, i.e. from KFM01B. This data point suggests SH ≈ 40 MPa and Sh ≈ 10 MPa. The minimum horizontal stress is very similar to the hydraulic data at that depth level and very close to the vertical stress, too, and therefore the argument that the hydraulic data contradicts the overcoring measurements is weak The measurements from borehole KFM07B are ranked as low confidence also.*
- *The boreholes DBT1 and DBT3 were drilled during the construction of the powerplant during the period 1977 to 1979 (R-05-35) and are located at the powerplant site (Figure 2). Furthermore, the measurements were performed with the precursor of todays Borre probe. The location of both boreholes is outside the candidate area in a different rock domain and the stresses were measured with an outdated cell; hence it is highly questionable if the data is valid and should be used for the modelling of the stress field and hence if the conclusion should be drawn that the hydraulic data contradicts the overcoring measurements.*

Is the stress data from DBT1 and DBT3 valid for the candidate area, although it was measured outside the domain with equipment that is considered to be not state-of-the-art?

- *The borehole KFM01B was drilled through deformation zone ZFMNNW0404 and intersected the zone at a depth of 415-454m (SDM, page 540). The stress measurements taken at that depth interval in the borehole show high values for SH. Due to the fact that at deformation zones it can be expected that stresses are locally altered, the data should be reevaluated.*

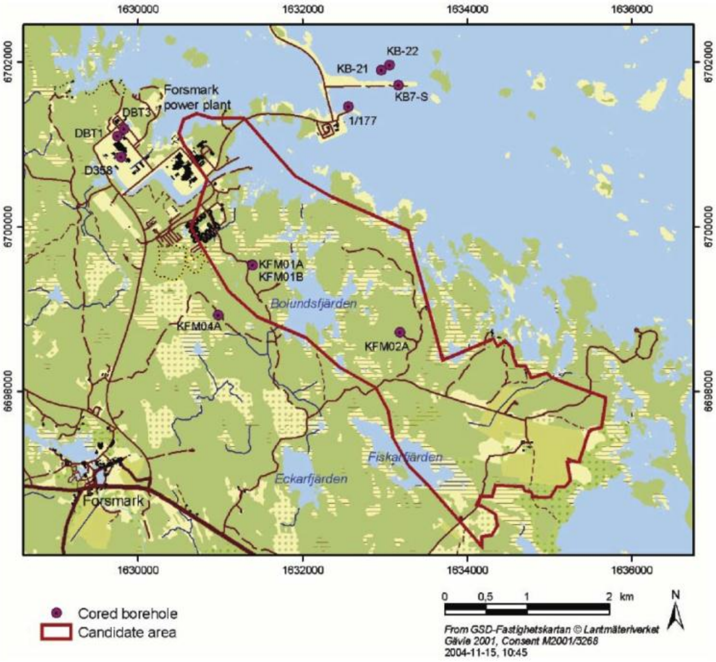

Figure 2. Map of the Forsmark site showing all boreholes in which rock stress measurements have been conducted. from R-05-35, Figure 3-4, page 17.

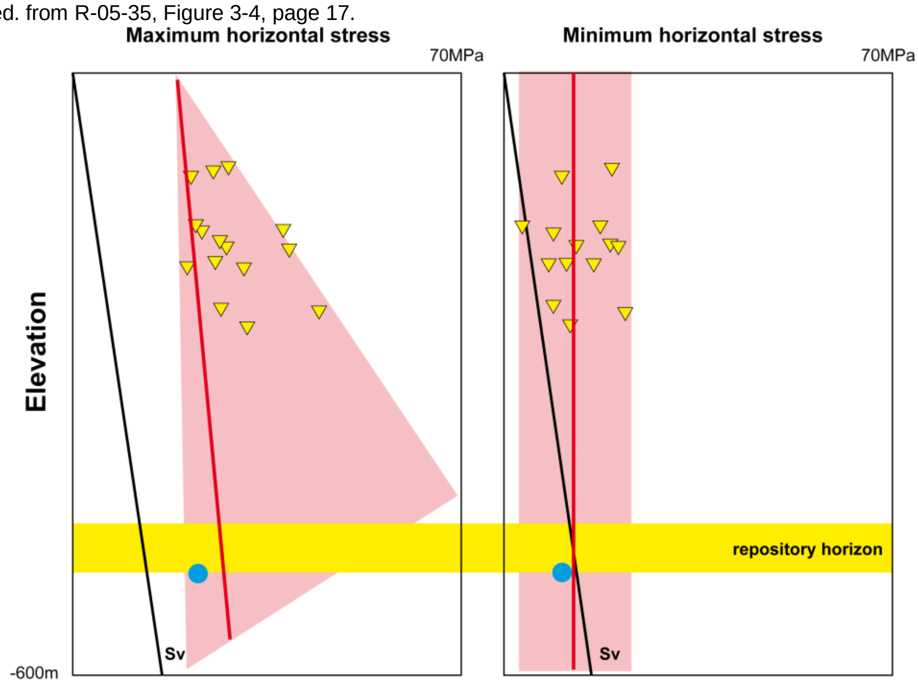

Figure 3. Possible ranges of stresses (red) based on hydraulic measurements (blue) and KFM07C (yellow) only. The schematic illustration is redrawn from Figure 6-48, SKB TR-10-52 (page 293), taking advantage of the argumentation before.

Is the stress measurement in borehole KFM01B influenced by the deformation zone?

- *Assuming the afore mentioned discussion points, the database for the stress modelling reduces significantly. If in consequence only the measurements from KFM07C (confined to depths -100m to -250m) and the hydraulic measurements are considered, all stresses may be represented by a single gradient with depth. Figure 3 utilises only the remaining data.*

Assuming validity of the hydraulic data, following the afore mentioned argumentation, and considering that locally the stress field may be different from the larger regional scale, the stress model could be as outlined in Figure 3. From 0 m to -400 m SH = S1, Sh = S2 and Sv = S3, at repository depth there is a transitional regime from thrust faulting to strike-slip below. This would mean that at the repository depth S2 ≈ S3 and S1/S3 ≈ 2.5. It needs to be emphasised that this is just a scoping interpretation of the stress field data.

However, the number of reliable data points at repository depth is insufficient to draw any sound conclusions; this is also true, if all data that was not ranked as low confidence is used. Although it is stated by SKB that no additional stress measurements are conducted from surface boreholes and the issue is solved by measurements during construction (TR-08-05), it is suggested to perform additional stress measurements at the depth interval of interest. The stress field assumptions have major impact on all analyses of repository integrity. If additional stress measurements have to be performed from the surface, a proper judgement of the risks, like introducing potential fluid pathways, is needed.

It could be advisable to perform additional stress measurements at repository depth, as the data density at that level is quite low.

A proper revisitation of all data is highly recommended. This should include not only the critical review of all individual measurement data, but could also include a structural geology motivated fracture reactivation potential analysis. Ideally such analyses are performed by independent consultants. A structural geology approach helps to narrow the possible ratios between the stress components and hence allows identifying unreliable stress measurements; a reference that such an analysis has been performed has not been given in the reviewed reports.

It is suggested to revisit all stress measurements and give them a ranking. Based on this a more reliable stress model could be derived.

It is suggested to perform a fracture reactivation potential analysis. The simple analysis can help narrowing the possible stress ratios and hence allows identifying unreliable stress measurements.

The stress field orientation seems to be roughly consistent in all measurements, i.e. the overcoring data, the hydraulic measurements, and the borehole breakout analysis. The pore pressure is assumed to be initially hydrostatic which can be assumed a valid model.

The above argumentation that gives some credibility to the hydraulic data might be discussed. However, it is clear that the data available suggests possible stress field models with the hydraulic data (Ask et al 2007) being the lower boundary, the SKB stress model (R-07-26) being a high stress model, and even some of the reported data points suggest that the stress field might be even higher than the SKB stress model.

This high uncertainty needs to be considered in the analysis of the long-term safety of the repository and this was not consistently done in the analyses. Instead, SKB argues that the assumption of a high stress model is conservative (TR-10-52, page 277). This statement is not true under all circumstances when looking at the long-term stability of the repository

It is true, that if the stresses are high, and the stress difference is large, as it is in SKB‘s stress model compared to the low stress model by Ask et al (2007), the potential for rock burst and spalling is higher, and therefore the SKB stress model is conservative. This concerns the integrity of the repository during construction, operation and the initial thermal heating phase. If the stresses are low, the risk for those failures of rock is generally lower.

On the other hand, if the in situ stresses are initially low, some scenarios may arise in the long term that are unfavourable for the long term safety, especially during the glacial and post glacial periods, with impact on groundwater flow and nuclide transport. The potential scenarios are deliberated in the following.

For further discussions of the conservativeness of SKB’s stress model, the stress models by Martin (R-07-26) and Ask et al (2007) are considered; for the sake of scoping simplicity the stresses for the two models are rounded for the repository level as given in Table 1.

„Hydrostatic pressures in the subglacial conduits may be as low as atmospheric pressure and occasionally as high as, or even higher than, ice overburden pressure“ (TR-11-01, page 443). Furthermore, it is assumed, that during a glaciation the fluid pressure at repository level is increased by about 26MPa (TR-11-01, page 441), resulting in a total of about P_P = 31MPa.

Table 1. Stress magnitudes at repository level for the high stress and low stress level. Definitions for further scoping calculations. The values used are rounded for simplicity from the actual values at -400m.

	S_H	S_h	S_v	P_P
Martin 2007	40 MPa	20 MPa	10 MPa	5 MPa
Ask et al 2007	20 MPa	10 MPa	10 MPa	5 MPa

The vertical stress S_v will increase by roughly the weight of the ice cover, which will be about 26MPa, assuming an ice sheet thickness of 2,600m for Forsmark. The effective vertical stress $S_{v,eff}$ will therefore be in both models about 5MPa, which is no change from the initial state.

The maximum horizontal stress will also increase by some value, probably 1/3 of the overburden increase, i.e. 9MPa. Hence, the effective maximum horizontal stress $S_{H,eff}$ is about 18MPa (i.e. 40 MPa + 9 MPa - 31 MPa) for the high stress model, but about -2MPa (tensile) (i.e. 20 MPa + 9 MPa - 31 MPa) for the low stress model.

Furthermore, assuming an increase of the minimum horizontal stress by about 9MPa also, the effective minimum horizontal stress $S_{h,eff}$ is about -2MPa (i.e. 20 MPa + 9 MPa - 31 MPa) for the high stress model and -12MPa (i.e. 10 MPa + 9 MPa - 31 MPa) for the low stress model. This ignores the increase of horizontal stress of tectonic origin, but should be valid for at least the first glaciation.

In conclusion, this scoping calculation shows, that if the initial high stress model is used, the stresses are such that the fractures are mostly stable, but for the initial low stress model tensile stresses are acting at depth, and hydraulic fracturing can be expected; therefore the stress model by SKB is not conservative at all circumstances.

The initial stress field assumption can be expected to have some implications on the shear displacements due to earthquake movements. Lower initial stresses can be assumed to lead to higher stress changes and hence displacements on fractures that are subject to an earthquake of same magnitude. This has been demonstrated in the EQ report (TR-08-11), see Figure 5-13 and following (page 72 ff).

In addition, the earthquakes are to be expected at the end of ice sheet coverage, where there might be some remaining increased fluid pressures acting on the fractures in the repository. At higher fluid pressures, the normal stress acting on the fractures is reduced, and the shear displacements, that can be expected to occur during seismic events, can be again higher.

