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Workshop on Seismology

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SSM perspective

Background

In SSM:s preparation for reviewing SKB:s license application for disposal of spent nuclear fuel, a series of technical workshops have been conducted. The main purpose of this type of workshops is to get an overall understanding of the state of knowledge on interdisciplinary issues as well as of questions in the research front by inviting several experts. Several workshops have been carried out and addressed for example the concept for long-term integrity of the Engineered Barrier System (EBS) and of the Corrosion Properties of Copper Canisters.

Objectives

The objective of this workshop was to bring experts in the field of seismology and rock mechanics together to discuss intersecting issues related to seismology and the long-term stability of the proposed system of a deep geological repository for nuclear waste.

Results

This report summarizes the issues discussed at the workshop and extracts the essential viewpoints that have been expressed. The report is not to consider as a comprehensive record of all the discussions at the workshop and individual statements made by workshop participants should be regarded as opinions rather than proven facts. This report includes, apart from the workshop synthesis, the review reports from the participating experts. The participants in the workshop identified a number of issues that not is fully understood and therefore suggested to be dealt with in more detail later on. However, it is necessary to look at these issues in the context of the overall safety case, in particular the key safety functions and threats, and to assess them in a quantitative fashion.

Need for further research

This type of workshop and other research in different specified research questions are likely to continue during the review of the SKB license application.

Project information

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Contents

1. Introduction

Swedish Radiation Safety Authority (SSM) is preparing to review the licence application being developed by the Swedish Nuclear Fuel and Waste Management Company (SKB) for a final deep geological repository for the disposal of the Swedish spent nuclear fuel. As part of its preparation, SSM and previously the Swedish Nuclear Power Inspectorate (SKI) are conducting a series of technical workshops on key aspects of the Engineered Barrier System and spent fuel and related issues. This workshop concerns the seismicity and risk of faults and fractures intersecting the canisters and thereby jeopardizes the canisters in the repository. This will provide a basis for the review of SKB`s scenarios and source term modelling in future safety assessment (SA) work for the safety report about the Forsmark site (SR-Site) and the licence application to build the repository at Forsmark.

Previous workshops arranged by SKI and SSM have addressed the overall concept for long-term integrity of the EBS system (SKI Report 2003:29), the manufacturing, testing and QA (SKI Report 2004:26), the performance confirmation for the EBS (SKI Report 2004:49), the long-term stability of buffer and backfill (2005:48), the corrosion properties of copper canisters (SKI 2006:11), the mechanical integrity of KBS-3 spent fuel canisters (SKI Report 2007:36). As a preparation for the safety report about the site of the repository (SR-Site) SKB presented in 2006 the preliminary safety assessment SR-Can. An international expert evaluation review of the engineered barrier issues in SR-Can was conducted by SKI (SKI Report 2008:10).

The workshop on seismology is part of a series of workshops held in 2010 and organised by SSM. The other workshops were about Copper corrosion and Buffer erosion (SSM 2011:08), Spent fuel performance and Radio Nuclide chemistry (SSM 2011:21) and Regulatory Review and Safety Assessment Issues in Repository Licensing (SSM 2011:07).

This report describes a workshop that was organised by SSM in Stockholm, March 23-25, 2010, for assessment of seismicity, late glacial faulting and fracturing in Swedish bedrock by SKB. The general objective with this type of meeting is to improve the knowledge and awareness of recent developments within SKB and elsewhere and to provide review comments to the safety analysis to SR-Site.

This report sets out the detail objectives and format of the workshop in section 2. Section 3 provides the long-term safety requirements that need to be taken into account. Section 4 gives a brief overview of an expert panel elicitation of seismicity following glaciation in Sweden. Section 5 – 8 presents a summary of the main topics discussed in the workshop and the review comments of the technical reports delivered by the invited experts. Instructions to and results of the discussions in the working groups are presented in Section 9. The seven experts received the same five technical reports for review and their comments are presented in Section 10. Section 11 presents overall conclusions from the workshop.

The four technical reports and the single publication selected for review and oral presentation were selected by SSM and given to the experts for review before the workshop. The experts were specialists on seismology, rock mechanics, rock engineering, structural geology, geophysics and quaternary geology. Thereby the work presented for us was reviewed from different angles by experts with in-depth knowledge in different disciplines.

2. Workshop structure

2.1 Objectives

The detailed objectives of the workshop were to:

- obtain an overview of SKB´s current work with their demonstration of long-term canister integrity related to earthquakes, faulting and fracturing
- review a handful of key technical SKB reports related to the effect of earthquakes, faulting and fracturing
- to summarise outstanding issues and further work that may require consideration and analysis by SSM or SKB

The scope of these issues is large in relation to what could be handled during the three days of the workshop, so some issues were only addressed very superficially like for example late-glacial faulting. Viewpoints expressed in this report should be interpreted as examples of issues that may be brought up in the context of scientific and regulatory review, rather than the result of a comprehensive review.

2.2 Workshop format

The Workshop on Seismology was held on March 23-25, 2010 at Elite Hotel Marina Tower in Stockholm. The participants were SSM staff and invited consultants. Representatives from STUK (the Radiation and Nuclear Safety Authority of Finland) attended the workshop as observers. Staff from SSM opened the workshop and gave an overview of long-term radiation requirements in Sweden and a summary of the results of an expert panel elicitation of seismicity following glaciation in Sweden. SKB staff participated the first day and gave presentations of key issues about seismology and issues related to faulting, modelling of stress state and earthquake induced fracturing.

On the second day invited consultants gave presentations about the major findings and conclusions from reviewing five technical reports about SKB´s approach to late-glacial faulting, effects of earthquakes on a repository, stress evolution and fault stability during a glacial cycle in Sweden and the concept of respect distance and full perimeter intersection criteria. Prior to the workshop each of the participating consultants plus Professor Kurt Lambeck(not attending the workshop) of Australian National University, Canberra has delivered a review report about the following technical reports:

1. Lagerbäck R, Sundh M, (2008). Early Holocene faulting and paleoseismicity in northern Sweden. Research Paper C 836. SGU - Sveriges Geologiska Undersökning. 167 pp.

2. Lund, B., P. Schmidt and C. Hieronymus (2009). Stress evolution and fault stability during the Weichselian glacial cycle. SKB TR-09-15, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden. 106 pp.

3. Bäckblom, G. and R. Munier (2002). Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. SKB TR-02- 24, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden. 115 pp.

4. Munier, R. and H. Hökmark (2004). Respect distances. Rationale and means of computation. SKB R-04-17, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden. 218 pp.

5. Hedin, A. (2008) Semi-analytical stereological analysis of waste package/fracture intersections in granitic rock nuclear waste repository. Mathematical Geosciences 40:619-637.

The third (half) day was devoted to discussions in two working groups. SSM staff had prepared a set of questions related to seismic risk due to future glacial periods in Sweden. Each working group reviewed the prepared questions in order to clarify their intent, and to prepare questions to be used in future review process of SR-Site and licence application.

In the final session on the third day the participants draw the conclusions from the presentations by SKB staff, the review of the technical reports and discussions in the working groups. This report and the conclusions of the workshop have been developed from these sources of information.

Viewpoints presented in this report are those of one or several workshop participants and do not necessarily coincide with those of SSM.

3. Long-term radiation protection requirements

In 2006 SKB published the safety report SR-Can (SKB TR-06-09). SR-Can is the first assessment of post-closure safety for a KBS-3 spent nuclear fuel repository at the candidate sites Forsmark and Laxemar, respectively. The analysis used data from the initial stage of SKB's surface-based site investigations at Forsmark and Laxemar sites and on data from full-scale manufacturing and testing of buffer and copper canisters.

SR-Can can be regarded as a preliminary version of the safety report that SKB has to deliver in connection with its licence application for a final repository in 2011. The authorities' review of SR-Can is to provide feedback to SKB on their safety reporting as part of the pre-licensing consultation process. The main result of the authority's review of SR-Can (Dverstorp and Strömberg, 2008) was presented at the workshop.

The purpose of the safety assessment SR-Can is to investigate whether a safe spent nuclear fuel repository of KBS-3 type can be built at the Forsmark or Laxemar sites. In June 2010 the Forsmark site was selected by SKB based on findings from the extensive surface based site investigations conducted at depth at the Forsmark and Laxemar sites. The assessment of long-term safety for a KBS-3 repository concept at Forsmark has been conducted in the SKB project SR-Site and reported in the main report of the SR-Site project (SKB TR-11-01). The report is one of the main documents in SKB´s licence application to construct and operate a final repository for spent nuclear fuel at Forsmark. The content of the report aims at demonstrate long-term safety for a repository of KBS-3 type at Forsmark.

The requirements of the Swedish society about long-term safety of nuclear waste repositories are ultimately expressed in legal regulations issued by the Swedish Radiation Safety Authority (SSM) under the Nuclear Activities Act and its regulation "The Swedish Radiation Safety Authority´s regulations concerning safety in final disposal of nuclear waste" (SSMFS 2008:21) and the Radiation Protection Act, "The Swedish Radiation Safety Authority´s regulations concerning the protection of human health and the environment in connection with the final management of spent nuclear fuel or nuclear waste" (SSMFS 2008:37), respectively. The regulation SSMFS 2008:37 require description of the evolution of the biosphere, geosphere and repository for selected scenarios with respect to defects in the engineered barriers and other identified uncertainties.

The long-term safety of the repository is dependent of the following conditions and processes:

1. The performance of the Engineered Barrier System (canister and buffer)
2. Shear-movement in granitic rock from thermal loading and earthquakes
3. Earthquake magnitude, frequency and location (seismic hazard).

In the review of SKB´s SR-Can the authorities pointed out risk of the combined loading cases of simultaneous shear load of faults and fractures intersecting the canister holes and the hydrostatic loading from an excessive groundwater pressure during the melting phase of an ice sheet. Also, the authorities pointed out the need of further development and confirmation of the existing DFN models for the selected site and in particular for the size range 10-1000 m.

One of the scenarios that SKB has identified and considered in the safety report SR-Can, which also turns out to be one of the critical, is canister failure due to shear load. If the shear load on the canister is too large, the canister will break and lose its containment capacity. The shear load subjected to the canister is determined by the likelihood that the deposition hole is intersected by a fracture of particular size which depends on the properties of the fracture network in the host rock and to what extent unsuitable long fractures can be detected and avoided in deposition holes drilled from the deposition tunnels. To resolve the problem of deposition hole rejection, SKB has developed a methodology called Extended Full Perimeter intersection Criteria (EFPC). This concept was reviewed and discussed in this workshop because in the review of SR-Can the issue was only addressed to a small extent by SKI/SSI.

The discovery of long and major late glacial faults in northern Fennoscandia in the 1970s made SKB aware of the risk of reactivation of such faults in the vicinity of a repository. Therefore, over a number of years SKB has studied the late-glacial faulting of northern Fennoscandia and in particular the widespread reverse faulting associated with major strong earthquakes. From the studies it has been concluded that the late-glacial faults are limited to northern Fennoscandia and that they are related to the very last episode of the glacial melting at the centre of the former ice sheet. The concentration of the late- to post-glacial faulting to northern Sweden is strongly supported by the regional distribution of the paleoseismic records of landslides and soft-sediment deformation features. The size of the faults and the recorded paleoseismic structures seem to indicate large magnitude earthquakes around M=8. A summary report about the faulting and paleoseismicity in northern Sweden produced by the Swedish Geological Survey for SKB (Lagerbäck and Sundh, 2008) was reviewed by the invited experts of the workshop.