In return, if the stresses are such at the end of a glaciation, that one of the effective principal stresses is close to zero, it may be discussed if this increases the potential for reactivation of one of the larger deformation zones in the Forsmark area, and this in consequence triggers an earthquake on one of the major deformation zones. It is suggested that this case needs reconsideration by a structural geologist or similar.

It is suggested that a structural geologist analyses the potential for seismic activity, if the in situ stresses are low at Forsmark and the fluid pressure is high at the end of a glaciation.

As can be seen from the scenarios discussed before, a good understanding of not only the initial stress state is essential, but also of the stress field evolution. It is acknowledged that the changes of stress due to several isolated effects (e.g. heating, ridge push, isostatic rebound) have been considered. However, an integrated analysis of the stress paths for the repository has not been presented. To be able to identify periods that are critical in terms of stability, and to be able to judge the impact of earthquakes on the shear displacements on fractures in the repository volume, it is important to have the most likely stress paths and also possible deviations.

It is suggested that the stress history of the repository due to the operation, heating etc is analysed for a more comprehensive understanding of the critical periods in the post closure/long term phase of the repository. This will help also to quantify the impact of a large earthquake on the repository.

3.2. Fracture extension

In general, the analyses by SKB do not consider extension of fractures. It is known, however, that different mechanisms of fracture extension exist for different loading situations. Generally, at and above a critical loading, fractures extend spontaneously at high speeds, whereas at loads below the critical value, they can extend slowly by stress corrosion mechanisms. Background information may be found in e.g. Lawn (1993).

There are several implications that would arise if fracture extension would be considered a mechanism. With stress changes due to the loading history of the rock mass in the repository, fractures may potentially extend and coalesce, which in return may lead to extension of fluid pathways.

Further, in SKB‘s concept deposition holes are to be rejected, which are intersected by fractures exceeding a certain length. The lengths are defined in Table 7-2, page 120, EQ report, and are in the order of 62.5m to >300m. Assuming that fracturing is a mechanism that needs to be considered, this bares some challenges:

- *It is hardly possible to determine the length of a fracture underground (see e.g. TR-10-21, page 7).*

What are the strategies to determine the length of a fracture underground?

- *Fractures that do not intersect deposition holes, but terminate close to them, might propagate (by whatever mechanism) into the deposition holes with consequences for fluid migration, buffer erosion, and shear slip during earthquakes.*
- *Fractures may propagate dynamically during earthquakes into deposition holes. Dynamically loaded fractures carry excess energy and will only stop if they run into a clear energy sink (so-called arrester).*
- *Fractures may propagate and coalesce with other fractures so that two fractures of uncritical radius connect to a fracture with critical radius whose centre is close to deposition holes.*

This has been also acknowledged by SKB for the earthquake scenario case, but is not mitigated into the analyses. On page 474, TR-11-01, it reads:

„Due to the large time spans considered in this assessment, up to 10^6 years, the effect of repeated earthquakes and hence of cumulative slip across canisters must also be considered. The concern is that though the induced slip due to an individual earthquake might be insufficient to damage the canister, the cumulative slip due to several earthquakes, on the same or different faults, might exceed the canister failure criterion of 5 cm.

There are several different cases to consider (Figure 10-120).

1) The fracture that intersects the canister is large enough to host a slip exceeding the canister failure criterion. It can either host its maximum possible slip allowed by its size (1c) or slip in smaller increments, one for each seismic event, that accumulates to a value exceeding the failure criterion (1a + 1b +…).

2) The fracture does not initially intersect the canister (2a). Triggered by nearby earthquakes (or itself hosting a small earthquake) the fracture grows into the canister position (2b), thereby enabling slip across the fracture. For large enough a growth, the fracture will eventually be able to host a slip across the canister that exceeds the canister failure criterion (2c).

3) The fracture intersects the canister position (3a), but is too small to host a critical slip. The fracture grows (3b) to a size that is able to host a critical (cumulative) slip (3c).“

Why has it been decided not to consider fracture growth, although the mechanism has been identified important?

The largest displacements on fractures will be at the centre or close to it (Eshelby 1957), hence the induced shear on the buffer and canister will be small if a fracture propagates into a deposition hole. But if two or several fractures coalesce and form a larger fracture which centre is close to a deposition hole, significant amounts of shear displacements may be generated during an earthquake.

SKB‘s argument brought forward to exclude fracture extension in the analysis of the shear slip on target fractures due to large earthquakes is that ignoring the mechanisms gives conservative results (TR-08-11, page 109). This argument cannot be easily followed.

The longer a fracture, the more it deforms at a given loading at otherwise constant conditions. If a fracture is subject to shear stress, and the fracture extends, the shear displacement generated and leading to fracture extension will hardly snap back as the shear load is still acting on the fracture. This issue needs to be clarified before the argument by SKB can be accepted.

It needs to be explained, why it is conservative in the simulation of the effect of large earthquakes to neglect fracture propagation.

The stress concentrations at the tips of a fracture can be estimated by

$$K_I = (\sigma - P)\sqrt{\pi a} = \left\{\tfrac{1}{2}(SH + Sh) + \tfrac{1}{2}(SH - Sh)\cos 2\beta\right] - P\right\}\sqrt{\pi a}$$

$$K_{II} = (\tau - \tau_{frict})\sqrt{\pi a} = \left\{\tfrac{1}{2}(SH + Sh) + \tfrac{1}{2}(SH - Sh)\cos 2\beta\right] - \mu \cdot \left\{\tfrac{1}{2}(SH - Sh)\sin 2\beta\right] - P\right\}\right\}\sqrt{\pi a}$$

where σ is the acting normal stress, τ is the shear stress, τ_{frict} is the frictional resistance, P is the pore pressure, β is the angle with the S_h direction, μ is the friction coefficient, and a is the fracture half length (see Figure 4). Assuming the high stress model as given in Table 1 the resulting stress concentrations are given in Figure 5. At both stress models no fracturing should be assumed at the given stress fields. However, if some excavations are introduced, the thermal load is increased, and the fluid pressure increases during glaciation, the fracturing potential may be increased.

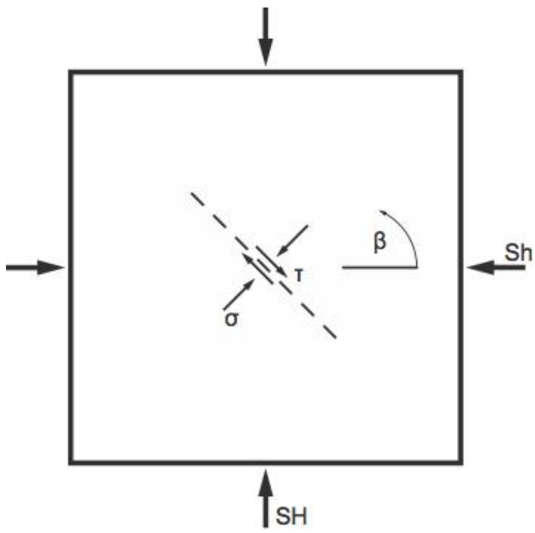

Figure 4. Notations for the determination of stress intensities.

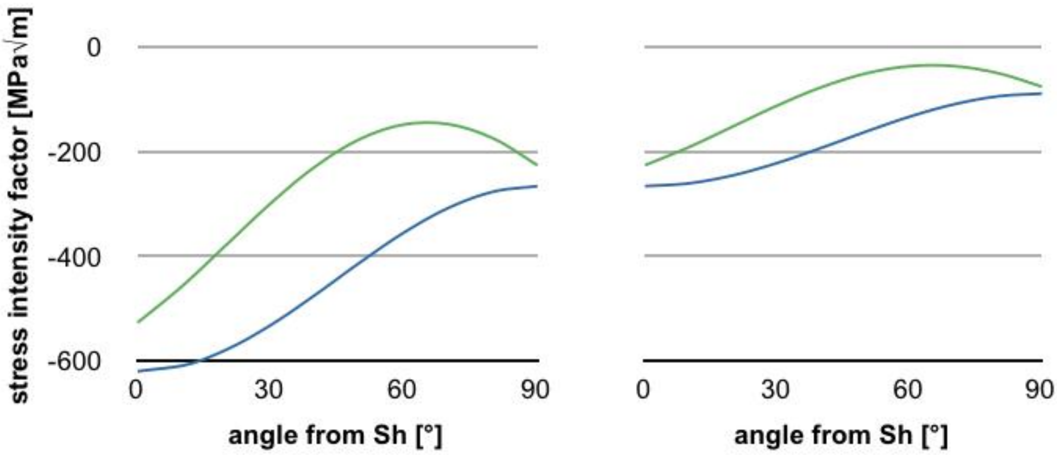

Figure 5. Stress intensity factor as a function of loading angle for (left) the high stress model and (right) the low stress model. SH = 40MPa, Sh = 20MPa, P = 5MPa, a = 100m, μ = 0.85. The values are negative at all orientations, meaning that the fractures can be assumed stable. Colour code: green - Mode II, blue - Mode I.

As an example, Figure 6 shows the influence of fluid pressure on the stress intensity factors for the low stress model. An increase of fluid pressure by ΔP = 3 MPa results in a maximum Mode II intensity of $K_{IImax} \approx 10$ MPa√m, which can be considered sufficient for fracture extension. As stated above, the possible increase during glaciation amounts to 26MPa, so taking ΔP = 3MPa at this point of the review shows the effects even a small increase of the pore pressure can result in, not speaking of the possible increase of 26MPa.

The response of the DFN to the typical loading history of a set of deposition holes in a repository was simulated using a fracture mechanics code by Backers and Stephansson (2011). This study clearly showed that the fracture network is potentially subject to fracture extension during selected phases of the stress changes in the history of a repository. The amount of fracture extension depends on the in situ stress model applied, but significant fracture extension may be expected for increased fluid pressures during glacial periods.

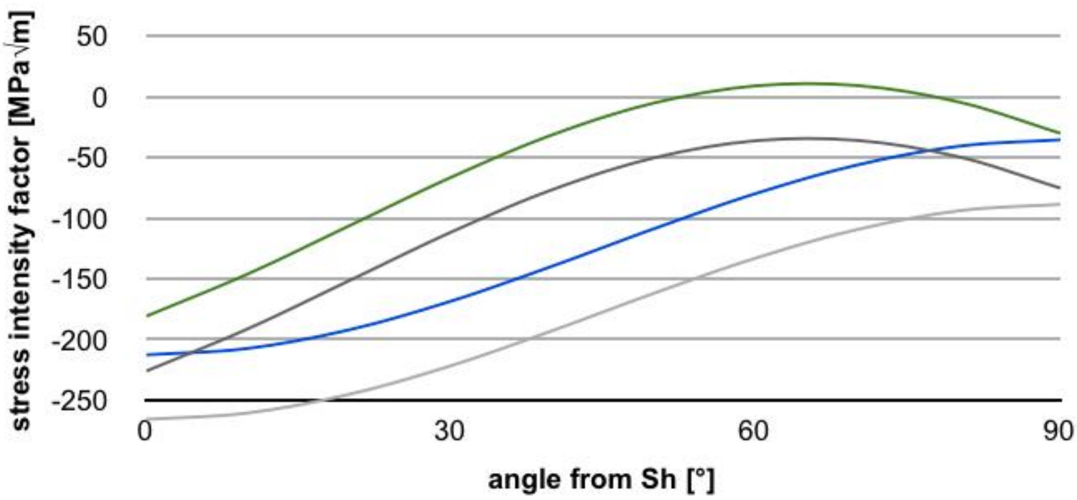

Figure 6. Stress intensity factor as a function of loading angle for the low stress model. SH = 20 MPa, Sh = 10 MPa, P = 5 MPa / 8 MPa, a = 100 m, μ = 0.85. An increase of pore pressure by ΔP = 3 MPa results in a maximum Mode II intensity of $K_{IImax} \approx 10$ MPa√m, which can be considered sufficient for fracture extension. Colour code: dark grey - Mode II, P = 5 MPa; light grey - Mode I, P = 5 MPa. green - Mode II, P = 8 MPa; blue - Mode I, P = 8 MPa.

It is suggested to analyse the fracture growth potential for the loading history of the repository. Some scenarios have been discussed already, but others like permafrost or tectonic loads remain unexamined.

SKB also assumes that time-dependent effects including subcritical fracture growth need not to be considered in the analysis of rock deformation (TR-11-01, page 336). The justification they take from a paper by Damjanac and Fairhust (2010), where it is concluded that „the threshold (for long term strength) is of the order of 40% of the unconfined compressive strength or higher for laboratory specimens under unconfined compressive loading, and increases rapidly in absolute value with confinement.“

Firstly, the study by Damjanac and Fairhurst considers Mode I (tensile) micro-fracturing only, which might be appropriate at ambient conditions, but is questionable at higher confining stresses, as Mode II/III (shear) micro-fracture growth becomes an issues (Backers et al 2002).

Secondly, they consider creep of rock material, which is different from subcritical fracture growth. Creep of rock material is generally the time-dependent deformation of rock, which may be linked to different mechanisms like twinning, dislocation, and time-dependent micro-fracture growth. In contrast, and this is of bigger concern in the context of the mechanical behaviour of fractures, time-dependent, i.e. subcritical, fracture growth is the slow extension of fractures under static loads. This hydrochemical process has been shown to exist for Mode I, Mode II, and Mode III loading (Atkinson 1984, Backers et al 2006, Ko and Kemeny 2011).

If the stress intensity at the fracture tip is below the critical threshold for rapid fracture extension, i.e. the fracture toughness, it was shown for different materials that a fracture will grow stable and slowly, and if the loading is reduced, the fracture stops. The higher the stress intensity is, the faster the fracture propagates. This can be described by Charles law as a linear relation in log-log space. Although continuously discussed for good reasons, a lower threshold was never experimentally determined. The velocity of fracture growth is amongst others dependent on humidity (higher humidity -> higher velocity), and temperature (higher temperature -> higher chemical activity -> higher velocity).

It can be assumed that today the DFN is more or less stable, hence that there is no or little subcritical fracture extension. However, during times of increased loading and increased temperatures, which will go hand in hand in the KBS-3 concept, a possibly existing lower threshold for subcritical fracture growth may be exceeded and some fractures in the DFN might propagate and connect to others. This will be in particularly true for fractures close to deposition holes, where the stresses are increased due to the redistribution and heating from the canisters. Kemeny (2005) showed that time-dependent failure of rock bridges is an important issue close to excavations.

The longer a fracture the higher the stress concentration at the fracture tip. Therefore, long fractures are more prone to subcritical extension, which could lead to connection of fractures and intersection with deposition holes, meaning that the critical radii defined for dismissal of deposition holes may be exceeded. Also, if the fractures have grown to a certain length, they may be prone to critical, i.e. rapid extension, at increased loading.

It is suggested that the potential for subcritical fracture growth is determined and the implications are evaluated.

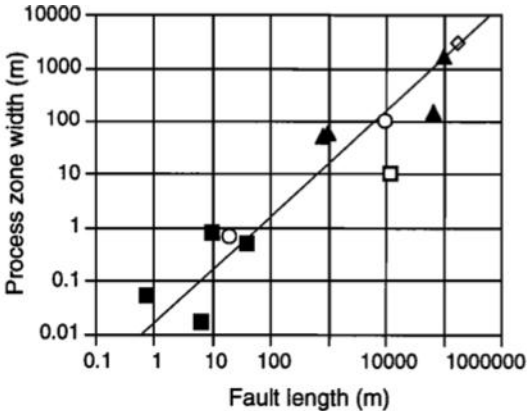

Figure 7. Process zone width versus fault length. (Vermilye and Scholz 1998, Figure 15).

The relevant parameters for the analysis of fracture extension can be determined by laboratory experiments (e.g. ISRM SM for the determination of Mode I fracture toughness, 1988; ISRM SM for the determination of Mode II fracture toughness, 2012). For Äspö rock fracture toughness is reported in Backers and Stephansson (2008) and the subcritical fracture growth parameters are presented in Backers et al (2006).

The respect distance concept proposed by SKB suggests, that no deposition hole may be placed closer than 100m to a deformation zone, i.e. away from the core of the fault. The major deformation zones around the Forsmark target area are >30km, i.e. Singö, Eckarfjärden and Forsmark deformation zone. Vermilye and Scholz (1998) showed that there is a linear scaling between the process zone width and the length of the associated fault (16:1,000) (see Figure 7). According to that regression the process zone width would be about 480m, i.e. >100m for those fault lengths. The distances proposed in the respect distance concept seem to be applied to the repository layout (cf. Figure 8).

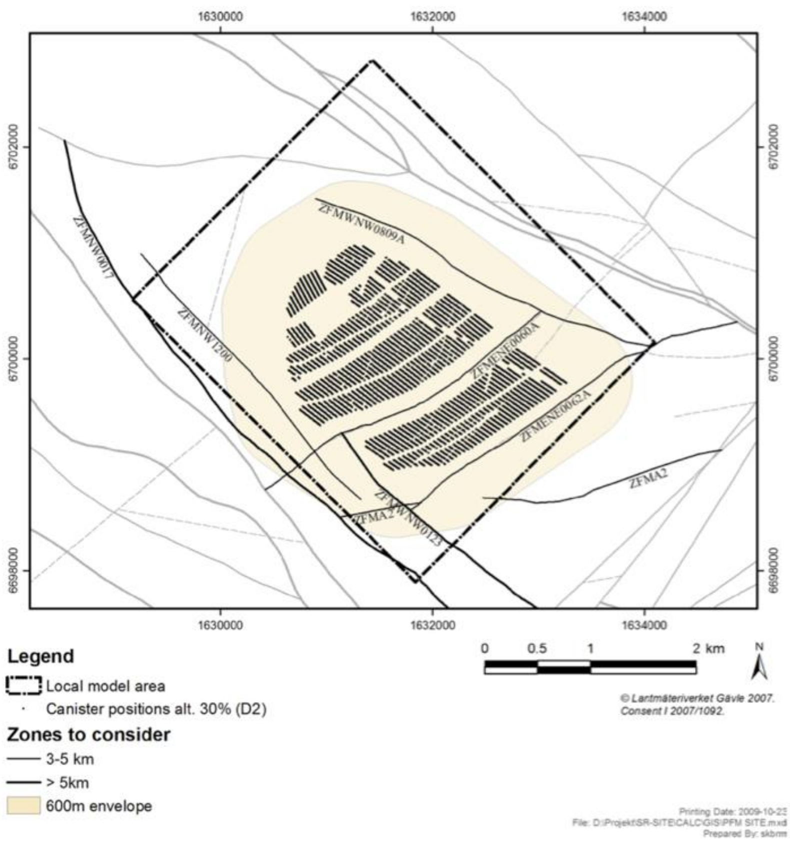

Figure 8. Deformation Zones and repository layout (from TR-10-21, page 65, Fig. 7-2).

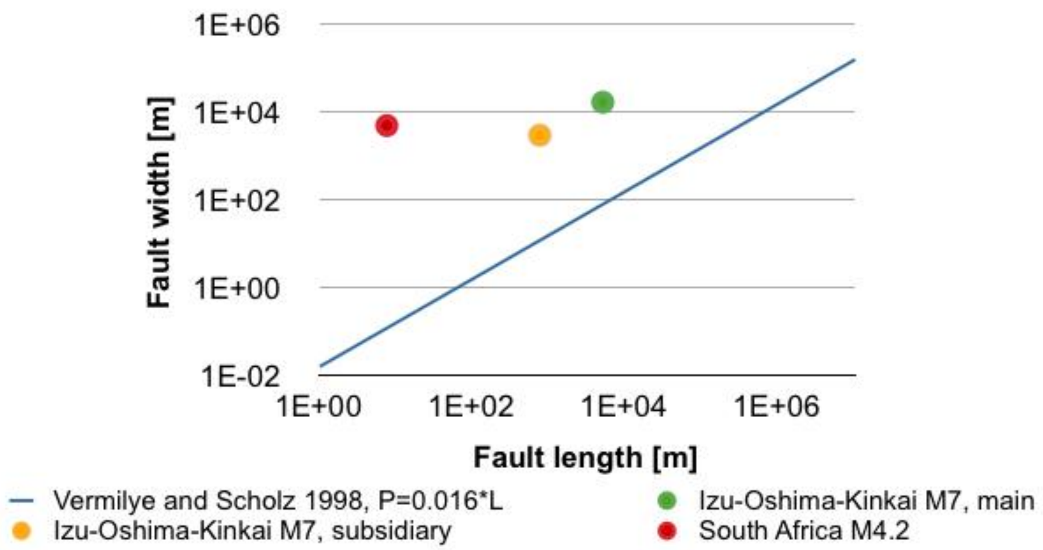

Figure 9. Fault width vs. fault length data from the report plotted with the regression from Vermilye and Scholz (1998) (from a review report for SSM by Backers 2010).

For the deformation zones in the repository volume the lengths are reported to be around >5km. The Vermilye and Scholz (op. cit.) relation predicts process zone widths of about <100m. Therefore, the respect distance criterion seems sensible.

However, in an earlier review of Bäckblom and Munier (2002, TR-02-24), Backers (2010) commented that the scatter in the fault zone width is enormous, and that it has to be confirmed that the relation is observable in Sweden if it is used for the definition of the respect distance. Figure 9 shows some of the data from Bäckblom and Munier's report in the context of Vermilye and Scholz data, giving rise to the discussion if such a plot should be established for Fennoscandia.

However, the data on trace length vs deformation zone thickness for the fracture zones at Forsmark suggest that the approach is sensible as the fracture zones show consistently more narrow process zone widths than predicted by the Vermilye and Scholz regression (see Figure 10).

The respect distance criterion also assumes static fault systems, and the distance definition is applied to the direction perpendicular to the fault trace only. However, in front of a fracture (zone), there exists a quite large area of stress redistribution and concentration. Depending on the magnitude of the stress concentration, existing fractures may be activated and even coalesce to form new fault surface. This is also valid if a long fault terminates at another one. At the t-junction on loading a stress concentration will exist, that may lead to fracturing, if the load is changed, as it may be the case during the complex loading history of such a repository.

Figure 11 shows the large fractures zones in the repository volume. ZFMWNW0123 terminates at ZFMENE006A. Ahead of the termination junction the placement of deposition holes is planned (see Figure 8). As discussed in the paragraph before, the fracture may continue to grow NW of ZFMENE006A if the loading situation changes. The fracture network as evident in Forsmark shows various cases of intersecting fracture zones, hence this is an issue and needs to be considered. For example ZFMWNW0123 crosses ZFMA2 or ZFMNW1200 crosses ZFMENE0060A.

This needs to be considered and possible scenarios need to be evaluated.

It is suggested to analyse the effect of the complex stress path history of the repository on the fracture zones and their interaction and propagation potential in the repository area.