Also, earthquake-triggered, fast shear movements along fractures intersecting a canister hole can potentially affect the canister containment of the spent fuel once the shear displacement exceeds the failure limit. Reactivation of fractures as a consequence of single earthquake or the accumulative effect of several earthquakes is therefore an important mechanism for the long-term integrity of the repository and therefore was reviewed and discussed in the workshop. Analysis of earthquake impacts on the repository in SR-Can was restricted to M6 earthquakes. A sensitivity analysis about the influence of smaller and larger earthquakes and their frequency was missing in SR-Can as pointed out in the SKI/SSI review. In judging the probability about the frequency of earthquakes greater the magnitude 6 within 10 km for the Forsmark and Laxemar sites in connection with a glaciation cycle SKB together with SKI and SSI carried out an expert panel elicitation of seismicity following glaciation in Sweden (Hora and Jensen, 2005). A summary of the main findings in the elicitation study is presented in the next Section of this report.

4. Expert panel elicitation of seismicity following glaciation in Sweden – short review

An expert panel elicitation project (Hora and Jensen, 2005) on the issue of glacial induced Swedish earthquakes at the suggested sites for the final repository of spent nuclear fuel was launched in 2005 jointly by SSI, SKI and SKB and with a steering committee with representatives from the three organisations and representatives from each of the municipalities of Östhammar and Oskarshamn who at that time were hosting SKB´s site investigations. The selection committee agreed upon the following two questions on seismicity following glaciation in Sweden:

1. What will be the frequency of magnitude 6.0 or greater earthquakes within 10 km of Forsmark and Oskarshamn during the immediate post glaciation period assuming that the average thickness of ice above the repository reached a maximum of 1000 meters, 2000 meters, 3000 meters? Give an uncertainty distribution for this quantity at each repository under these three assumptions about thickness of the ice overlay.
2. Given a magnitude 6.0, 7.0, and 8.0 earthquake occurring within 10 km of a repository in Forsmark and Oskarhamn, give an uncertainty distribution for the maximum displacement (slip or shear) in an existing or new fracture in the repository. Your uncertainty distribution should include the possibility that no displacement occurs with the repository.

A selection group of experts provided a list of 16 scientists considered for selection to the expert panel. From the list the following 5 experts were selected:

- John Adams, Geological Survey of Canada, Natural Resources Canada,
- Hilmar Bungum, NORSAR, also affiliated to the University of Oslo,
- James Dieterich, University of California, Riverside,
- Kurt Lambeck, The Australian National University, Canberra, and
- Björn Lund, University of Uppsala.

The expert group met twice and at the first meeting they decided to omit the second question due to limited time allocated for the work. In addition the group reformulated the first elicitation issue to be:

1. What will be the frequency of moment magnitude 6.0 or greater earthquakes per unit area (e.g. per 100 sq. km) in the middle and south of Sweden (Forsmark and Oskarshamn) during a glacial cycle (app. 100 000 a) assuming conditions similar to the Weichsel glaciation? Give an uncertainty distribution for this quantity for each area.

In addition the group agreed upon the assumptions of maximum moment magnitude of 7,6 for the earthquakes and a seismogenic thickness of 30 km for the Earth's crust.

Despite the different approaches applied by the experts they were very close in predicting the frequency of large magnitude earthquakes for the two sites. Magnitude-frequency distribution from deglaciation applied by Adams gave 10 magnitude $M \geq 6$ earthquakes within 100 km distance over a period of 100,000 years. Bungum based his analysis on the paleoseismic observations in northern Fennoscandia and applied the Gutenberg-Richter relationship with variations of a- and b-values in the relationship. His results were presented for an area of 100 km2 and were later scaled down to an area having a radius of 100 km. His best estimate for southeast Sweden was 5,1 earthquakes for the entire 100,000 year time period.

The judgements of Dieterich, Lund and Lambeck were all using ice model stresses developed and provided by Lambeck. The analysis employs the Coulomb failure criterion to determine the amount of stress relaxation due to fault slip. The cohesion term in the criterion is omitted and the friction coefficient is assumed to be 0.6. To find the total number of earthquakes from moment release, Dieterich calculates the relationship between seismic moment and earthquake magnitude. The number of earthquakes with magnitude $M \geq 6$ due to glacial stressing within 100 km radius is 121 for Forsmark and 206 for Oskarshamn. Considering a variety of uncertain factors that are expected to modify the actual seismic response from that of the idealized model, Dieterich predicted a seismic response at the 0.5 fractile to 42 $M \geq 6$ earthquakes at Oskarshamn and 24 at Forsmark. The analyses by Dieterich, Lund and Lambeck show that the greatest seismic hazard occurs at the rim of the ice sheet as the ice is advancing or retreating over a site. The larger number of events at Oskarshamn is due to the effect of a larger ice sheet which gives larger stresses and greater hazard.

The judgment of Lund was based upon the ice model stresses of Lambeck and a maximum magnitude event 7,6. He was using five different steps to evaluate the magnitudes and frequencies of events. For a cumulative probability of 0.5 he estimated 12 earthquakes/100,0000 years for the southeast Sweden. He does not consider the different location of Forsmark and Oskarshamn to be significant with respect to the ice model used in the estimation procedure. Lambeck presented an uncertainty distribution for the frequency of a magnitude 7.6 and greater earthquake with a best estimate of 0.9 earthquakes at Oskarshamn and 0.016 for Forsmark within a radius of 100 km. To translate from magnitude 7,6 or greater to magnitude 6,0 data about the b-value in Gutenberg-Richter relationship is needed. Assuming a b-value of 1.0 the best estimate for 100 km radius and magnitude 6,0 is 52 earthquakes per 100,000 years.

As pointed out in the final report of the elicitation study (Hora and Jensen, 2005), despite the different approaches and methods applied by the five experts, the estimates is unusually narrow for elicitations. The distributions all have the best estimates between 0 – 50 magnitude 6 or greater earthquakes per 100,000 years. By averaging the presented probabilities from four of the experts and excluding Lambeck’s distribution, the cumulative distribution function for the frequency of events were calculated and plotted for the Oskarshamn and Forsmark sites.

5. Early Holocene faulting and paleoseismicity in northern Sweden

This section presents the invited experts review comments and questions about Early Holocene faulting and paleoseismicity in northern Sweden presented by R. Lagerbäck and M. Sundh and published as the Research Paper C832 of the Geological Survey of Sweden in 2008. The content of this report was not presented orally at the Workshop on seismology.

The majority of the experts are of the opinion that the report gives an outstanding overview of late-glacial and paleoseismicity of northern Sweden. It is based on extensive and thorough field work over more than 35 years. The results of the investigations have been published in international scientific journals and a large number of excursions and visits for the science community have been arranged since the first description of the Pärvie Fault by Lundqvist and Lagerbäck (1976). The scientific recognition and impact of the phenomena and quality of work presented by Lagerbäck and Sundh are of first rank.

The fast land uplift from the deglaciation of the Weichselian ice sheet is thought to generate the Early Holocene faulting in Northern Sweden. The largest fault – the Pärvie fault – is 155 km long and has a scarp height of 3 – 10 m. The sandy-silty sediments formed in low elevation at the time of the ice recession were liquefied due to seismic activity from the faulting. The saturated glaciofluvial sediments formed large landslides and it is striking how the landslides are located close to the border of the highest shoreline. The composition of the landslides is entirely dominated by glacial till. Such till deposits are not expected to slide or flow under normal conditions and in particular in the gentle slopes often existing in the area surrounding the faults above highest shoreline. In addition tills are normally not expected to generate liquefaction structures. These structures are common in the vicinity of the end-glacial faults in northern Fennoscandia. Such deformation structures are known to occur elsewhere and the association made here is reasonable. In particular Lagerbäck and Sundh emphasize that this is an inference only. That the occurrence of these secondary effects like landslides and liquefaction structures occur in greatest concentration near the large faults in northern Sweden gives added strength to this inference.

Lagerbäck has conducted a number of studies of late-glacial or neotectonic studies all over Sweden, including the areas around the Forsmark and Laxemar sites. He has found evidences of short and small escarpments in southern Sweden but these structures are formed prior to the last glaciation and most likely under different stress conditions. The small number of the secondary features in the central and southern areas, compared with the north, is consistent with an almost absence of post-glacial faults and with the assumption that the faulting and instability of the sediments are related and that, by inference, there is no strong evidence for faulting triggered by the last ice retreat across southern-central Sweden.

5.1 Questions

1. The dating of the large landslides is still a problem and it seems that additional efforts have to be done to reach a final conclusion about the genesis of the landslides and their relation to the seismicity from the faulting.

2. Another issue to be resolved is the genesis of the landslides entirely dominated by glacial till and located above the highest shoreline in Lapland. Such till deposits are not expected to slide or flow under normal conditions and in particular in the gentle slopes often existing in the area surrounding the faults above highest shoreline.

3. The Pärvie fault is located above the highest marine level. What criteria for fault-related distortion of sediments are SKB using for permafrost area?

4. If it is correct that the late-glacial faults in northern Fennoscandia represent a one-of-its-kind earthquake activity burst concentrated in time and space. Why did it happen and what were the underlying causes for this?

5. During the last decennium there has been examples of quite large and much unexpected (not in well mapped active areas) earthquakes occurred in the Fennoscandian *present* geological conditions (no extra glaciation stresses). Would it not be time to conduct a high level earthquake hazard investigation of probabilistic type and based on present day conditions at low annual probabilities?

6. Reactivation with creep on pre-existing faults might be an alternative mechanism for late-glacial deformation of the large faults in Lapland. Are there evidence that the energy release of the large faults have happened in several recurrent events during the ice retrieve?

7. Are there any new observations in northern Sweden about previous glaciations having fault structures (orientation, dip, escarpment height) different from fault structures during the last deglaciation?

6.0 Stress and faulting during the Weichselian glacial cycle

Björn Lund and co-workers (Lund et al., 2009) have presented a series of technical reports and a few publications in international journals (Lund and Näslund, 2009) about the state of stress in the Fennoscandian Shield during a glacial cycle. The purpose of the modelling is to increase the understanding of the stress variation in the Earth's crust during a glacial cycle and to provide regional and local stresses to different earth science site descriptive models for the repository sites. In performing the analyses they have been using the commercial finite elements software ABAQUS. In the SKB report reviewed by the invited experts from SSM, the team is modelling a series of benchmarks to illustrate the results from different assumptions regarding GIA models and modifications of the treating material properties at layer boundaries. In addition they have studied relationships between 2-D and 3-D models constrained from using GPS data. The main parts of the report deals with glacially induced stresses for different stratified models and fault stability during glaciation for the two selected sites at Forsmark and Oskarshamn and the postglacial faults in Northern Sweden.

In previous studies by Lund and his group, 2-D profiles of the glaciation models were used. In Chapter 3 of this report the group is presenting the comparison in stresses between the two modelling approaches at fixed time intervals. It is clear that there are substantial differences in calculated stresses for the two different models. The authors reach the conclusion that previous presented 2-D models are not suitable to derive at correct stress state for a particular ice model and site. This is an important result from this study.