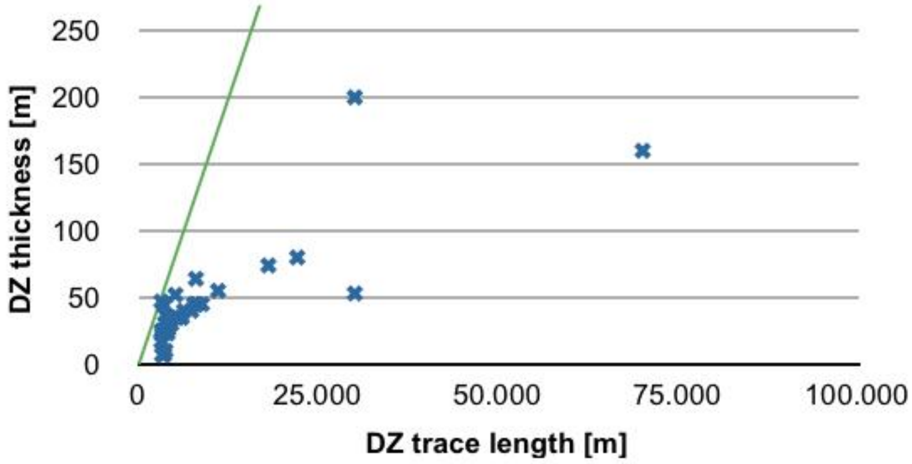

Figure 10. Data from Table 10-15, TR-11-01, page 470, in combination with the Vermilye and Scholz (1998) regression (green line). The measured data shows consistently smaller DZ thickness compared to the regression.

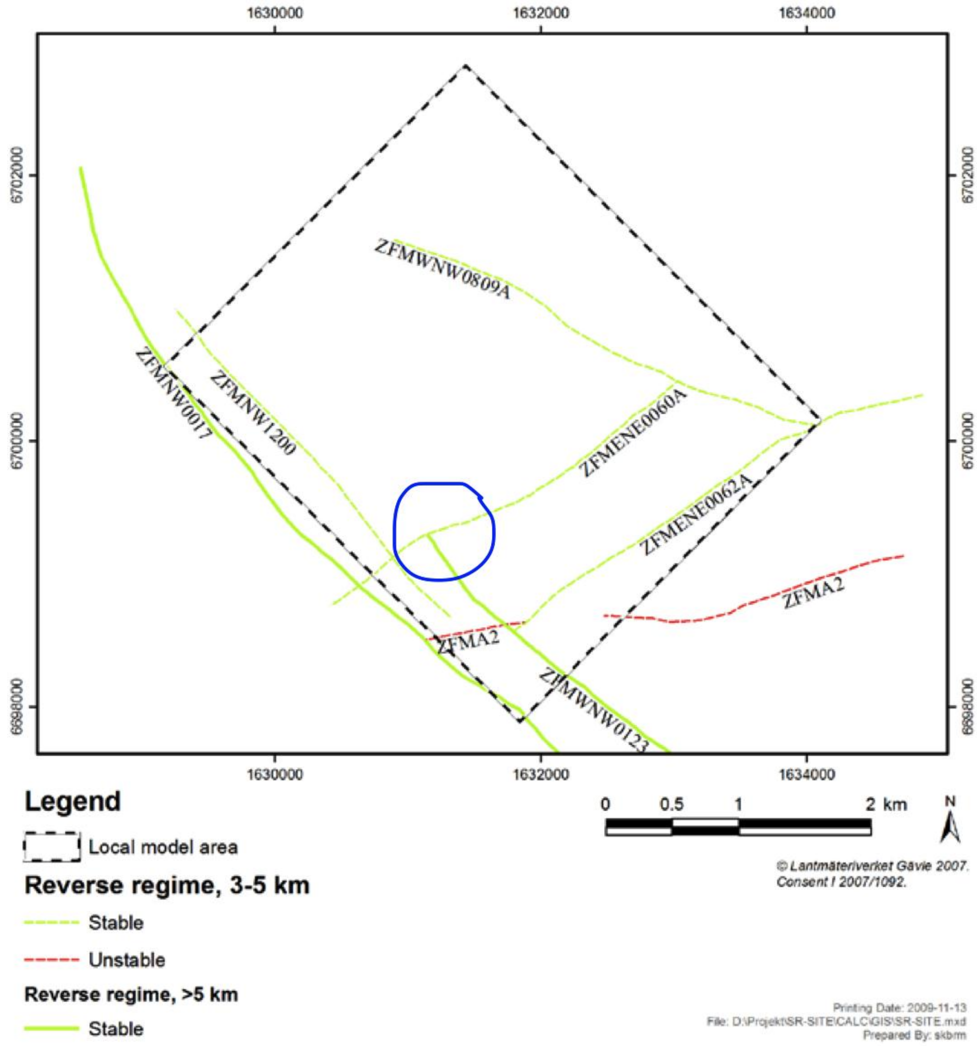

Figure 11. Fracture zone geometry (from TR-10-21, page 66, Figure 7-3 (b)). The blue circle highlights the junction of fractures that needs further consideration.

3.3. Simulation of the response of fractures to large earthquakes

The simulation of the response of fractures to large earthquakes is mainly reported in TR-08-11. The following discussion is mainly referred to that report.

The report summarises simulation results of a 3DEC campaign in which a host fault (primary fault) slips and generates dynamic motion that acts on target fractures. The target fractures strike parallel to the host fault and varying inclinations. The report gives a very good introduction to the issue, however, it assumes some simplifications that need to be commented.

The simulations were in principle carried out with one code only. This bares the risk that possible interactions and systematic errors are overlooked due to the limitation to one methodology and model approach. Therefore, some comparison simulations employing a different numerical approach as well as variation of some of the conceptual models would be beneficial to gain confidence in the most critical results. It was only one approach used to analyse a process that is not well understood, which may lead to uncertain/questionable results.

It is suggested to do example calculations with at least one alternative code to check the model validity used in the earthquake study.

In general the comments to the simulation of the response of target fractures to seismic slip generated on a primary fault can be grouped into four main groups:

- *validity of the seismic source motion,*
- *limitation to static fractures, i.e. no fracture propagation,*
- *limitation to target fracture orientations that strike parallel with the primary fault,*
- *stress conditions including contrasting pore pressure assumptions.*

3.3.1. Seismic source motion

The applied seismic boundary conditions do not compare well to measured events. It should be made sure that the boundary conditions are more realistic, e.g. tuning the ground motion, using a code that can have a pre-inscribed dynamic motion, etc. Figure 12 shows that most of the simulations carried out do not compare well with real earthquakes, that are displayed by white boxes with arrows. Some justification by SKB is given, trying to proof that the results are conservative, but a better representation of source motion would be beneficial to gain confidence in the results.

It is suggested to revisit the issue of fault motion generation to get more realistic scenarios for the simulations.

3.3.2. Stress field and pore pressure

One of the major outcome of the EQ study is that the stress field is of major importance to the simulation results (page 79, TR-08-11). However, all analyses have been performed for a reverse stress field only, and hence, if the type of stress model changes, the results of the study need reinterpretation.

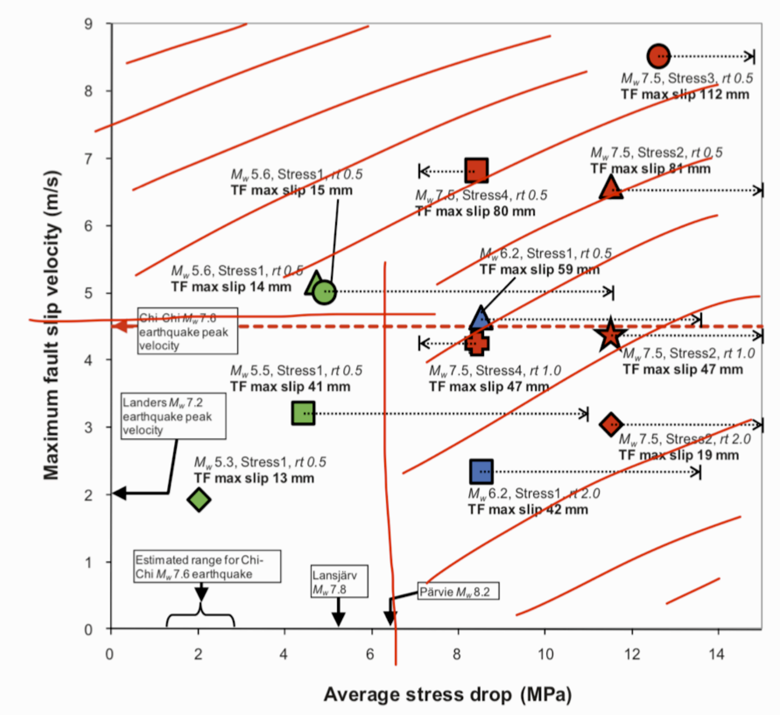

Figure 12. Stress drop versus slip velocity (from p99, TR-08-11). Most of the simulation cases fall out of the reasonable regimes, as indicated by the red sketching.

Depending on the initial loading on the target fractures the seismic motion may lead to quite different shear deformation. This becomes very clear when consulting Figure 5-13, page 72, TR-08-11. If the initial loading is different, as it is for varying depth levels in the analysis of stresses on the target fractures due to seismic motion, the amount of instability is quite different. The stress field model used is assumed to be quite similar to the high stress model as discussed earlier in this review, however, the low stress model might give considerably larger shear displacements with obvious implications for the acceptable target fracture lengths.

It is suggested to repeat the analysis for the different realistic stress field scenarios.

The pore pressures are inconsistent between SR Site and the EQ report. Whereas the earthquake simulations presume a constant and static increase in pore pressure of 1 MPa due to an ice cover post-glacial, in SR Site a pore pressure increase of about 26 MPa is assumed for the end of the glaciation. It (a) needs to be clarified how the pore pressure assumptions are to be understood, and (b) why the more conservative high fluid pressure assumption is not used in the simulation of the impact of post glacial seismicity.

What are the pore pressures to be expected at the end of the glaciation and directly after the glaciation when the large earthquakes could happen?

Why is a static constant low pore pressure increase used in the simulation of the impact of seismicity on target fractures, instead of discussing the more conservative high pore pressure increase?

If fractions of such a high fluid pressure would get trapped, e.g. below a permafrost zone, the effective normal loads on fractures would be close to zero (see stress model and fracture propagation discussions also) and hence shear displacements would be much larger.

No poroelastic effects were presumed in the simulations. The applied fluid pressure (or pore pressure) was kept static at 1MPa. It is well known that changes in stress lead to a change in pore pressure in porous media. If the system can be modelled undrained, like a fracture under dynamic loading, the changes in fluid pressure need to be considered.

It is suggested to determine the effect of dynamic loading on fluid pressure on target fractures.

3.3.3. Fracture propagation

As is generally the case in all analyses by SKB, fracture extension has not been considered in the simulation of the influence of large earthquake on the target fractures. But as can be seen from the analysis of the stress evolution on target fractures (Figure 5-13, page 72, TR-08-11) there is a considerable seismic impact on the stresses acting on fractures. Such a dynamic loading can lead to fracture extension and needs to be considered. The arguments for such an analysis have been delivered already in the previous discussion. If a fracture propagates due to a large earthquake and then intersect a deposition hole, it not only changes the potential fluid pathways, but also in a second seismic event it could result in exaggerated displacements.

From Figure 5-13a (TR-08-11, page 72) the maximum instability is at an early stage of the seismic impact and the stresses are roughly τ = 15 MPa and σ = 0 MPa. The fracture half length is a = 150 m and the stress concentration at the tip of the almost purely shear loaded fracture is

$$K_I = \sigma \cdot \sqrt{\pi a} \approx 0MPa \cdot \sqrt{\pi \cdot 150m} = 0MPa\sqrt{m}$$
$$K_{II} = \tau \cdot \sqrt{\pi a} \approx 15MPa \cdot \sqrt{\pi \cdot 150m} = 325MPa\sqrt{m}$$

A stress concentration of more than 325 MPa√m is sufficient to initiate fracture extension; the dynamic Mode II fracture toughness for granitic rocks is estimated to be in the region of about 25 - 30 MPa√m (cf. Zhang et al 2000).

It is suggested to analyse the potential for dynamic fracture extension due to an earthquake.

One aspect not considered at all in the analysis is the resulting slip of an earthquake on one of the major deformation zones on e.g. ZFMWNW0123. In the analysis of the impact of large earthquakes on target fractures the target fracture size was kept constant at 150m half length, and a linear scaling of the displacement with length was assumed (see the specific comments to the report for additional discussion). This would mean that potentially the slip on the before mentioned fracture zone would be several decimetres. This could potentially lead to the jump of the fracture zone ZFMENE0123 over ZFMENE0060A with implications for the planned deposition holes ahead of ZFMENE0123 (cf. Figure 11).

It is suggested to analyse the impact of a large earthquake on the fracture zones and the implications for repository layout.

3.3.4. Target fracture orientation

Only target fracture orientations that strike parallel to the host fault were considered in the analysis. It appears important that also other orientations of the target fractures with strikes oblique to the host fault are considered. As can be seen e.g. in Figure 5-13, page 72, TR-08-11, the resulting stresses and hence displacements strongly depend on the orientation. However, no analysis or discussion of oblique orientations has been carried out; this should be done to exclude the possibility of larger shear displacements on other than parallel striking fractures.

Why have no oblique striking fractures been considered in TR-08-11?

It is suggested to analyse other than parallel striking target fractures.

3.4. Additional general comments

3.4.1. Induced seismicity

Not only can a large earthquake trigger slip motion on target fractures, but also can changes in the repository volume trigger seismicity.

The probably most pronounced change in the course of the repository history is the increase of temperature in the repository. This will result in a local volume expansion in the repository body, resulting in an increase of stresses in that region, but also potentially increase the stresses in a larger volume around the repository.

In a recent study by Yoon, Backers and Dresen (2012) the hydraulic stimulation of reservoir fracture networks has been studied. It could be shown that not necessarily the augmentation of pore pressure is the trigger for seismic events, but the elastic response of the rock mass due to the injection of fluid is enough to trigger large magnitude events well outside the zone of increased pore pressure with some considerable time delay.

Transferring the result by Yoon et al (op. cit.) to the repository scenario at hand gives rise to the assumption that the volume enlargement in the repository due to heating may lead to a response on the large deformation zone in the area, that is solely elastically. It should be considered to analyse if such a mechanism may lead to triggering an earthquake in the deformation zones.

It is suggested to perform an analysis studying the influence of the thermally induced volume increase on the large deformation zones surrounding the repository compartment.

It is suggested to discuss the mechanism of elastic trigging of earthquakes and the possible resulting magnitudes with a seismologist.

Such a mechanism may also have some implications for smaller seismic events and rock burst during the operational phase of the repository. While some parts have been decommissioned already and the generated heat leads to volume expansion, other regions are subject to construction work. It should be analysed if this could be an issue for workers safety.

3.4.2. Permafrost

It is stated that the permafrost will not reach down to the repository to that extend, that the buffer will freeze and loose its integrity. However, the water freezing in the permafrost zone, irrespective of how deep it reaches down, will result in an increase of volume, and hence may result in ground heave and stress field changes. This could cause an extensive opening of fractures and probably fracture extension. During the melting of the water locally excess pore pressure may result in larger fracture displacements during seismic impact. Any influence of this kind on the DFN has not been discussed in the reviewed reports.

What will be the influence of the freezing water in the fractures during and after a permafrost period on the integrity of the repository and DFN?

4. Specific comments to individual reports

In the following specific comments to specific sections will be given with reference to the page the statements commented can be found. As the reviewed reports cite each other to some extend the descriptions and arguments repeat several times; not necessarily each repetition is commented upon.

4.1. Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. TR-08-05.

comments to 3. Evolutionary aspects of the Forsmark site

The section contained valuable background information that helped understanding the setting.

comments to 4. Surface system and surface-bedrock interactions

The information on the surface system was not of interest for the assignment.

comments to 5. Bedrock geology

page 134, second paragraph. The bedrock is described as anisotropic at Forsmark in the conceptual model (see page 139 also). This interferes with the assumptions made in the data report, TR-10-52, page 265, where the rock mass is assumed to be mechanical isotropic. This issue needs clarification and discussion of the impact of the simplifications on the outcome of all simulations.

Clarification of the contrasting assumptions about rock anisotropy in TR-10-52, p265, and TR-08-05, page 134, needed.

comments to 7. Rock mechanics

page 216. The reasoning for omitting the hydraulic stress data is given. This was commented upon in the general discussion.

page 218, third paragraph. The tensile strength data gives no indication for anisotropy. This is in contrast to other statements like e.g. in chapter 5 of the report, where the rock is considered anisotropic.

section 7.3.4 In situ stress state. The issue about the stress stated has been discussed already, it appears interesting to review Glamheden et al 2007a for a better understanding of the stress model.

It is suggested to review the report by Glamheden et al. 2007a.

comments to 11. Current understanding of the site

No additional comments that have not been addressed before.

4.2. Data report for the safety assessment SR-Site. TR-10-52.

comments to 6.2 Bedrock thermal properties

The section turned out to contain no relevant information to the review assignment.

comments to 6.3 Discrete-Fracture Network (DFN) models

page 234. Is also the genesis of the fractures and the relative history incorporated in the modelling? If the sequence of fracturing is not realistically included in the model, it may be that fractures intersect each other, that would not do so in reality. This would have impact on the fluid flow simulations as well as on mechanical aspects like fracture network extension. The effect may not be as significant for granitic rocks as it is for sedimentary, but the implications should be discussed. Potentially a structural geologist should be consulted. Figure 13 gives an illustration of the argument.

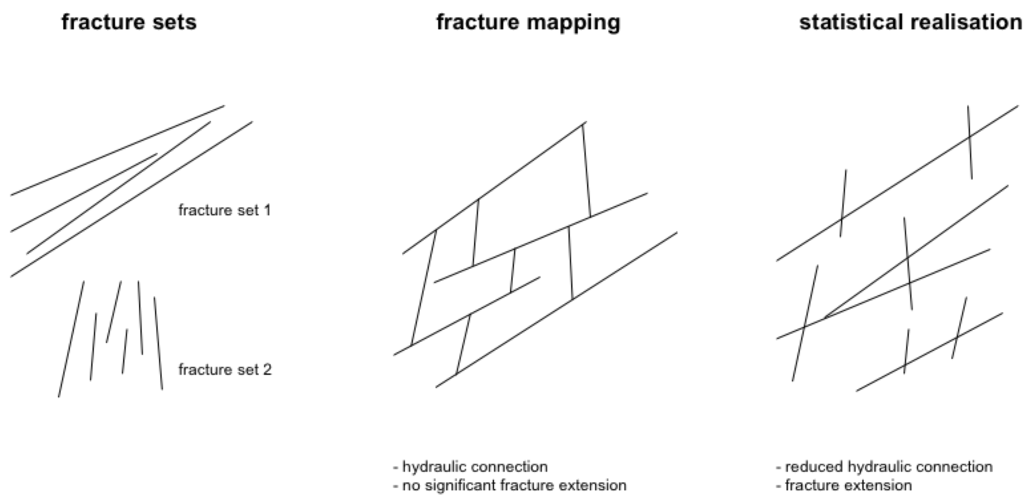

Figure 13. DFN genesis. From fracture mapping two fracture sets were identified, that may give a statistical realisation that is not capable of mirroring all aspects of the mechanical and hydraulic attributes.

comments to 6.4. Rock mechanics

page 258. In 6.4.1 it is defined what parameters should be delivered by the supplier. However, it is not defined according to which standards the parameters should be determined. As most of the parameters depend on boundary conditions it is most important that all measurements of one kind are done constantly with specified procedures. No indication of or reference to such specifications is given.

page 260, Sensitivity to assessment results in SR-Can. It is stated that in situ stresses are most important. This is absolutely true. However, the stress field is not really understood at Forsmark, as is discussed in a separate section in the main review findings (section 3.1).

page 261. Most of the simulation results in SR-Can and SR-Site were produced using 3DEC. In the data report (or any other report that was reviewed) any argument why the code was chosen is missing and also no crosscheck with results from other codes was done. This very limited approach prevented the usage and interpretation of alternative models. It is advisable to use an alternative approach to check on selected cases for validation.

page 265, Deformation properties of rock mass, third bullet. It is assumed for any mechanical analysis that the rock mass is isotropic. It is not clear where this conclusion comes from. To judge this, the report by Glamheden et al. 2007 needs to be analysed. The assumption of isotropy is a massive simplification and may have significant impact on mechanical analyses. As e.g. the ductile features of the bedrock in rock domain RFM029 (SDM page 137, Fig. 5-25) shows distinct preferred orientations and it is stated on page 139, SDM, that the ductile deformation between 1.87 and 1.85 Ga at Forsmark contributed to the development of strong bedrock anisotropy at the site, the assumption and application of isotropy needs extended justification.

The report by Glamheden et al. 2007, where the rock mass is discussed, needs review.

page 265, In situ stresses, first bullet. It is stated, that the results from the hydraulic fracturing and HTPF methods were not used to model the stress field, and that this results in a more cautious estimate of the stress model. This statement is not supported by any argument. The given reference (SDM Section 6.4.7.) does not exist. However, in SDM 7.2.4. and on page 277 of the data report (see below) it is stated that it is suspected that the hydraulic data measured the vertical stress. No more qualified discussion is given. A more thorough discussion of the stress field is presented in a separate section of this report (section 3.1).

page 273, In situ stress. It is stated that a considerable amount of scatter is in the measured stress magnitudes, due to thermal strains in the over-coring process, meaning that the measurements are of poor quality. Values for uncertainties are estimated to be up to 25%. It is not clear /a/ if the poor data was used for the estimate of the stress field, or /b/ how the uncertainty is accounted for in the stress model.

page 277, In situ stresses. It is stated that the hydraulic stress data were not used, /a/ as it is suspected that the vertical stress was measured instead of the minimum horizontal stress, and /b/ that the results contradict the general trend for Fennoscandia. This results in a higher and according to the report a more conservative stress model. There is no argument given, why the stress model is more conservative, if the stresses are higher. If the stresses are higher, there is a larger potential for spalling and other compressive failure. However, if the in situ stresses are low, an increase in pore pressure can result in hydraulic fracturing. An increase in pore pressure is likely for the end of glaciations and therefore a high stress scenario is not per se conservative. For a broader discussion of potential implications of a low in situ stress field scenario refer to Backers and Stephansson (2011).

Further, as the repository is planned in a compartment that is surrounded by fault zones, there is a possibility that locally the stresses are different from the general trend. This needs a much more comprehensive discussion. The argument, that the data is discarded, as it does not fit into the other data, is not really convincing and needs a more distinct evaluation.

A more comprehensive discussion of the assumptions for the stress field model is needed.

page 293, Figure 6-48. The figure is the same as Figure 7-18 in SDM and is discussed there. The figures seem to be identical.