In simulating the stress evolution during the Weichselian glaciation the group has been using the thermo-dynamic ice sheet model by Näslund 2006 which is also the model used by SKB. The solid Earth model is a finite element model with 8-node infinite solid elements and spring elements for simulating the gravity forces at the layer contacts, a total of 260,000 elements. The large 3-D model is a half-sphere with infinite elements at the boundary. The ice model forms a box in the large model and this allow analysis of different sub-models for the uppermost 15-20 km of the crust. This is a new and innovative method of modelling ice sheet models. As pointed out by Lambeck in his review the use of a flat Earth model has some limitations in that it does not include

- self gravitation,
- the water loading of the concomitant changes in loading by the changes in ocean volume,
- the effect of Laurentide ice sheet which adds a regional character to the stress field over Scandinavia.

These limitations are recognised by the authors and their approach is probably sufficient for the first order stress modelling in view of the uncertainties in the ice history information. They will not be adequate, however, for high accuracy modelling of sea level change.

Lund and co-workers analysed six different horizontally stratified models and four models of laterally varying lithosphere thickness. GPS data from Fennoscandia and countries along the Baltic and North Sea coasts and relative sea-level data have been used to calibrate the models.

The modelling team presents glacially induced stresses in the models for two different times, at the ice maximum (18,5 kyr BP) and when the ice sheet has disappeared (10 kyr BP) (Chapter 7). The region of high stress due to glaciation generally follows the shape of the ice sheet and the maximum horizontal stress varies from over 70 MPa to 30 MPa depending on the model geometry and stiffness of the elastic lithosphere. The higher elasticity the larger stresses. The crust is supposed to be elastic but it would be worthwhile to consider other non-elastic components to represent stress relaxation within the crust for the time scale of the ice load. The presented results of maximum and minimum stresses, stress orientation, maximum shear stress and stresses versus depth for the two sites Oskarshamn and Forsmark for the two types of crustal models studied provides an impressive and very interesting reading and the conclusions drawn are solid and well founded. In addition, the results from the modelling supports many of the field observations presented for the neo-tectonic fault structures in Northern Sweden and it provides valuable data for the interpretation of the change in the stress field due to a glacial cycle at the Forsmark and Oskarshamn site. Based on the evaluation of the evaluation of the ten studied models the authors have selected models 2, T9 and T12 as the most appropriate models for the subsequent fault stability analysis. As a reader of the report one would also like to have the results about stresses in the models at present time. This would allow one to assist in the calibration of the different models and also provide interesting data about magnitude and orientation of the stresses in the Fennoscandian Shield.

In Chapter 8 of the report the authors describe the background stress field that is later used in the fault stability analysis for the different earth models. As stated in the report the data about the orientation of the maximum horizontal stress as presented by the World Stress Map project is far from uniform in the Fennoscandian Shield and the variation in direction is the most in the northern part of the Shield. In the most recent version of the World Stress Map data base there is an option to statistically resolve the maximum horizontal direction by means of a smoothing routine. This can be used to try to find a possible border of the strike-slip and thrust faulting regimes for Sweden. However, it is clear that there is a need for more stress data in the Fennoscandian Shield to be able to confirm the different stress regimes and to obtain magnitude and orientation of the principal stresses.

The authors are presenting maps of the modelled fault stability field over Fennoscandia at 10 km depth in the Earth’s crust and a pore pressure at 50 % of that at ice maximum at 18.5 kyr BP and at the end of the glaciation 10 kyr BP. As expected the weight of the ice at ice maximum will enhance the stability of the Earth’s crust over Fennoscandia and instability is appearing at spots in areas of the forebulge at the border of the ice sheet. When the ice has melted the assumption of strike-slip faulting result in remained stability over central Fennoscandia. The assumption of reverse faulting condition causes failure over large areas in central Fennoscandia with a maximum in the northernmost parts where the late Holocene faulting appears. So for example the Pärvie fault is located just at the edge of the highest faulting potential. The presentation of the fault stability maps in plain view and as depths profiles illustrate in an excellent way the stability conditions at the selected time spots. As a reader of the report one likes to have the same presentation of the stability like in Figures 9-1, 9-2, 9-5 and 9-6 for the present time, i.e. 0 BP. However, the results presented clearly show the importance of selected far field stress conditions for the final results about stability and it emphasis the need of obtaining better understanding of the regional extension of the different far-field stresses in Fennoscandia.

In the report the authors are presenting the optimal orientation of faults for causing failure and earthquakes at the depth of 9.5 km for the two sites Oskarshamn and Forsmark with the assumption of 50 % pore pressure and R = 0.5. As expected the optimal fault direction for generating slip is governed by the orientation of the synthetic far field stress.
The presented results also show that at the time of maximum instability at the Forsmark site (11 kyr BP) and with the assumption of reverse faulting condition, the instability of faults at 500 m depth is governed by a set of NE striking faults with moderate dip to the SE and NW (see Figure 9-14). With the assumption of strike-slip faulting condition at Forsmark at the time of maximum instability at 32 kyr BP, the risk of slip is highest for the steep dipping NW-SE faults.

The temporal evolution of the stability field of the Pärvie fault shows that faulting takes place when the ice is melted and only during reverse faulting synthetic stress field and for all tested pore pressure conditions and variation of the direction of the maximum horizontal stress field (± 45 degrees). This modelling result is in direct agreement with the field observations at Pärvie. The modelling results also give strong support to the neotectonic field studies in the area of Oskarshamn where no indication of Late Holocene bedrock tectonics is found.

In the discussion (Chapter 10) it was mentioned that the pore pressure under the ice sheet is lubricating the crust and hence the accumulated strains are released aseismically. From a fracture mechanics perspective this concept may be supported. It is known that fractures in rock may propagate at loads that are only a fraction of the critical stresses for failure. The propagation of the fractures is slow and hence small energies are radiated only. The presence of a fluid promotes this so-called subcritical fracture growth, as the creation of the fracture is driven by chemical processes; pressurisation may even enhance those effects further. Hence, fractures may grow slowly under the increased stresses at glaciation and become longer aseismically. From the concepts of fracture mechanics it can be derived that the longer a fracture, the smaller the imposed load needed for propagation. Therefore, if a fracture becomes subcritically longer, it may reach at some point at constant loads a length suitable for criticality, i.e. seismically detectable, fracture propagation. This could explain co-glaciation earthquakes. Or the stress field is altered, giving way to critical fracture propagation. This is a possible scenario for earthquakes developed during deglaciation.

The results presented in the report clearly illustrate the lithosphere properties and thickness and the viscosity of the mantle have minor influence on the stress-time history during a glaciation cycle. This is partly new and interesting results. The conclusion reached in the report is that glacially induced faulting is unlikely at Forsmark and Oskarshamn based on the assumption that strike-slip faulting condition exists in the Earth’s crust and that the direction of the maximum horizontal stress is NW-SE and corresponds to the direction of the plate movement of the Eurasian plate and that the sub-glacial pore pressure head is 50 % of the weight of the ice column. Our present knowledge of the orientation of the maximum horizontal stress is not conclusive for Fennoscandia although the orientation of the stresses down to approx. 1000 m in Forsmark and Oskarshamn support the orientation NW-SE. We certainly need additional deep stress data from seismic focal plane analysis and in-situ stress measurements to confirm the far field stress model. In addition we need to have better understanding and data about the prevailing sub-glacial pore pressure from glaciated terrains.

In conclusion, the results presented in this report show a major improvement in the modelling of stress evolution during the Weichselian glacial cycle. The introduction of 3-D modelling and the generation of the FE models are very much improved compared with the 2-D models. The idea to superimpose the present day stress field in the post-processing stage is another improvement. The work presented in the report is of high quality and put the group and SKB in a strong position for further modelling of stress field and fault stability during a glacial cycle.

6.1 Questions

1. The authors have developed two synthetic models of the stress field to be used as background stress field in the stability analyses (strike-slip and reverse model). It is not clear why the authors have left out the pore pressure terms for the vertical stress component for the two stress models and for the intermediate (least horizontal stress) for the reverse stress model (see eq.8-3).

2. For the indication of stability the authors are using the well-known term Coulomb Failure Stress, CFS, which means that if CFS is positive the shear stress is larger than the frictional force and the fault will fail in frictional sliding. The situation that CFS = 0 has been used to define the background stress as shown in Figure 8-3 of the report. As pointed out above, it is not fully clear how the authors derive the equations used to define the background stresses.

3. In simulating the stability conditions for the ice model during a glacial cycle the authors have considered the influence of the intermediate principal stress and have used R = 0.5 (equation 8-2). The selection of this value for R needs further explanation.

4. How sensitive is the new 3-D model for lateral variability in crustal and mantel structure?

5. Has SKB considered the likelihood of postglacial rupture along blind faults?

6. Has SKB conducted a stress and fault stability evaluation during a glacial cycle for other ice models and regions?

7. Is the Weichselian glaciation representative for future glaciations?

8. How can SKB improve the Fennoscandian rock stress model for relevant depths?

7.0 Effects of earthquakes on the repository for spent nuclear fuel in Sweden

The SKB technical report TR-02-24 about “Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results “ presents the main results from the SKB project *Effects of Earthquakes on Underground Facilities.* The fact finding with interviews, literature surveys, Internet searching, circular letters and study-tour started in 2001 and the final report was released in 2002. This is a very short time for such an ambitious programme and search activity of an important issue in the safety programme for the location of a repository. Published records from earthquakes and underground damage to openings in China, Italy, Japan, South Africa, Taiwan, USA and former Yugoslavia are compiled and presented. Of special interest to the issue of respect distance is the information about data on earthquake influence presented in Chapter 3 and 4 of the report.

In Chapter 3 the authors present a countrywide overview of cases on earthquake influence on underground facilities for each of the countries listed above. From China, Italy and Taiwan one single earthquake and its effect on underground openings are described. From Japan and the other countries several events and damages are presented. One can raise the question if the number of earthquakes and underground construction damages studied are enough to reach valid conclusions about the effect of earthquakes on a deep repository for spent nuclear fuel. Many of the studies presented and discussed are located in rock types of little relevance for the deep repository in Sweden. The most relevant data are gathered from the Hyogoken-Nan-bu (Kobe) earthquake in an area of granitic rocks, January 1995, pp.53-55.

It is a well-known fact, and also supported by the presented case studies from the literature in the report, that damage from an earthquake is much less underground than at the surface. In Table 3-6 the authors present an overview of measured displacements observations close to re-activated faults and they claim that even for very strong earthquakes, deformations are confined to a few hundred meters from the re-activated fault.

One has to bear in mind that the width of the damage zone, or sometimes called process zone, is a function of the length of the faults. Scaling data of the fracture (fault) process zone from laboratory and natural faults have been presented by Zang and Stephansson (2010). Double logarithmic plot of process zone width versus fault length for natural faults are presented in the classical paper by Vermilye and Scholz (1998) with a regression slope of 1/62 and the regression slope of 1/50 for laboratory faults produced by Zang et al. (2000). Note that the width of the process zone (and also the fracture toughness) scales with the length of the fracture.
If we apply this diagram to the situation in Forsmark and to the mapped faults as presented in different SKB reports from the site investigations we find that most of the data points for the faults in Forsmark fall slightly below the regression line presented by Vermilye and Scholz(1998) with a regression slope of about 1/45. Three of the invited experts have presented information about the relationship between fracture/fault length and the width of the zone of brittle deformation and the fact that this information can be used to estimate the respect distance between fracture/fault and canister position in the repository.