4.3. Effects of large earthquakes on a KBS-3 repository. TR-08-11.

page 16. It is stated on the changes in hydraulic conditions, that „the shaking and the stress redistribution generated by an earthquake will propagate, shear, close and dilate fractures in the host rock. The extent of these deformations will depend upon the size, location and orientation of the individual fractures in relation to each other and to the earthquake generating fault. It will also depend on the fracture properties, on the in situ stress situation and on the character of the earthquake. Some of these deformations will be permanent and result in increased or reduced transmissivities, depending on whether the fracture closed or opened in response to the earthquake, and on whether shear displacements took place under low or high normal stresses /Hökmark et al. 2010/.“ This statement is absolutely true from a geomechanics point of view, and although determined with such clearness fracture growth and related implications were not considered any further.

Why was the extension of fractures not considered in the dynamic simulation of the impact of large earthquakes, although it was clearly stated that SKB realised that it is an important issue?

page 36, 4.4.2, Target fracture. The target fractures are represented by circular perfect planar discs. It is argued that the perfect shape results in larger simulated displacements, as irregularities may restrain shear movements. This is true to some extend, if it is assumed that the fractures do not extend. However, if the outer shape of the fractures were modelled irregular (i.e. the fracture tip), this may lead to fracture growth, and hence increased displacements as displacement scales with fracture length.

page 40, Table 4-1. Table 4-1 summarises the material properties used for the study. What is the influence of variations of the parameters on the results? Has a sensitivity study been performed? What if the parameters were modelled depth sensitive? With depth most of the parameters change. This has not been considered in the simulations. What would be the effect of such a variation of parameters with depth? If e.g. the Young‘s modulus would increase with depth, the resulting strains from a dynamic loading would be different, and hence the displacements on the target fractures might be different.

Have the parameters in Table 4-1 been varied in some simulations to show the effect on the target fracture displacements?

What would be the effect if the parameters in the simulations were depth dependent?

page 45, Initial stresses, second paragraph. The convention about the y-axis in Figure 4-8 and the text are different. It needs to be clarified if this is just a typo or if the interpretations of some results show wrong orientations.

page 47. It is stated that the maximum residual excess pore pressure is about 1 MPa. This contradicts to some extent the statement in TR-11-01, page 441, that the additional hydrostatic pore pressure related to the maximum thickness of ice at Forsmark is about 26 MPa. This might have severe impact on the simulations of the influence of earthquakes on target fractures. In addition, Figure 4-11 shows the Mohr circle representation of the target fractures in relation to the failure envelope. The fractures with a dip of 30° are almost unstable (margin 0.1 MPa), hence an increase of pore pressure by 25 MPa would cause instability.

The pore pressure assumptions in the simulation of the impact of large earthquakes needs clarification, as the reference glacial cycle uses a maximum increase in pore pressure of 26 MPa compared to a 1 MPa assumption in the simulations.

page 48, 4.9.5 boundary conditions. It is stated that if models are too small, it results in overestimated shear displacements. The statement is not supported in any means; it would be good to know if some tuning of the model size has been performed.

Has the size of the models in the EQ simulations been optimised for boundary effects?

page 53. The stress field assumptions need more justification. It does not become clear if the stress field model for the repository depth is used. Further, in the repository the presence of the excavations, which are soft inclusions, will alter the stress state and hence the target fractures will be partially exceeding their strength (cf. Figure 4-11).

As it reads from the report, the locally increased stresses in the repository due to the presence of the excavations have not been modelled, although an increase in local stresses will result in fracture slip pre-seismic. This needs confirmation and discussion of the implications.

page 63, Figure 5-4. The figure needs some explanation. After initiation of the rupture the slip starts first at the closest distance from the rupture initiation point, and increasingly later at more distal points. However, the maximum of shear displacement seems to reach the most distal point first; this is counterintuitive and needs justification.

Why is in Figure 5-4 (TR-08-11) the maximum slip at first at the most distal points?

page 66, Figure 5-7. Towards the bottom of the model, i.e. with increasing depth, the discretisation density is reduced. Does that have an influence on the simulations?

page 72, Figure 5-13. The figure shows the simulated stress histories on six hypothetical fractures at different orientations with the primary fault. The simulated stress evolution is compared to a Coulomb failure criterion and the times of instability are indicated. The results are very instructive, and it would be also very interesting to see the results represented in that way for different relaxation times. Some observations are not discussed in the text, but might help to understand the implications of the results.

(a) a fracture with the same orientation with respects to the primary fault shows less instability if it is located at a larger depth. This compares well to the observation that underground constructions are less prone to damage with increasing depth (compare SKB TR-02-24). It seems to be important that the ground motion is correctly modelled, but this was not shown in the results or discussed.

It is suggested to run comparative simulations where the ground motion is calibrated or superimposed with an alternative code to get more realistic stress and displacement response on the target fractures.

(b) horizontal fractures show much severe permanent stress changes than inclined ones. The observation should be discussed for the sub-horizontal fractures in FM002, which is close to the surface (so (a) applies also) and horizontal. Hence, a post glacial seismic event could massively affect the hydraulic conductivity of that zone.

(c) the stresses computed for the target fractures can be directly used to calculate the potential for fracture extension. As presented in the main discussion, a further rough analysis of plot (a) yields an argument for the consideration of fracture extension.

page 79, last paragraph. The stress field is stated to be of significant influence. Hence any conclusion from the report makes only sense if the stress field assumptions are justified.

page 81, third bullet. The argument does not become clear and needs a better explanation.

page 81, Figure 5-21. The data points in (a) and (b) seem to be somehow different. This is most obvious at low fault slip velocities. What is the implications on the interpretation after correcting the wrong data representation and regressions.

Why is the data is Figure 5-21, TR-08-11, different in (a) and (b) although it is indicated the same dataset is represented?

page 84, fifth paragraph. Has the mesh been calibrated for this analysis?

page 93. The model by Eshelby 1957 is valid for static shear loading of a planar fracture. The formulation basically scales the displacement linearly with the loading. The relation is brought forward in SKB‘s argumentation line that displacements and velocities both scale linearly with fracture length. Four simulations with two fracture lengths were performed. At doubled fracture length the resulting displacement is doubled.

The argumentation is really weak.

(a) two points can always be represented by a linear relation and the factor two might be a coincidence or model artefact. Minimum three points would make a case.

(b) it would have been instructive to compare the simulation results with the analytical solution. This would give some confidence in the approach, which employs an analytical solution for static displacements to predict dynamic slip.

(c) the model has been compared to the distribution of displacements along the trace of the fracture and fails to do so, hence there should be some scepticism about the applicability.

(d) it is not clear what the relation of Eshelby has to do with the velocity, but is stressed to deliver an argument for a linear relationship.

What is the justification for using Eshelby‘s formulations for predicting displacements and velocities of target fractures of different length?

page 95, first paragraph. The assumption of a pore pressure increase of 1 MPa (20%) resulted in an increase of maximum induced slip of 10% (Table 5-4). Therefore two issues should be considered that have not been analysed:

(a) the seismic waves will change the stresses locally on the rock matrix and hence the fluid pressure might change due to the poro-/fractureelastic response.

(b) the increased pore pressure which is discussed for the end of glacial periods in the reference scenario needs to be considered, as (1) it is potentially higher than the acting stresses in the rock mass and might directly lead to hydraulic fracturing, and (b) it is 520% higher which could result in 260% higher slip, (i.e. 26 cm instead of 5 cm) if one extends the usage of the Eshelby linear scaling relation.

The poroelastic/fractureelastic response needs to be considered to be able to judge the maximum slip on the target fractures.

The fluid pressure as defined in the reference glacial cycle needs to be accounted for in the earthquake simulations.

page 98 following. Figure 6.2 summarises all simulations in maximum fault slip velocity vs. average stress drop space. Most of the simulations show higher fault slip velocities and average stress drops than comparable measured events. This needs proper explanation. The argument brought forward is that, as the numerical simulations have shown that the slip velocity is directly linked to the target fracture displacement, the results are conservative. This appears logical. However, it would be beneficial if it would be possible to get the stress drop, the fault slip velocity and also the ground motion correct. As the ground motion is compared and judged to be in good agreement with measurements (page 105, needs review by an expert on that for verification) the question arises why the source fault movements are not.

Why is the ground motion comparable to field measurements, whereas neither the maximum fault slip velocity nor the average stress drop is?

page 107, section 6.6, Pore pressure. It is stated that pore pressure on faults may increase by about 20MPa, presumably by dynamic shear effects. However, on the target fractures no such effect is assumed, as the target fractures are several hundred meters away. The arguments are not straight forward and need justification for two reasons: (a) pore pressure pulses can travel considerably if there is a hydraulic connection, and with the little stability margins assumed for the target fractures this may lead to increased slip, and (b) if slip on the primary fault produces pore pressure peaks, why should there be no change in fluid pressure on the target fractures that slip?

Why is a potential pore pressure pulse on target fractures not assumed in the simulation of the impact of large earthquakes?

page 107, last paragraph. It is stated that „ignoring pore pressure variations is (...) conservative“. This statement is absolutely not clear and needs justification. A pore pressure increase, by whatever mechanism, will considerably reduce stability on fractures, magnify slip, and increase the potential for fracture propagation.

Further it is stated, that „the influence of the fixed 1 MPa pore pressure (...) was found to be modest“. This contradicts the statement on page 95, first paragraph and Table 5-4, that the assumption of a pore pressure increase of 1 MPa (20%) resulted in an increase of maximum induced slip of 10%. This is quite pronounced, especially in the light of the questions about the stress field model.

Why is it conservative to ignore pore pressure variations in the context of simulating the impact of earthquakes on target fractures?

page 109, section 6.8, Fracture propagation. The argumentation why ignoring fracture propagation is conservative needs justification. Not only scales the slip on fractures with their length (Eshelby), but also coalescence of fractures lead to increased slip if hit by a second event and create extensive potential fluid pathways.

Why is it conservative if fracture propagation is ignored?

page 114, Target fractures. The conclusion that both the shear displacement as well as the shear velocity scale linearly with fracture length is not well supported and is only valid for static conditions. This needs clarification as discussed in earlier review comments.

page 115, end of fourth paragraph. It is concluded that „the induced fracture shear displacements may be viewed as overestimates of the potential seismic response, and are therefore conservative“. This statement may be considered valid in the light of the made assumptions for the numerical simulations. However, as fracture extension was not considered at all the statement needs some additional disclaimer.

The implications of the omitting of fracture propagation needs to be discussed for the induced shear displacements on target fractures.

page 115, last paragraph. As discussed before the pore pressure has a quite pronounced influence on the shear displacements on target fractures. A 10% increase in slip can be assumed to result in a significant increase in stress concentration at a fracture tip and hence the potential for fracture extension.

page 117, Table 7-1. The maximum reported slip on page 75, Figure 5-16 is >50mm, this is not reflected by the table. It needs to be explained why the data reduction was performed. What is the implication of this?

Why was the data base of Fig. 5-16 TR-08-11 reduced for the final conclusions?

page 118, Figure 7-1. It does not become clear how the simulation results were transferred into the linear regressions, therefore the implications cannot be judged. It appears that for the M7.5 models the regressions are underestimating the slip.

How was the regression analysis for Figure 7-1 TR-08-11 performed?

page 119, equation 7-1. Valid only if the validity of the linear scaling is proven. See comments above.