What can we learn from the data presented about Forsmark in the review work by Stephansson? There is a relationship between fault length and fault width which follows the general trend reported in a number of studies worldwide. This gives confidence that the fault tectonic situation at Forsmark follows the normal behaviour and is valid worldwide and for different geological conditions although the slope of the regression line is somewhat less than what is reported in the literature. Hence, the regression line for Forsmark is valid for the geological conditions in the region. The regression line for Forsmark can be used to put an upper bound on the selected respect distance for canister location in the vicinity of faults. This application of the result of the fault data needs a correct determination of the fault length.

SKB has stated in the Site Engineering Report (SKB R-08-83) that a respect distance of 100 m is required for major deformation zones with a trace length at ground surface greater than 3 km. If we apply this criterion to the presented results for Forsmark we find that the 100 m respect distance, corresponding to 100 m fault width, for a 3 km long fault fall just below the regression line for the majority of faults in Forsmark. If one considers the scatter in the data about the faults the selected respect distance is not enough. The information from the compilation can be used to define the best estimate fault width for each individual fault in the repository area once the fault length has been determined. This might be a better methodology than using the measured fault width which comes from a limited number of measuring points as suggested by SKB for Forsmark.

In section 4.2 the authors of the report raises the question “Can new fractures be created?” and they supports the main hypothesis put forward by SKB and several scientists that release of energy is dominated by shaking and by displacements along pre-existing faults and fractures rather than by creation of new fractures. Under normal rock condition with averaged fractured rocks and stress conditions the faulting is governed along pre-existing faults or within the existing process zone from previous faulting. Later in the section the author is referring to the work by Ortlepp (2001) and his work about faulting in the deep South African gold mines. Ortlepp states and the author of the report agrees that the absence of faults and fractures is a less favourable factor in high-stress regimes because the mining-induced fracturing occurred at very high stresses in very good rock quality where there are no faults or fractures that could accommodate the stress build up. The work by the authors of the report was completed about the time when the site investigations started in Forsmark in 2002. When the site investigations in Forsmark were completed in 2007 it turned out as a result that the rocks at the target area is of very good rock quality and very few fractures. Whereas the target area has high stresses or not is still an open question. SKB is of the opinion that the stresses are higher than normal for Scandinavian conditions while the INSITE group of SSM claims that the stresses are typical for Fennoscandia hard rock conditions. We have to wait for the final answer till the underground works have proceeded and reached the deposition level.

The issue of whether a groundwater overpressure may cause complete friction loss in the rock is not convincingly discussed due to a lack of available information and this fact is mentioned by the authors. But this only accounts for a temporal increase of fluid pressure. However, even if the fluid pressure is increased locally by an earthquake for some time, the stress conditions on fractures in or near a repository may change leading to activation of time dependent fracture growth in otherwise low permeable rocks such as granites. This issue is not addressed at all. This may lead to the creation of larger fracture with the potential of linkage to other fractures or deposition holes.

The issue about protecting the repository by means of deformation zones of different origin and size was very much discussed at the beginning of the location of a final repository for the spent nuclear fuel during the early 1980s (Stephansson et al.,1980). The idea is to locate the repository so that it is protected by a number of deformation barriers (faults) of different size, location and age. Any displacement related to an earthquake should be taken up by the barriers and the repository remains intact. At this time the author of this review advocated and still advocates that from a rock mechanical point of view a jointed rock mass with an intensity of 2-3 joints and fractures per metre prevents stress concentrations and the risk of brittle and semi-brittle fracturing within the repository, see Figure 2 in the review comments by Stephansson. The question still to be resolved is “What is the risk for new fractures to be created due to excavation and thermal loading on the near-field and far-field scale of the repository? This issue will be suggested to SSM for further studies.

In Section 4.8.1 of the report the authors bring up the issue “Can the repository itself induce earthquakes?” and refers to a study by Martin and Chandler (1996) which shows that the very low extraction rate (excavated volume versus total initial volume) of the order of 0.25-0.30 for a repository is not enough to generate earthquakes and damage. The author never considered the effect of the heating plus the excavation on the probability of earthquake generation.

"Can shaking induced by earthquakes before closure damage the repository?" is the title of Section 4.8.2. Damage of underground structures is known to result from earthquakes with a Peak Ground Acceleration (PGA) of 2 m/s^2 or more. The seismic risk analysis presented for the nuclear power unit Forsmark (Stephansson and Lande, 1976) gave PGA = 0.15 m/s^2 with a recurrence probability of 10^{-5}. The probability of damage of the underground facilities from an earthquake during the pre-closure phase is very small.

In the Conclusion of the report and its Section about earthquake impact during the pre-closure phase, the authors claim that it might be possible to experience local rock burst problems due to the heterogeneous rock strength and varying rock stresses. In this statement, the author has disregarded the additional loading of the rock mass from the heat of the waste and claims that in case the events appear they will take place when the tunnels are excavated rather when the spent fuel is deposited. Instead, it is more likely that the events appear after the closure of the repository and at the time when the rock temperature reaches the maximum after approx. 100 - 1000 years. To what extent the risk of fracturing and seismic activity can appear during the pre-closure phase is also an open question that needs to be explored.

7.1 Questions

1. Considering the very low number of damage reported from mines and underground facilities below 300 m, has SKB continued to collect and analyse damage data?

2. Has SKB analysed a rock mass configuration in which no zone of weakness can release the energy and new fractures generated?

3. Have SKB and Forsmark Kraftgrupp conducted any modern seismic risk and hazard analyses (GMPE) of the facilities above and below ground at Forsmark?

4. The full perimeter intersection criteria (FPI) is based on the fact that local fractures with a length >50 m can be mapped or detected underground. What are the proofs that this condition can be fulfilled in the underground repository?

5. What conditions other than Coulomb failure criteria can SKB use to difference between stable/unstable faults for a given stress field?

6. Has SKB considered the growth of primary faults from outside the target area into the repository area and their effect on target fractures?

7. The faulting model applied in the early FLAC3D models and later for the 3DEC models is simple. Has SKB the intention to use more complex and realistic rupture models with high stress drop patches?

8. So far SKB has been using earthquake magnitude M=6.0 as representative for large source earthquakes in the analyses. What additional analyses with other magnitudes is SKB considering?

8. Respect distances and semi-analytic analysis of canister/fracture intersection

This Section of the report presents the major findings of the experts after reviewing the following technical report and publication:

- Munier, R. and H. Hökmark (2004) Respect distances. Rationale and means of computation. SKB R-04-17, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.
- Hedin, A. (2008) Semi-analytical stereological analysis of waste package/fracture intersections in granitic rock nuclear waste repository. Mathematical Geosciences 40:619-637. DOI 10.1007/s11004-008-9175-3

The technical report SKB R-04-17 is somewhat outdated and is now succeeded by the following two reports by SKB:

- Fälth, B., H. Hökmark and R. Munier (2010). Effects of large earthquakes on a KBS-3 repository. Evaluation of modelling results and their implications for layout and design. SKB TR-08-11 Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.
- Munier, R. (2010) Full perimeter intersection criteria. Definition and implementations in SR-Site. Technical report SKB TR-10-21. Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.

At the workshop, SKB presented the main contents from the latest studies published in 2010.

8.1 Munier and Hökmark (2004)

The purpose of the SKB research report R-04-17 by Munier and Hökmark (2004) is to “discuss various aspects of the assignment of respect distances, propose a methodology for its assignment and apply the methodology to the Forsmark Site”. The layout of the report is somewhat weak. The summary of the numerical results is too short for a comprehensive understanding and the reprints of reports in the appendix are of the same style. However, the review of the postglacial faulting is very good. The respect distance is defined in this report as “the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to anticipated, future seismic effects on canister integrity”. One initial problem with the concept of respect distance is that it is not intuitively understood what it could mean. More important, however, is the fact that there appears to be a discussion about what should be included in the concept, as reflected by the fact that Posiva (Finland) has written a report (Lampinen, 2007) only about the terminology. What Lampinen finds is that SKB's respect distance considers primarily the seismic risk, such that it overshadows other effects (hydrological and mechanical), while Posiva's respect distances consider the seismic, hydrological and mechanical properties of the deformation zones as the most important issues with respect to the risk to the canisters. It is not clear to us if one can conclude like SKB is doing about the balance between seismic, hydrological and mechanical properties, even this is specifically tied to Forsmark and not intended to be generic. There are, after all, significant uncertainties tied to all of the different factors that are driving the risk to the canisters.

SKB assumes that fractures exceeding 100 m radius can be detected in the deposition holes and claims that fractures with a radii exceeding 50 m can be detected using standard mapping techniques. This assumption is most likely correct. However, the assumption that the additional fractures around the target fracture will absorb some of the strains and cause less strain to the target fracture itself is not very likely. The almost fracture free rock mass in the target area at 500 m depth of Forsmark prevents this redistribution of strains around a target fracture.

Geological evidence indicates that the geomechanical behaviour during past glaciation cycles have been highly variable, with some glaciation cycles giving rise to major earthquakes in some regions, whereas other have not given rise to major earthquakes (Lagerbäck and Sundh, 2008). It has not been possible to determine the reason for the variability in earthquake response during past glaciation cycles. This shows that it will be difficult to predict the earthquake response for the next glaciation cycle. Therefore, the only option is to conservatively assume that major faults could be reactivated during the next glaciation cycle.

The numerical analyses and assessments documented in Section 3 (and supported by several appendices) are thorough and solid, using a number of complementary approaches. What is found is that an Mw 6 earthquake and a 100 m radius target fracture did not produce displacements in excess of failure limit of the canister of 0.1 m for any of the simulations. For a 200 m distance the displacement was close to the threshold (0.065 m).

This analysis is, however, somewhat limited in that uncertainties are weakly covered and also in that only some parameter combinations are modelled, including only one magnitude. This is addressed briefly in some reflections on future simulation work in Section 3.4.3, and in the discussion of large earthquakes in Section 3.5. One of the reasons for the limited analysis is the great computational demands of the numerical simulations. It is correctly stated in the report that an essential question is the way in which an earthquake grows to become larger, and if this implies any change in the stress drop and seismic moment per unit area of ruptures, which is not the case in the simplest models. This discussion of scaling laws is useful and important, but could have been better supported from more recent publications.

The discussion in Section 6 on conservatism is also interesting but raises in turn also other related questions. We would like to note here that during the last few years many tools for more advanced final fault modelling has been developed based on both kinematic and dynamic approaches (e.g., Song and Somerville, 2010), including also the near field and the influence of various non-linear effects. For example, the rupture velocity is very important, and in general the variability of stress drop and thereby the ‘patchy’ distribution of slip across and along the fault. This even includes super-shear ruptures (e.g., Andrews, 2010), which now are considered to be less unlikely than what was judged earlier.

The discussion about target fractures size seems to be hinging on the assumption that fractures exceeding 100 m radius can be detected in the deposition holes, and that respect distances have been calculated on that assumption. Surely this is discussed elsewhere but in this report it does not seem to be; it appears that this detect ability is a critical assumption that should have been given more attention, including how it could be expected to be changing with time, thereby affecting also the respect distances.

The final comment in Section 6.5 on scale is more philosophical than really useful. The interesting thing with scale invariance (fractality) is not its existence (since it applies so widely) but where it breaks down (in both ends); barriers are often not effective since they are often jumped, and all long, continuous faults should therefore be considered suspect (Emile Okal, pers. comm., 2009; see also Kase, 2010). So the conclusion in the report is correct, to use regional models.

In a previous review of SKB’s work related to coupled THM processes within SR-Can, a number of issues related to damage and geomechanical changes in the fracture rock were identified (Rutqvist and Tsang, 2008). One issue closely related to seismology is the possibility of thermally-induced shear reactivation fractures and faults in the far field. The coupled THM analysis of Rutqvist and Tsang (2008) showed that the increased temperature will increase horizontal stress substantially (on the order of 15 to 20 MPa) in the repository horizon. This could lead to shear reactivation along shallowly dipping fractures across the repository. If the rock mass at Forsmark is initially critically stressed, the initial stress would be very close to failure. During the operational phase the stress initially goes to a more stable condition after the excavation. This is caused by the depressurization and associated increase in effective stress. After emplacement the fluid pressure is restored towards hydrostatic and thermal stress develops. Thermal stress develops preferentially in the horizontal direction and increases the horizontal stress by about 15 MPa. The high horizontal stress and the high shear stress are sustained for thousands of years. Therefore, the results presented by Rutqvist and Tsang (2008) and later by Min and Stephansson (2009) and Lee et al. (2010) shows that the shear stress increases more during thermal period than the estimated increases in the last glaciation cycle. Thus, it seems to be important to study the potential for induced seismicity and related risk for fracture initiation and propagation during the thermal cycle. The induced shearing also has implications on the groundwater flow in the repository and its surrounding.

8.2 Hedin (2008)

The journal paper by A. Hedin at SKB published in Mathematical Geosciences presents an interesting analytical and numerical application of DFN modelling to the problem of secondary shear slip along target fractures intersecting canister deposition holes in the repository. An attractive feature of the approach is that it is an analytical formulation, free of numerical limitations and uncertainties. In fact, it can provide special analytical examples that can be used to test numerical methods. The presented model uses the combination of the fracture radius distribution and the distribution of fracture orientation from the results of the mapping during SKB’s site investigation at Forsmark. Cylindrical canisters are oriented vertically and a mean intersection zone width (L) is calculated. From the calculated total critical fracture area (a) known from the mapping and the width of the intersection zone the volume of rock within which canisters would intersect fractures of critical radius is calculated. The product $a{\cdot}L$ is the fraction of the total volume for which positioning of canister centre-points should be avoided. This product is also the mean number of fractures intersecting a canister in the repository and this number follows a Poisson distribution. Therefore, the probability of a canister being intersected by a discriminating fracture, ε, can be written in the form $\varepsilon = 1 - \exp(-a\,(L))$.

The author has applied the stereological analysis to the deposition of 4500 canisters in Forsmark which results in 1.91 % of the canisters - 86 in number - are intersected by discriminating fractures. For this analysis the authors is using 4 sets of steeply dipping fractures and one set of subhorizontal fractures from the presented DFN model of the target area for the repository in Forsmark. The smallest fracture considered has a length of $r_0 = 0.318$ m. The exponent in the power law size distribution for the five fracture sets varies between 2.81 and 3.02. Additional data about the fracture sets are presented in Tables 1 and 2 of the article. Additional input parameters for the calculation are maximum and minimum fracture radius $r_{Max}.= 500$ m and $r_{Min}.= 100$ m, respectively.

The sensitivity analysis performed with the given data in Tables 1 and 2 clearly show minor increase in probability of failure for $r_{Max}.> 500$ m (see Figure 7). If the critical shear distance at deposition hole is doubled to 0.2 m compared to the assumed allowed maximum displacement of 0.1 m the likelihood of a canister being intersected by a fracture is down to 0.005 (Figure 9). The same likelihood is obtained when using the ratio b of fracture radius versus displacement (Figure 8). There is a large sensitivity of ε to the exponent k in the fracture radius model, showing a variation in ε by almost two orders of magnitude from a variation in k of only ±20%. This is noted by the author but not discussed, which clearly also would have been useful, given that uncertainties are so essential is these discussions.

In Section 6.2 of the report by Munier and Hökmark (2004) about respect distance the authors claim that fractures exceeding 100 m radii can be detected in the deposition holes and that respect distance used by SKB in the calculations have been based on that assumption. Also, the authors claim that it is reasonable to assume “that fractures with radii exceeding 50 m can be detected using standard mapping techniques, with adequate accuracy” (cit. p. 43). What will be the result of using the suggested model by Hedin if SKB assumes $r_{Min}.= 50$ m instead of $r_{Min}.= 100$ m? If SKB can prove the ability to detect fractures underground with a length less than 100 m the modelling results indicate that the likelihood of fracture intersections in the deposition holes will increase. The amount of reduction needs to be calculated by SKB and the results compared with data presented for $r_{Min}.= 100$ m in the article. Also, the importance for SKB to gain confidence in the description of fracture statistics in the interval from tens up to a few hundred metres is fully supported.

In the Discussion and conclusion, Section 8 of the article, Hedin mentions that results of the sensitivity analysis prove that the model is more sensitive to uncertainties in parameters related to fracture radii distribution than those related to orientation distribution. This can be an effect of the fact that four of the fracture sets applied in the simulation for Forsmark have sub-vertical plunge and one set is sub-horizontal. An application of the model to a site with more gently dipping fractures might show that orientation distribution is also sensitive to the results. Orientation of the deposition tunnel axes with respect to the trend and plunge of fracture sets will enhance the importance of orientation relative fracture radii and increase the probability of fracture intersections in the deposition holes.

8.3 Questions

1. The modelling performed with FLAC3D and related codes assume a flat, homogeneous, continuous fault surface. What is the expected effect of introducing more fault complexity in the modelling?

2. Linear fracture stiffness was assumed for the target fractures in the simulations. What will be the effect of using non-linear properties?

3. Static fracture toughness values have been used in the dynamic analyses of the target fracture response. Why not use rate dependent toughness values?

4. Has SKB analysed the risk of target fracture propagation from fault earthquakes for target fractures in the immediate vicinity of the deposition holes but not intersecting the hole?

5. Has SKB considered subcritical fracture propagation of the target fracture in computation of respect distance?

6. Has SKB considered stress concentration at the tip of a rupturing fracture?

7. How important is the uncorrelated distributions of fracture radius and fracture orientation in the stereological analysis presented by Hedin (2008)?

8. How can the existing FPC and EFPC be developed to describe propagation of existing fractures and development of new fractures in the vicinity of the deposition hole?

9. What are the arguments for changing the shear displacement from 0,1 to 0,05 m as rejection criteria for target fractures intersecting the deposition hole?

10. Has SKB determined probability distribution of slip on target fractures for intermediate magnitude earthquakes, and if so what is the result?

11. How is SKB considering the width of the faults in the FLAC3D and 3DEC analysis and what fault zone width should be used when there is a range?

12. Has SKB investigated the strength and deformability of the host rocks surrounding the granite lens to determine the strength and stiffness ratios between the lens and the surrounding metavolcanics?

9. Discussions in working groups

9.1 Instructions

Working group assignment: This is a preliminary and very brief structure of issues. Develop and modify this structure such that it is more complete and detailed. It should provide an effective basis for the upcoming SR-Site review. We should already before the application is submitted know where we should focus the licensing review. The key concern is the gathering of sufficient understanding and information to judge safety significance (and not to resolve research issues).

Please identify issues connected to 1) available data, 2) model assumptions and approaches, 3) safety significance, 4) issues not identified by SKB (in delivered materials).

1. Seismic risk due to future glacial periods

1a. Estimation magnitudes and associated frequency for earthquakes near repository area

Relevance of field observations at Forsmark and within Scandinavia in general

General understanding of mechanism of post glacial faulting

1b Definition of respect distance concept

Deformation zones that may host large earthquakes

Computation of shear movement distance in secondary features

Relevance of aseismic movement

1c Discriminating fractures and use of deposition hole placement criteria

Detection of discriminating features during operational phase

DFN model for Forsmark (e.g. maturity, relation between size and frequency)

Formation of new fractures during earthquake events

2. Thermally induced seismicity?

Can new fractures be formed due the thermal heat load?

Can there be seismic or aseismic movement?

Can existing fractures and faults be activated?

3. Seismic risk during initial and operational periods

9.2 Results from Working Group 1

Working Group 1 participants: Ari Luukkonen, Ove Stephansson, Jonny Rutqvist, Conrad Lindholm, Lena Sonnerfelt, Georg Lindgren, Karin Olofsson, Shulan Xu, Öivind Toverud.

9.2.1 Seismic risk due to future glacial periods

9.2.1.1 Estimation of magnitudes and associated frequency for earthquakes near repository area

Relevance of field observations at Forsmark and within Scandinavia in general

- The next glaciations may generate different surface faulting in other parts of the country compared to the latest postglacial faulting.
- The surface faulting in Lapland is a historical singularity (Lagerbäck). This does not exclude the likelihood of large postglacial earthquakes in southern and central Sweden without surface ruptures.
- The use of Lapland postglacial faulting in Forsmark is possibly a “worst case” scenario. It is useful to use this versus the public. Mmax=7.5 is accepted.
- Field studies at Forsmark provide no observations of postglacial movements and is generally undisturbed considering the repeated tectonic processes it has gone through.
- The frequency of large earthquakes in postglacial conditions was estimated in SSI 2005:20. See SR-Can report for the frequency.
- A site specific detailed seismic hazard analysis is recommended both for magnitude and frequency of M6+ earthquakes under the present tectonic conditions.

General understanding of mechanism of post glacial faulting

- The general understanding:
  - Dominantly reverse faulting (downdip to the east)
  - Occur over a short time period (often in one major event).
  - Can step over pre-existing lineaments (observed in Sweden and Finland).
  - Lengths up to 155 km and 10 meter escarpment height.
  - The mechanism has been confirmed with modelling (Lund et al., 2009)

9.2.1.2 Definition of respect distance concept

Deformation zones that may host large earthquakes

- It is important that the distance from the fault gauge is composed of two parts:
  - The width of the highly fractured zone (width = F(fault length)) + The respect distance
- Canisters should not be placed closer than the above combined distance
- This concept has a high safety significance.
- Model approaches and assumptions should be looked into and clarified: Is it 100 meter fixed? Present understanding is diffuse. Clarifications from SKB needed.
- The representativity of M=6 also for larger earthquakes is questioned. Assumptions and models adequacy should be addressed.
- If the swelling pressure in the bentonite is reduced, shaking from strong earthquakes may cause movement of the canister. This will increase corrosion and secondary effects. If a proper eq. hazard study can demonstrate low probabilities for strong shaking the risk of canister-rock contact is demonstrated to be low.

Computation of shear movement distance in secondary features

- The displacement of the target fracture used by SKB is limited to the centre of the fracture. There is strong need for studying fracture initiation and propagation out to and possibly in extension of the fracture tip. The assumption of a linear perfectly elastic medium

may not be conservative (as SKB claims). *Recommendation:* SSM is recommended to initiate a small demonstration study to this end.
- SKB can not use the glacial data to demonstrate thermal effects.
- *Recommendation:* The cumulative effect of thermal and glacial effects on displacements should be investigated, both seismic and aseismic slip.
- High safety significance and presently not adequately identified by SKB
- What is the ultimate limit of displacements on secondary fractures with repeated main earthquakes?
- The 10 cm limit has been changed to 5 cm limit. What is model behind this change and behind the numbers?