Chapter 7. The whole chapter goes much further than the analysis of the target fracture response to large earthquakes. It discusses broader topics like fault stability and stress field assumptions. This is done very condensed. It would be beneficial if such a discussion would be done in a separate report with a proper discussion of all implications and facets.

page 130, second paragraph. It is stated without referring to the database properly that the coefficient of friction is 0.78. It needs a broader discussion and justification. A reference to the work by Byerlee should be included. Further, with depth the coefficient of friction will be lower (about 0.6) depending on the normal stress. What would the implication on fault stability be?

The determination of the valid coefficient of friction in TR-08-11 Chapter 7 does not become clear and needs explanation.

The coefficient of friction should be lower at larger depths. Why has this not been accounted for in the analysis of fault stability?

page 138, sixth bullet. It is stated that the assumption of steeply dipping fractures is conservative, as they give larger slip than gently dipping fractures. This statement does not become clear as the faults in the Forsmark area seem to be steeply dipping (cf. Figure 4-10, page 114, SR Site).

Why is the assumption of steep dipping faults in the analysis of the impact of large earthquakes on target fractures in the repository conservative, when the faults are sub-vertical in the Forsmark area?

page 139, first bullet. It is stated that „aftershocks are a process of relaxing stress concentrations produced by the main shock“. This is again a statement that suggests that fracture propagation is an issues; and fracture propagation is always accompanied by displacements on fractures.

page 139, last bullet. Again, the statement of a conservative non slip assumption needs explanation.

page 140, bullet five. The results are valid only for a reverse stress field. What if the type of stress model is wrong? What would be the implications of the simulations, if the stress field was not of reverse type in the analysis of the impact of large earthquakes?

page 140, bullets six and seven. The understanding of dynamic loading of rock fractures is limited. It is suggested to perform a literature review on dynamic loading of rock fractures to get a better understanding of the mechanisms.

It is suggested to perform a literature review on dynamic loading of rock fractures to get a better understanding of the mechanisms.

4.4. Geosphere process report for the safety assessment SR-Site. TR-10-48.

page 91, Table 4-1. The row on groundwater pressure states that the fluid pressure is only accounted for by the effective stress concept. Does this mean that the fluid pressure on fractures is not accounted for, with the limitation that no hydraulic fracturing or hydraulically induced shear can take place?

page 94, Temperate climate domain, Boundary stresses. Why is the swelling pressure not applied? So the bentonite is not considered an active barrier in the temperate climate domain?

page 94, Model simplification uncertainties in SR-Site. It is boldly stated that there are no real simplifications and if there were they are too small to cause uncertainties. But how are spatial variabilities in the rock properties handled, what about strain localisation zones, like veins or competence contrasts?

A more reflected discussion of the uncertainties of the displacement in intact rock is needed.

page 96, Table 4-2. In rows 1 and 2 it is stated that no groundwater flow is assumed and that the temperature is only considered in form of resulting stress changes. However, if there is fluid bearing fractures, this may lead to local reduction of temperatures if the flow velocity is high enough. Has this case been considered and been excluded because the effect is considered to be too small? When drilling deep boreholes the reduction of temperature is actively used to control stability and hence a local reduction may lead to stability issues.

page 98, last paragraph. Again fracture extension is considered an issue, but it is not studied.

page 99, first paragraph. It is stated, that fracture shear stress and fracture normal stress are responsible for most fracture displacements. It is not clear what the other factors are; temperature changes stress, fluid pressure varies stress, ...

page 100, third paragraph. The arguments are not clear.

It is suggested to review La Pointe et al 2000 to validate the assumptions about fracture slip, that have direct impact on the conclusions drawn from the simulations of target fracture displacements due to large earthquakes.

page 110, first paragraph. It is assumed that the reference to Griffith 1924 is a typo and the 1921 paper should be referred to. Also, the whole paragraph does not become clear and needs revision. But as fracture extension is not considered an issue, this is of minor importance in the context of the current report.

page 112, Groundwater pressure. It is stated that „fracturing cannot have any effect on the groundwater pressure”. This statements needs additional explanation, as fracturing in general is accompanied by a local pore space increase.

page 116/117, last two sentences. „Stress corrosion reactions are likely to be among the mechanisms giving subcritical crack growth /Potyondy 2007/. The process requires the existence of cracks with tensile conditions at the crack tips, meaning that confinement will suppress fracture growth by stress corrosion“. These statements bare any justification. Stress corrosion is the leading mechanism in subcritical fracture extension in rock (Atkinson 1984), shear fracture growth is enhanced under compressive conditions, and there is no indication known to the reviewer why confinement should suppress stress corrosion, assuming a shear load to the fracture. Further, the study by Damjanac and Fairhurst (2010) only considers tensile fracture growth and therefore is of limited importance for the discussion of fracture processes under compression in the earth crust (see page 119 also).

page 117, third paragraph. The classical papers on subcritical fracture growth are by Wiederhorn on glass and by Atkinson on rock. These should be mentioned when discussing time-dependent fracture growth. Furthermore, there is a difference between creep and subcritical fracture growth that should be reflected in the argumentation.

It is suggested to review the available literature for the discussion of sub-critical fracture propagation and then update all reports accordingly. Creep and subcritical fracture growth are used equivalent, which is not appropriate. The conclusions drawn are not valid, as shear fracture growth is not considered a valid mechanism.

page 120, temperate climate domain, first paragraph. The argument assumes that the fractures extend infinitely. But this is not the case. If they propagate subcritically, they extend until they run into an energy sink, which might be another fracture or an excavation and stop. Hence, the deviatoric stresses are only locally reduced, but the DFN is extended.

4.5. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. TR-11-01.

As TR-11-01 is the top-level report to the application, it summarises most of the information given in the other reviewed reports. Not necessarily all issues that have been discussed in the context of the other reports are repeated here again. Also sometimes only reference to other comments is given.

general comment, example page 114. In general only top views are shown. Cross cut views are very limited, although they would help gaining a better understanding especially of the fracture zone geometries.

It would be beneficial to have selected cross sections through the deformation zone model.

page 114. There have been four fracture sets identified in the target area, two sub-vertical in NW direction and two sub-vertical in NE direction. In the southernmost region there are some gently dipping fractures that are accompanied by open (tensile?) fractures.

In the following the argumentation of the chronology aims at concluding that all fracturing after the formation of the main (ductile) deformation zones was only happening inside the lens. As this conclusion has some important impact on the interpretation of the activation potential of fractures for the lens, the lines of argument and data are suggested to be carefully reanalysed by a structural geologist.

Interesting is the change of major compression direction by about 90° with time. In the SDF no such information was found. Is there a chance that this will happen again during the time-period of the repository?

page 118/119. What is the main difference between FFM01 and FFM02? Could they be the same? If so, could it be that there is a largely inclined shear zone that has sub-parallel fractures on one side, i.e. hanging wall?

The separation between FFM01 and FFM02 shows the same orientation as the gently dipping fracture set. Is this coincidence? Or is this an indication that in the target volume there are gently dipping fractures but they have been overlooked as they possess not so distinct features as in other regions?

The gently dipping fractures are considered shear fractures? If so, they might have on one side a wide zone of extensile fractures, on the other sub parallel ones in the FPZ. Is this the case?

page 122. The stress model is discussed in the main section. Interestingly the stress model is ranked as high confidence by SKB.

page 249. The canisters are designed to withstand 45 MPa isostatic load. The repository is at 500m, and an ice sheet of 3,000m might be on top. Hence the maximum water column will be 3,100 * 1.05 = 32.6 MPa. Assuming that no additional stresses isostatically act on the canister the design criterion is sufficient. In table 8-1 it is stated that the swelling pressure add to the isostatic loading. If so, to what extend? This needs to be explained. Further, no mentioning of excess pore pressures by seismic events were discussed. Can an earthquake create a pore pressure plus of 12MPa?

Does the water pressure add to the swelling pressure of the bentonite? If so, during a glaciation the isostatic load on a canister could be in the region of >50MPa.

page 265. It is indicated though not specified that gas might need to escape when a canister is broken. Where does the gas come from and how much? Is the amount high enough that it acts as a driving force for fracture extension when shaken by an earthquake (like a bottle of water with gas when shaken)?

page 297. "Induced seismicity: The implications of induced seismicity can be excluded in the risk calculation". As discussed in the general review comments section there might be induced seismic events due to the thermal heating of the system.

page 313. What are the degrading products of the microbes from the organic matter? I assume it is also gas; what amounts can be expected? If so, these could trigger gas fracturing if an earthquake initiates the dissolving process. As gas is highly compressible this might drive quite some dynamic fracturing.

page 336, Potential for creep – time dependent deformation. The arguments presented in the section are a repetition of the underlying reports and have been discussed elsewhere in this review. The concepts of creep and subcritical fracture growth are used exchangeable, which is not valid and hence leads to wrong conclusions.

page 337. It is stated that the spalling and time dependent deformation of the rock mass around the deposition holes due to the thermal heating is suppressed by the swelling pressure of the bentonite. However, the resaturation is expected to take up to several thousand years, but the peak of the thermal heating is after some hundred years.

page 462. It is stated that „hydraulic jacking is a phenomenon that theoretically occurs when the pore pressure in a fracture exceeds both the normal stress acting on the fracture and the fracture's tensile strength“. The explanation is not precise and needs clarification. Hydraulic jacking, aka hydraulic fracturing, takes place if the stress concentration at the tip of the fracture exceeds the resistance to fracture growth; an increased hydraulic pressure on the fracture is the driving force for this fracture extension to take place. Does the misconcept of the mechanism have any implications on the interpretation and conclusions?

Lönnqvist and Hökmark (2010) have studied this mechanism and it is suggested that the report is reviewed for understanding the implications.

It is suggested to review Lönnqvist and Hökmark (2010, R-09-35) to judge the likelihood and understand the implications of hydraulic fracturing.

page 464. It is stated that creep can be neglected for the mechanical loads that may occur during permafrost, glaciation or temperate conditions. As the terms creep and subcritical fracture growth were used synonymously, this declaration could also refer to subcritical fracture growth. This statement is commented upon in other parts of the review. It needs clarification if the conclusion is really correct, as several of the assumptions are incorrect.

page 470. Table 10-15 gives trace length and thickness data for the deformation zones DZ in the Forsmark area, since it would be instructive to plot those data to see how it compares to the Vermilye and Scholz relationship. Figure 10 shows the data in combination with the Vermilye and Scholz (1998) regression. It becomes clear that the measured data plots below the regression presented by Vermilye and Scholz (1998), i.e. the DZ, are of less thickness than the regression used to justify the respect distance. Hence the approach by SKB is especially for large trace lengths conservative.

page 471. It is stated that at end-glaciation conditions, „residual pore overpressures will amount to about one MPa / Hökmark et al. 2010/. Therefore, combined effects of isostatic loads and shear movements across canisters are not taken into account.“ The over pressure of 1 MPa appears really low. Also, it is stated earlier that the over pressure at the end of the glaciation is about 26 MPa in the reference glaciation cycle. It needs to be discussed if a combination of boundary conditions (e.g. high fluid pressure plus permafrost leading to trapped pressures) can lead to overpressures larger than 1 MPa. This will have implications on the shear displacement analysis for seismic activation as well as fracture extension due to hydraulic fracturing.

Can any combination of boundary conditions lead to fluid pressures larger 1MPa at the end of future glaciations.

page 474. Table 10-16 is not understandable without reading reference.

page 781, Ge8 Creep. The comments given before apply here also.