A seismic scenario

- *Recommendation:* It is recommended that SSM generates an earthquake scenario with canister integrity violation. This may be based on a) sudden rupture, b) slow rupture, c) induced rupture due to excavation, d) induced rupture due to heating/cooling, e) induced due to swelling pressure. The scenarios should cover the early stages (the first ~10000 years) and the glaciation period(s).

Relevance of aseismic movement

- The aseismic slip is of potential high relevance. Significant horizontal and vertical movements on the surface are observed (GPS) without known correlation to seismicity. Small strains are involved.
- This relates to the question if the absence of seismicity below thick ice sheets (Greenland) also reflects lack of movements. The lack of seismicity under glaciated areas is also reflecting a lack of monitoring capabilities (i.e. there is a lack of large earthquakes but micro-earthquakes have not yet been ruled out).
- Question: Is the Forsmark site “sufficiently” protected as lens embedded within faults and the softer meta-volcanic rocks that will take up the movements or is it the rock strength of the lens that makes internal deformations less likely?
- *Recommendations:* Instrumentation of Forsmark with surroundings with GPS and seismic sensors and InSAR images.

Formation new fractures (large scale)

- SKB claims it will not occur (or extremely unlikely). The issue has *high safety relevance*.

Extension of deformation zones

- This issue has *high safety significance*.
- The continued growth of existing faults is well demonstrated on all scales.
- Claim by Munier: Growth will not cross another fault (arrested faults).
- *Recommendations:* One should model various geometric and stress direction scenarios to demonstrate to which extent “arresting faults” may stop fault extension and to which extent “arresting faults” may be cut. Models at depth may differ from models at the surface.

9.2.1.3 Discriminating fractures and use of deposition hole placement criteria

Detection of discriminating features during operational phase
DFN model for Forsmark (e.g. maturity, relation between size and frequency)
Use of EFPC critiera
Use of geological characterisation and geophysical methods during excavation phase

- This review group does not feel competent for fair judgment on these issues. SSM specialists that have a better grip on the problem should be challenged on these issues.

9.2.2 Seismic risk connected to the evolutionary stages before the glacial stages (thermally induced seismicity or seismic risk prior to glaciation)

Probability of significant earthquake during first 1000 years

- *Recommendation:* A proper high quality, site specific hazard study is requested (SSHAC Level 2 or 3). Probability of significant earthquake(s) due to the heating/cooling process should be included.
- *Recommendation:* A seismic monitoring system is needed before, during and after construction and operation. This is important for scientific investigations, safeguard, safe working conditions during construction and for public information.

New fractures formed due to the thermal heat load

- Spalling in tunnels and in deposition holes are likely. The important question is if it will be limited to spalling or extend to fault growth.
- Two SSM reports are available on this issue.
- Model: The repository situated in a horizontal stress regime. The heating may increase the anisotropic stress and favour sub-horizontal fracturing at dipping angles through the repository. This model is recommended to be investigated and should be seen in connection with fault reactivation.
- *Recommendation:* Modelling has been recommended (see above).

Seismic or aseismic movement

- See above discussions.

9.3 Results from Working group 2

Working Group 2 participants: Tobias Backers, Björn Brickstad, Hilmar Bungum, Mikael Jensen, Katriina Labbas, Maria Nordén, Paula Ruotsalainen, Bo Strömberg, Sven Tirén.

9.3.1 Classes of issues

Period/location	**Local/repository**	**Regional**
Construction phase up to the initiation of the first glaciation	**1**	**2**
Glacial cycles	**3**	**4**

When needed (no ranking)

A. Needed in the planning of the underground construction
B. Needed during construction
Input data to the safety assessment/evaluation is continuous, decrease conservativeness.

Ranking list (based on safety)

1. most important
2., 3, …

Issue	**Class**	**When needed**	**Ranking**
Description of structural pattern/incl. mapping procedures: - fracture termination/connection - length of structures - length distribution of separate fracture sets/families	1	A+B	2
Discriminating structures (>50m?) FPI/FPC, EFPI/EFPC - characteristics - identification	1	B	1
Characterization of deformation zones (e.g. tunnel mapping): - deterministic description per set/family - geometry of internal fracture pattern, incl. natural variability along the structure (reference structures) - transition/disturbed zone vs. core zone - hydrogeology	1	A+B	1
Respect distance - reasoning for 100m + transition/disturbed zone - guideline with – e.g. a plot	1	B A	2
“Complete knowledge” of the location of reactivation?	1		1
Site specific hazard analysis for the construction phase	1	A	1
Excavation effects: - vs. depth - stress concentration - stability - hydrology - hydrochemistry - induced seismicity - hydrology -hydrochemistry - effect on Rock Suitability Criteria (cf. Posiva), cf. current conditions - EDZ	1	A+B	1
Heat: - induced seismicity - hydrology - new fractures - effect on Rock Suitability Criteria (cf. Posiva), cf. current conditions - propagation of EDZ - comparison to the effect of glaciation	1	A A+(B)	1
Probability of earthquakes - limited impact of smaller earthquakes during construction - larger earthquakes on larger time scale - geological evidence of previous earthquakes (cf. hidden earthquakes)	1+2+3	A	2
Combination of all sources of stresses (excavation, heat, tectonic, glaciation and lateral variations incl. topography): - new fractures - propagation of fractures, critical and sub-critical; incl. <50m to fractures >50m (a reason for missing FPC/EFPC, cf. Hedin)	1+3	A	2

Seismic pumping (Muir-Wood and King 1993): - hydrogeology/water transport/mass transport - hydrochemistry/upconing of saline water	1+2+3	A	2
More realistic finite fault model/modelling (simplicity of the driving model)	1+3	B	2
Shear length vs. fault length (underestimate slip? Consideration of realistic stiffness models for fractures)	1 to 4	A	1
Width of transition/disturbed zone vs. fault length (cf. respect distance)	1 to 4	B	2
Effect of advancing future glaciers - Background stress field - contributing sources of the background stress field - lateral variation in crustal structures - effect of uncertainties (result sensitive) - Synthetic stress model (vs. depth)	3	A	1
Uncertainties related to the ice model (time & space)	3	A	2
Weichselian glaciation similarity of the next glaciation (worst case?)	3	A+B	1
Systematic treatment of uncertainties, propagation of uncertainties: conservativeness	-	A+B	1

10. Review by invited experts

10.1 Dr. Tobias Backers, geomecon GmbH, Potsdam, Germany

10.1.1 Introduction

This documents contains short summaries and comments to the publications listed in the next section. The review was done from an engineering geology and fracture mechanics perspective. Hence, not all aspects of the reports could be judged upon in all detail. Besides the questioning of details of the report also some suggestions for further studies are given.

The selected reports are about the generation of earthquakes in Sweden, mainly triggered by glaciation and related rebound of the crust, and the possible effects of such an event on a potential repository. When it comes to the effect an earthquake could have on a repository the analyses are mainly concerned to analyse under which circumstances an earthquake could result in damage of the canisters. However, in this analysis only static slip on existing fractures is assumed. The mechanical effect of introduced slip on fractures in the repository is generally not considered. Also lack the analyses the study of the influence of the excavations in the repository on the local stresses. The combination of the elevated stresses in the repository due to the excavations (and thermal stresses), plus the stresses and displacements from glaciation, tectonics and earthquakes needs to be considered when analysing the potential for creation of not only canister damage, but also development of fluid pathways to the biosphere.

List of articles:

Bäckblom, G. and R. Munier (2002). Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. SKB TR-02-24, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.

Hedin, A. (2008). Semi-Analytic Stereological Analysis of Waste Package/Fracture Intersections in a Granitic Rock Nuclear Waste Repository. In: Mathematical Geosciences, DOI 10: pp 008-9175.

Lagerbäck R. and M. Sundh (2008). Early Holocene faulting and paleoseismicity in northern Sweden. Research Paper C 836. SGU - Sveriges Geologiska Undersökning.

Lund, B., P. Schmidt and C. Hieronymus (2009). Stress evolution and fault stability during the Weichselian glacial cycle. SKB TR-09-15, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.

Munier, R. and H. Hökmark (2004). Respect distances. Rationale and means of computation. SKB R-0417, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.

Reviews

The individual papers are discussed separately in alphabetical order of the first author in the following.

10.1.2 Bäckblom and Munier (2002)

Effects of earthquakes on *the deep repository for spent fuel in Sweden based on case studies and preliminary mode) results. SKB TR-02-24, Svensk Kämbränslehantering AB (SKB) Stockholm Sweden.*

Bäckblom and Munier give in their study a broad survey on the effects of earthquakes on a repository for spent nuclear fuel in Sweden. The conclusions are drawn from summarising information form literature, interviewing of different persons and institutions and own impressions from field trips. The very complex data was gained and evaluated in about a years time, which appears very short.

After an introduction to the topic and the problem statement the report provides empirical background to the influence of shaking introduced by earthquakes in underground excavations, followed by the presentation of the influence of faulting on the openings. The summary of the studies mostly based on observations is followed by a discussion of the observations in combination with a supportive presentation of numerical and other studies.

In general, it was stated that the influence of earthquakes on underground openings is much less than on surface buildings. The influence of shaking on underground excavations is judged very little and it is concluded that more severe damage is limited to the direct vicinity of displaced faults only.

Comments

The summary of the arguments from the different sources is very short and appears to be not comprehensive in some cases. Understanding the argumentation in the context of the study at hand is sometimes hard, as the conclusions are not fully supported by facts. The conclusions presented at the end however appear much more precise as might be derived from the text itself without reading the cited publications. The results gained from the survey need to be explained in much more detail to be able to comprehensively understand the implications.

In the problem statement (section 1.2, page 14) only one possible issue before closing the repository is mentioned, which is related to the damage of equipment. No scenario is sketched that accounts for the possibility that during the transportation of the canister to the deposition hole and the subsequent placement in the deposition hole an earthquake happens. During the transportation not only the equipment for transportation and placement could be damaged, but even more important also the canister itself. This might be a little off the geology related discussions, but still is a possible scenario, where damage could be done to the canister. A rockburst / rockfall in the open access tunnels might damage the canisters and interrupt operations of the repository. Further, additional damage in the EDZ might be introduced with implications for fluid pathways.

The list of possible issues after closure (page 15) addresses topics related to damage of the integrated multi-barrier isolation only. Another requirement, which might be of interest, is the retrievability of the deposited canisters. I do not know if this is a requirement from the Swedish legislation. If an earthquake hits a repository the barrier system might stay intact, but probably the access tunnels or shafts may be destroyed such that the retrievability is made more complicated or impossible under certain circumstances.

The figures 2-4 through 2-6 show empirical information as ‚number of cases' vs dass (depth), dass (rock type) and dass (support) bar charts. However, as the amount of information, i.e. number of cases, of each dass is not the same for each dass, the conclusions drawn from the figures appear weak. The following table A and figure A reworks the data as given in table 2-3 and figure 2-4. The strong statement on page 35, that „the frequency of damage reports decreases with depth [...]" is not as clear in the reworked data. The cases with <no damage> show no trend with increasing depth and the highest percentages of moderate to heavy damage are at the depth levels of the planned repository. If the classes for <slight or no damage> are combined into one, the picture looks different; the likeliness for moderate to high damage is low in all cases.

On page 37 it is stated that the stress situation in mines can be quite different from that in civil engineering constructions. This statement should be discussed to be able to decide if observations from mines can be transferred to be used for a repository. In a mine preferred orientations for failure are used as design criterion whereas in building a repository all caution is take to reduce damage.

The facts on the 1976 Tsangshan earthquake (page 43) appear regarding the number of casualties doubtful; most sources claim about 250,000 deaths.

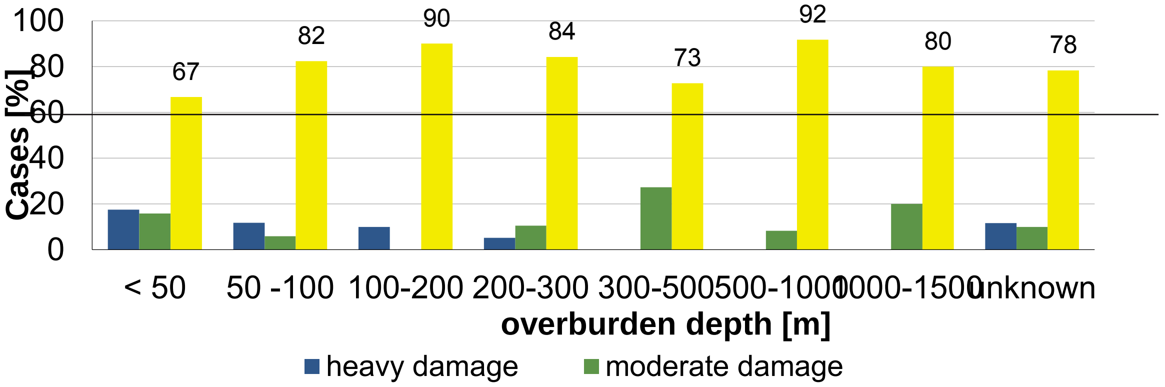


Figure A. Adapted and extended from Figure 2-4, page 36. (top) reworked presentation of data as in the report, (bottom) the cases for <no to slight damage> are taken as one cäss as the judgment on damage is a quite subjective matter, and it was not always clear how the damage classification was done (see page 35, second paragraph).

Depth [m]	Extent of damage											
	heavy		moderate		slight		no		sum (slight; no)		total	
	[1]	[%]	[1]	[%]	[1]	[%]	[1]	[%]	[1]	[%]	[1]	[%]
< 50	10	*18*	9	*16*	14	*25*	24	*42*	38	*67*	57	*100*
50 -100	2	*12*	1	*6*	2	*12*	12	*71*	14	*82*	17	*100*
100-200	1	*10*	0	*0*	3	*30*	6	*60*	9	*90*	10	*100*
200-300	1	*5*	2	*11*	3	*16*	13	*68*	16	*84*	19	*100*
300-500	0	*0*	3	*27*	4	*36*	4	*36*	8	*73*	11	*100*
500-100	0	*0*	1	*8*	9	*75*	2	*17*	11	*92*	12	*100*
1000-1500	0	*0*	1	*20*	0	*0*	4	*80*	4	*80*	5	*100*
unknown	7	*12*	6	*10*	14	*23*	33	*55*	47	*78*	60	*100*
total	21		23		49		98		147		191	

Table A. Adapted and extended data from Table 2-3, page 35.

In section 4, page 74 issues of relevance are defined, that are to be discussed. One aspects appears to be missing: Is there a chance that a canister gets into contact with the rock? The bentonite buffer is in comparison to the rock material an incompetent soft inclusion. (a) If deformation on fractures is not happening instantaneously but is accumulated successively due to time-dependent stress relaxation at some distance from a major fault, the bentonite also behaves plastically and will “flow‘ around the canister until the canister will be partly in contact with the rock material. This might introduce a local stress concentration on the canister and could introduce damage. (b) A shock wave from an earthquake might cause the bentonite buffer, which may be assumed to be water saturated, to liquefy due to the thixotropic nature of bentonite suspensions, as made use of in the drilling industries. The key arguments in the cited study by Pusch (2000) do not become clear (section 4.5, page 80), why the risk of the buffer being liquefied is not evident. If the buffer might be liquefied the risk for a rotation, sinking in the suspension (buoyancy?), or similar of the canister might be given, with the consequence of a contact of canister and rock heading unfavourable stress peaks on the canister. (c) Another issue not discussed is the influence of an earthquake on an improper manufactured Bentonite buffer. If the buffer has fluid filled larger pores, these may be the nucleation point for liquefaction and cause dewatering channels giving way for later for fluid flow. However, these might be assumed to be closed again due to the rheological nature of the bentonite, but still the possibility and consequences of such fluid pathways should be considered.

The first issue on page 15 ‚Damage could occur on the canister since the earthquake could create a pulse of high water pressure in addition to the dynamic stresses created by the earthquake‘ is not further convincingly addressed in the report. On page 76, it is mentioned that there is an abundance of papers on the issue available, but only two are referred to shortly. It is stated that in normal faulting and strike-slip regimes an increase in expel of water was observed in the field without discussing the causes. For reverse faulting, which appears to be the main regime for (northern) Sweden after the last glaciation, no increase of expel of water was observed. However, it would be interesting to know if the same mechanism, which increases the water pressure in normal regimes, reduces the water pressure / table in reverse faulting regimes, yielding an increase in effective stresses. In return, it would be instructive to discuss if there is a chance for normal faulting (see Lund et al 2009, e.g. page 65, ice load induced stresses show normal regimes at start of glaciations) or strike-slip (evident in southern Sweden?), which then might trigger faulting / fracturing by local fluid pressure peaks.

The issue of whether a groundwater overpressure may cause complete friction loss in the rock is not convincingly discussed due to a lack of available information and this fact is mentioned by the authors. But this only accounts for a temporal increase of fluid pressure. However, even if the fluid pressure is increased locally by an earthquake for some time, the stress conditions on fractures in or near a repository may change leading to activation of time dependent fracture growth in otherwise low permeable rocks such as granitoides. This issue is not addressed at all. This may lead to the creation of larger fracture with the potential of linkage to other fractures or deposition holes.

The questions whether new fractures can be created are not conclusively answered. It is stated that the release of energy is dominated by displacements along existing faults and fractures. This is intuitively correct; however if there is no such feature in a direction favourable for slip, or not enough fracture surface for accumulation of the slip, new fractures may be created. The rock at Forsmark is of comparably good quality and features only few fractures.

It should be considered analysing if there might be a configuration in which no zone of weakness can release the energy and new fractures are created, or if there might be a change of stress regime causing such configuration. Moreover, the combination of external stresses on the repository (tectonics, glaciation, earthquakes) plus the internal stresses (stress redistribution around excavations, thermal stresses due to radiation from canisters) is not considered. It may be anticipated that the combination of the external stresses with the internal stresses might draw a different picture.

But even when assuming that only existing fractures are made active, clearly they may extend and create new fracture surface. A train of thought might start from the publication of Vermilye and Scholz (1998). They have argued that the width of a zone of brittle deformation (fracture process zone) around a fault is about 1.6% of the fault length (figure B). If a main fault is increasing its length for some reason, the width of the process zone increases also. Hence there is evidence for the risk of the creation of new fractures.

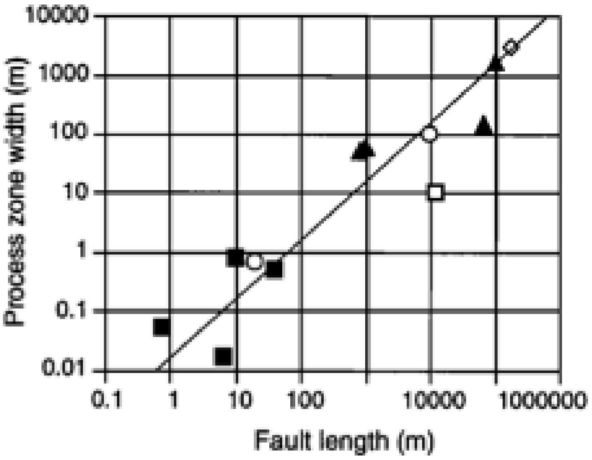


Figure B. Process zone width versus fault length. (Vermilye and Scholz 1998, figure 15.

In the discussion of the proper respect distance it is stated that „all faults surrounding any potential site for nuclear wastes must be examined and respect distances estimated for each fault". The concept by Vermilye and Scholz (op.cit.) is referred to. However, the concept of Vermilye and Scholz has not been used to discuss the reported cases. This would have been very instructive. Cowie and Scholz (1992) and Vermilye and Scholz (1998) showed that (a) the process zone fracture density shows a logarithmic decrease away from the fault and (b) there is a linear scaling between the process zone width and the length of the associated fault (16:1,000) (see figure B). This observed linear relationship between process zone width, i.e. the zone of influence of fracturing introduced by the main fault, and the length of the fault should be considered in the discussion of the respect distance.

An observation not discussed in the context of the definition of a respect distance is the M7 Izu-Oshima-Kinakai earthquake. The data set presented includes information about the length and the width of the fault. The ratio of width to length is 1:1.7 for the main fault and 1:2 for the subsidiary fault. The width of the fault is much larger than one would expect from the Vermilye and Scholz observations. This implies 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 C shows some of the data from Chapter 3 of the report in the context of Vermilye and Scholz data giving rise to the discussion if such a plot should be established for Fennoscandia.

The discussion of the questions if the repository itself can induce earthquakes ignores the fact that canisters heats up the rock and introduces additional stresses in the repository. The influence of such should be considered in the analysis. Assuming linearity and isotropy, a temperature change ΔT may result in a stress change Δσ of $\Delta\sigma = \Delta\theta = 3\beta K\Delta T$, where β is the coefficient of thermal expansion and K is the bulk modulus. β for Forsmark granite is about 7.5·10-6 1/°K (Åkesson, 2007, P-07-33) and K is calculated from the Young's modulus and Poisson's ratio, K ≈ 48.7GPa. With these values and the assumption that the rock is constrained in its expansion a temperature increase of 1°K will result in a stress increase of about 1MPa.

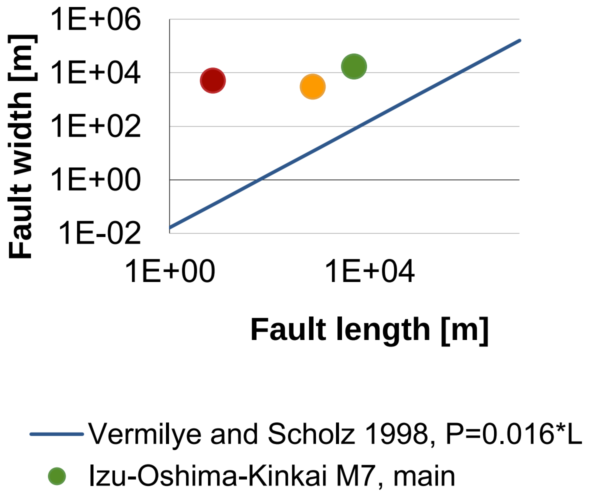


Figure C. Fault width vs. fault length data from the report plotted with the regression from Vermilye and Scholz 1998.