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APPENDIX 1

Coverage of SKB reports

Table 2: Reviewed SKB reports

Reviewed report	Reviewed sections	Comments
SKB TR-11-01. Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project.	*Summary, 1. Introduction, 4.1. Introduction to the Forsmark site, 4.2. The Forsmark area, 4.3. Rock domains and their associated thermal and rock mechanics properties, 4.4. Deformation zones, fracture domains and fractures, 4.5. Rock stress, 4.7. Integrated fracture domain, hydrogeological DFN and rock stress models, 8.3.4. Safety functions for containment: Geosphere, 8.4.5. Safety functions for retardation: Geosphere, 8.5. Factors affecting temporal evolution of safety function indicators, 10.1. Introduction to Analysis of a reference evolution for a repository at the Forsmark site, 10.4.4. The remaining part of the reference glacial cycle: Rock mechanics, 10.4.5. The remaining part of the reference glacial cycle: Canister failure due to rock shear movements, 12.8. Analysis of containment potential for the selected scenarios: Canister failure due to shear load, 14.3.3. Potential for shear failure, and 15.4.5. Canister shear movements.*	*short: SR-Site*
SKB TR-10-52. Data report for the safety assessment SR-Site.	*6.2, 6.3 and 6.4*	*short: data report*
SKB TR-10-48. Geosphere process report for the safety assessment SR-Site.	*1. Introduction, 4.3. Mechanical processes: Reactivation - displacement along existing discontinuities, 4.4. Mechanical processes: Fracturing, 4.5. Mechanical processes: Creep*	*short: geosphere report*
SKB TR-08-05. Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark.	*1. Introduction, 3. Evolutionary aspects of the Forsmark site, 5.2.4. Bedrock geology: Ductile deformation, 5.2.5. Bedrock geology: Brittle deformation, 5.2.6. Bedrock geology: Character and*	*short: SDM*

	kinematics of deformation zones, 7. Rock mechanics, 11.3. Current understanding of the site: Deformation zone, fracture domains and fractures, and 11.4. Current understanding of the site: Rock stress.	
SKB TR-08-11. Effects of large earthquakes on a KBS-3 repository. Evaluation of modelling results and their implications for layout and design.	*The report was reviewed completely.*	*short: EQ report*
SKB TR-10-21. Full perimeter intersection criteria. Definitions and implementations in SR-Site.		*short: FPR* *The report was evaluated mainly for information purposes to understand the concept*

APPENDIX 2

Suggested needs for complementary information from SKB

The listing summarises the conclusions drawn in the review, that appear to be of importance to the review assignment. Other comments to areas not directly related to the review assignment may be found in the text but are not listed here.

1. *The data from DBT1 and DBT3 have been used for determination of the stress field and make up the majority of data points. The boreholes are outside the target domain with equipment that is considered to be not state-of-the-art. Why does SKB believe the data is representative for the target area / repository?*
2. *Borehole KFM01B was drilled close to / through a deformation zone. Is the stress measurement in borehole KFM01B influenced by the deformation zone or is it giving representative results?*
3. *The pore pressure assumptions in the simulation of the impact of large earthquakes need clarification, as the reference glacial cycle uses a maximum increase in pore pressure of 26 MPa compared to a 1 MPa assumption in the simulations. The pore pressure path needs a proper argumentation and discussion, as a major impact on the conclusions about the shear displacements of fractures in the repository can be expected.*
4. *As it reads in TR-08-11, the locally increased stresses in the repository due to the presence of the excavations have not been modelled, although an increase in local stresses will result in larger fracture displacements pre- and co-seismic. This needs confirmation and discussion of the implications.*
5. *It has been identified by SKB that fracture growth (both critical and dynamical) is an important mechanism. However, the mechanism is not included in any analysis. Why has it been decided not to consider fracture growth, although the mechanism has been identified important? Why is it conservative in the simulation of the effect of large earthquakes to neglect fracture propagation?*
6. *The arguments for not considering time-dependent fracture growth do not become clear and ignore a distinct amount of literature evidence. Also, there is some confusion about the mechanism (sub-critical fracture growth), the resulting integrated rock deformation (creep), and the potential of time-dependent extension of larger fractures. It needs to be clarified by SKB how they differentiate the individual issues, as it does not become clear from the reports, and which mechanism/phenomenon needs consideration.*
7. *The implications of permafrost on the mechanical and hydraulic integrity of the repository has not been considered. What will be the influence of the freezing water in the fractures during and after a permafrost period on the hydraulic and mechanical integrity of the repository and DFN?*
8. *The implications of omitting fracture propagation needs to be discussed for the induced shear displacements on target fractures.*
9. *No oblique striking fractures have been considered in the simulation of the impact of large earthquakes on fractures in the repository (TR-08-11). What is the reason for that?*

10. *Have the parameters in Table 4-1, TR-08-11, been varied in some simulations to show the effect on the target fracture displacements? What would be the effect if the parameters in the simulations were depth dependent?*
11. *What is the justification for using Eshelby's formulations for predicting displacements and velocities of target fractures of different length? The simulation evidence is scarce.*
12. *Why is it conservative to ignore pore pressure variations in the context of simulating the impact of earthquakes on target fractures?*
13. *Why is the assumption of steep dipping faults in the analysis of the impact of large earthquakes on target fractures in the repository conservative (page 138, TR-08-11), when the faults are sub-vertical in the Forsmark area?*
14. *Why does the maximum slip occurs at the most distal points at first in Figure 5-4 (TR-08-11)?*
15. *Why is the data in Figure 21 TR-08-11 different in (a) and (b) although it is indicated the same dataset is represented?*
16. *Why is the ground motion comparable to field measurements, whereas neither the maximum fault slip velocity nor the average stress drop is?*
17. *Has the size of the models in the simulations on the impact of large earthquakes been optimised for boundary effects?*
18. *Has the mesh been calibrated for the analysis presented page 84, TR-08-11?*
19. *Why was the data base (Table 7-1) of Fig. 5-16 TR-08-11 reduced for the final conclusions?*
20. *How was the regression analysis for Figure 7-1 TR-08-11 performed?*
21. *It is suggested to review the available literature for the discussion of sub-critical fracture propagation and then update all reports accordingly. Creep and subcritical fracture growth are used equivalent, which is not appropriate. The conclusions drawn are not valid, as shear fracture growth is not considered a valid mechanism.*
22. *What are the strategies to determine the length of a fracture underground?*
23. *The determination of the valid coefficient of friction in TR-08-11 Chapter 7 does not become clear and needs explanation.*
24. *The coefficient of friction should be lower at larger depths. Why has this not been accounted for in the analysis of fault stability?*
25. *A clarification of the contrasting assumptions about rock anisotropy in TR-10-52, p265, and TR-08-05, page 134 is needed.*

APPENDIX 3

Suggested review topics for SSM

26. *The presented initial stress field at Forsmark seems to be quite uncertain. A proper revisitation of all stress data is highly recommended. This should include not only the critical review of all individual measurement data, but could also include a structural geology motivated fracture reactivation potential analysis. Such an analysis helps to narrow the possible ratios between the stress components and hence helps identify unreliable stress measurements. An independent revisitation of the existing stress data helps SSM to better evaluate SKB's application.*
27. *It is suggested to review the report by Glamheden R, Fredriksson A, Röshoff K, Karlsson J, Hakami H, Christiansson R (2007) Rock Mechanics Forsmark. Site descriptive modelling Forsmark stage 2.2. SKB R-07-31, Svensk Kärnbränslehantering AB to clarify the made assumptions on the stress field and its evolution.*
28. *A good understanding not only of the initial stress state is essential, but also of the stress field evolution. It is suggested that the stress history of the repository due to the operation, heating etc. is analysed for a more comprehensive understanding of the critical periods in the post closure/long term phase of the repository. This will also help to quantify the impact of a large earthquake on the repository. Such an analysis could incorporate independent simulations of the stress field evolution by modelling a sequence of boundary conditions as defined by SKB, i.e. thermal heating and cooling, ice sheet loading, fluid pressure, permafrost, and tectonic stresses. Such an analysis could be performed by e.g. the FEM code COMSOL Multiphysics by COMSOL AB.*
29. *It is suggested that a structural geologist analyses the potential for seismic activity, if the initial in situ stresses are low at Forsmark and the fluid pressure is high at the end of a glaciation.*
30. *In all analyses by SKB fracture extension by whatever mechanism was excluded. The reasons for the omitting are not always clear (see proposed requests to SKB for clarification), but in general it is stated that omitting fracture extension is conservative. As was shown in the main discussion, this is not always the case.*
    a. *It is suggested to review La Pointe et al 2000 to validate the assumptions about fracture slip, that have direct impact on the conclusions drawn from the simulations of target fracture displacements due to large earthquakes.*
    b. *It is suggested along with the analytical evaluation of the potential for fracture extension to perform a literature review on dynamic loading of rock fractures to get a better understanding of the mechanisms.*
    c. *It is suggested in a first analytical analysis step based on the reviews (a) and (b) performed before to systematically analyse the potential for fracture extension by different mechanisms under the two stress field models available (i.e. Ask et al 2007 and Martin 2007). This could include fracture mechanics based mostly analytical calculations of the potential at the given boundary conditions for sub-critical, critical and dynamic fracture growth.*
    d. *In a second step the identified issues could be further numerically analysed for their fracture interaction and coalescence potential by a fracture mechanics based numerical simulation campaign. This should address the influence of different stress fields and the stress field evolutions (see suggestion before) on the fracture extension in the near field due to static and dynamic loads. The study by Backers and Stephansson (2011) could be the starting point for such an analysis that needs to be broadened to account not only for the closure, bentonite swelling, thermal evolution and ice cover, but also for permafrost, tectonic stress increase and*

seismically induced strains. For such an analysis the fracture mechanics codes fracod2d (BEM) and roxol (XFEM) could be used in an integrated analysis.

31. *The simulation by SKB of the effects of large earthquakes on a KBS-3 repository is suggested to be extended by an independent simulation campaign. The simulation results by SKB inhibit some uncertainties arising from the limitation to only one simulation approach (3DEC), the deviation of applied seismic motion from field observations, the limitation to certain target fracture orientations, the application of only one pore pressure scenario, and the fact that no pore pressure variations (i.e. poroelasticity/fractureelasticity) was accounted for. Such a verification and extension analysis of the SKB results could involve the application of seismic accelerations to one side of the model as might be done with some codes like the FEM based COMSOL Multiphysics by COMSOL AB. The model should also incorporate target fractures of different lengths and orientations, not limited to one strike and one length only. The analysis would not only confirm the complex results and interpretations of SKB analyses, but also extend them for a broader understanding of the impact of earthquakes on the displacements of the target fractures. The analysis could also shed some understanding on the critical issue of dynamic poroelastic effects in combination with different pore pressure scenarios.*
32. *As fracture extension was not considered an issue for all analyses of the long-term safety analysis of the Forsmark area, also the extension of the fracture zones was not considered. However, fracture zone ZFMWNW0123 terminates at ZFMENE006A, but as the t-junction is a stress concentrator it cannot be ruled out that ZFMWNW0123 jumps and continues to grow into the repository. A fracture mechanical motivated analysis could determine the potential for extension of the fracture zone for different loading scenarios. Such an analysis would require a better understanding of the three-dimensional geometry of the fracture zones and the possible stress field models.*
33. *From recent literature there is some evidence, that the thermal expansion of the repository volume could elastically trigger seismic events on fracture or deformation zones. It is suggested to perform a numerical analysis of such a scenario. In addition to that, the mechanism itself and the possible resulting magnitudes should be discussed with a seismologist.*
34. *It is suggested to review Lönnqvist and Hökmark (2010, R-09-35) to judge the likelihood and understand the implications of hydraulic fracturing during glacial and post glacial.*

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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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