10.1.3 Hedin (2008)

Semi-Analytic Stereological Analysis of Waste Package/Fracture Intersections in a Granitic Rock Nuclear Waste Repository. In: Mathematical Geosciences, DOI 10: pp 008-9175.

The paper presents a semi-analytical methodology to estimate the likelihood E of a canister being intersected by at least one fracture that may show a displacement larger than tolerable for canister integrity. The method is developed for the current KBS3V layout with the canisters vertically deposited. The fracture intensity, radius and orientation distribution are the geostatistical input to the proposed method. The maximum allowable displacement on a fracture is suggested from literature to be 0.1m and the minimum fracture radius that has to be avoided is derived from a given empirical relationship.

It is calculated from the DFN data of the Forsmark site that the total likelihood of a canister being intersected is about 2%, corresponding to roughly 86 canisters in a 4,500 canister layout.

After an un-discussed sensitivity analysis the proposed methodology is verified using a numerical approach. The calculated E and its independency of repository rotation were shown by the numerical simulations. The simulation consisted of 50,000 generated fractures from the Forsmark data.

It is concluded that the method is capable of analytically calculating the likelihood of fractures intersecting canister deposition holes from frequently used fracture statistics descriptions. The results of the analytical solution are sensitive to the input data such that the fracture radii distribution is more critical than the orientation distribution for the given assumptions.

Comments

Due to my lack of expertise on the statistics I may not judge on the proposed method itself. My comments are more like hints to the assumptions and as how to adopt the outcome.

The method is based on the assumption that the host rock is behaving linear elastic and hence the displacement at the periphery, i.e. tip of a fracture, is zero. This is not strictly valid and so is the assumed r'crit (equation 9). One could consider replacing the equation for the displacements on a fracture with a model from non-linear fracture mechanics to yield more realistic results. 1f such an approach works needs some clarification.

The given calculation of E in the results section is based on the canister height and diameter of the canister rather than the deposition hole. It should be tested if this analysis may also be adopted to estimate the likelihood of fractures being present close to the deposition holes in the area of increased stresses due to redistribution around the holes. This information may help to estimate the risk for the generation of a fracture network giving way to fluids.

10.1.4 Lagerbäck and Sundh (2008)

Early Holocene faulting and paleoseismicity in northem Sweden. Research Paper C 836. SGU - Sveriges Geologiska Undersökning.

Lagerbäck and Sundh present in their research paper a compilation of observations and indications for late- or postglacial faulting and related seismicity in Sweden.

From air photograph interpretation, literature compilation and field work they derived a map of the faults inferred to have been active during late- or postglacial times. The identified fault scars are mostly oriented NNE-SSW and show reverse faulting. The identified scars are clustered in northern Sweden with little evidence for significant features of similar origin in the southern part of the country. The major faults or fault systems of concern are the Pärvie fault system, the Lainio-Suijavaara fault, the Merasjärvi fault and the Burträsk and Röjnoret faults, besides several smaller features such as Sorsele, Storuman, Malaa & Ismunden and others.

The fault scars show offsets of few meters up to some decametres. With the assumption that this offset has been generated in a single occasion, this suggests that significant seismicity must have accompanied the brittle events. The seismic events are brought into connection with the disappearance of the inland ice sheet alter the last glacial. It is argued that the start of the uplift of the Fennoscandian shield is the cause of the seismic events.

For specification of the time of the faulting activities, mapping and interpretation of landslides and soft sediment deformation structures yielded support that the faulting has most likely taken place late- or postglacial. The paleoseismic records comprise low angle landslides, liquefaction records such as sediment compaction or dewatering structures. Further, as some boulders are still in labile positions today, it is concluded that alter their deposition during the melting of the ice cover no major seismic event has occurred.

Comments
The research paper is a good compilation of geological observations.

It is suggested with reference to Muir Wood (1989) that the uplift of the Fennoscandian shield is the reason for the recent seismicity in the Scandinavian countries. This is in contradiction to several authors (Wahlström 1993), and this fact is also acknowledged in the introduction. However, the discussion of the fault scars and their temporal evolution is solely based on the uplift theory, and lacks discussing a tectonic approach to the causes and possible conditions of seismicity.

Wahlström summarised arguments from different sources, and concluded, that not only the isostatic heave is the main reason for the seismicity but also the influence of tectonic stresses from the Mid Atlantic ridge. Wahlström suggests a strong evidence from the revisitation of the findings reported in literature that tectonic forces acting throughout the period of glaciation might have accumulated large energies, prevented from being radiated by the load of the ice cap. The release of load from melting the ice with the start of rebound would then have been a condition for, but not the cause of the intense seismicity.

If the conclusion of Wahlström (op. cit.) is right, that the tectonic forces accumulate the energy and an ice cap prevents radiation, one should also revisit the conclusion that the faults were created in a single events. If the melting of the ice cap is giving the condition for seismicity through reduction of normal load, the stresses are approaching the condition for failure slowly. Assuming existing faults being reactivated, which is not explicitly discussed in the report, creep and pre- existing faults may be a likely mechanism of deformation also. This would mean that the release of energy would not necessarily have happened in a single high energy event, but the energy might have been released in several events.

The different possible causes for the seismicity in Sweden should be discussed and the field evidence reconsidered for those models. If the tectonic forces have delivered the energy for seismicity and the ice load has buffered the energy, this should be considered when identifying the possible scenarios under which seismic events may occur.

What if the faults were activated or created during the glaciation? This makes a difference in time of about several 10ka. Probably the faulting was initiated at the peak ice load. This does not necessarily contradict the observation made in the quaternary sediments and boulders. Is there any configuration which a reverse faulting may be achieved by an ice cover? Can it be ruled out?

10.1.5 Lund, Schmidt and Hieronymus (2009)

Stress evolution and fault stability during the Weichselian glacial cycle. SKB TR-09-15, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.
This well documented piece of work addresses the stress evolution and fault stability during the Weichselian glacial cycle. The numerical modelling work employs a finite element approach (ABAQUS) to determine the stress field evolution due to the ice cover during the last glaciation cycle, i.e. the last 70ka before present (BP).

The development of the up to 2.5km thick ice cap in Fennoscandia made the lithosphere to sink down due to the additional vertical stress of up to ASv = 23MPa. This causes the stress field in the crust to alter with time. The deglaciation results in uplift of the lithosphere and related stress relaxation processes. The mode) of the Weichselian glaciation used spans 120ka BP including two peaks of ice cover at about 68ka BP and 18ka BP and the related deglaciation periods. The extend of the ice cap is defined by the SKB reference model.

The used physical approaches are referred to and some benchmarks show the validities and shortcoming of the simulation setup. Besides general agreement, the most important shortcoming of the model according to the authors is the lack of the representation of the sea-level, which may be giving errors of about 10% on the rebound velocity field. Further, earlier glaciations and their remnant effects are not included in the model.

The ice cover is modelled as an elliptical boundary load. The solid earth models used for calculation of the glacial isostatic adjustment (GIA) are built up of elastic layers (low Young's modulus and Poisson's ratio < 0.3) representing the lithosphere on top of incompressible viscoelastic half space (high Young's modulus, Poisson's ratio 0.5, viscosity 10^{21}-10^{22} Pas). The topography is not represented. An internal block of high discretisation is 4,100 x 2,800 x 1,200 km and is embedded in a 10 times larger half sphere. Out of the large scale domain two sub models are calculated covering the regions of interest in Fennoscandia. The small scale models inherit the material properties and is driven by the computed displacements from the large scale model.

Ten different models are tested initially, covering different layer configurations with different sets of parameters. Six models show a horizontal stratification of lithosphere and underlying strata, whereas four models are made up of laterally varying lithosphere models. The Young's moduli used are generally increasing with depth. Some of the Input data sets use comparably high Young's moduli for the uppermost layers.

From a series of test runs aiming at comparing the simulated velocity results to GPS data (Bifrost) it was concluded that a mantle viscosity of 10^{21} Pas produces rebound velocities that fit the measured data reasonably well. The structure, i.e. stratification, of the lithosphere is reported to be less important for simulation of the velocities, whereas the average Young's modulus and thickness are sensitive parameters. The different models were used to simulate the glacially induced stresses in their spatial and temporal variation.

In the horizontally stratified models the general pattern of the glacially induced horizontal stresses is very similar, but the magnitudes of the highest stresses varies significantly. From the models it was seen, that /a/ the decrease in maximum magnitudes of stress corresponds to the decrease in Young's modulus, /b/ a viscosity decrease of the underlying strata results in higher maximum stresses, and /c,/ the stresses are affected by the lower mantle. Comparing the stresses at the height of glaciation at 18.5ka BP to the deglaciation phase 10ka BP, the simulations consistently show that the stress magnitudes decrease during deglaciation. The largest horizontal stresses are concentrated in Northern Sweden and Finland, north of the Bothnian Bay. At both times the models predict the maximum horizontal stress SH to be approximately perpendicular to the strike of the large end glacial faults, in agreement with the sense of slip in a reverse stress state. The computed shear stresses show an increase from 18.5ka BP to 10ka BP and the maximum shear stresses are concentrated in the northern Sweden and Finland in the region of the end glacial fault scarps. All models show a zone of tensile stresses around the edge of the glaciation.

Depth profiles of stress are shown for a 100km thick layer along a profile through the locations of Oskarshamn, Forsmark and the Pärvie fault. Most of the models show a concentration of shear stress at the base of the lithosphere below the region of the end glacial faults at 18ka BP that moves upwards for 10ka BP. The temporal pattern of the glacially induced stresses at the sites is governed by the ice history.

In the models with laterally varying lithosphere thickness the stress fields show less undulations, but the shape and magnitudes of stresses are in general similar to the outcome of the flat layered models. Again, a concentration of stress is predicted in the northern part of Sweden near the Bothnian Bay. Significant tensile stresses are evident in some areas of the models. The depth profiles show similar results to the flat models also.

The temporal variation of stresses is plotted for three locations, i.e. Forsmark, Oskarshamn and the Pärvie fault. The results for the two potential candidate sites show at times of glaciation normal stress regimes. On unloading the ice load is quickly removed, and at the computed 500m TVD the stress regimes turn into reverse. At the start of glaciation significant stresses as high as roughly 4-7 MPa are predicted. In general, the stresses at Oskarshamn are smaller than at Forsmark, which is consistent with the reduced exposition to ice cover.

At the Pärvie fault the stresses are computed for a depth of 9.5km. The stresses do not vary as much as for the locations of the candidate sites as the ice coverage was almost for the whole period of computation. At most times the stress field is normal in most models, however, at the end of the last glaciation all models consistently predict reverse stress states. Interestingly the two simplest horizontally stratified models predict reverse faulting regimes at all times during glaciation. None of the models suggest very large induced stresses at Pärvie, nor are the stresses larger than at Forsmark or Oskarshamn. As magnitude 8 earthquakes are reported, this needs discussion.

It is concluded from the simulation runs on the glaciation induced stresses that the earth model is of less importance when predicting stress distributions than the ice model. The earth model mainly affects the range of the stress magnitudes and rate of stress change. The main difference in the response of the flat and laterally varying earth models is a slight shift of the area of high stresses to the West, and increased focussing of the high stress region during deglaciation.

The background stress field is assumed to be governed by plate tectonics and the stress direction is following the push from the Mid Atlantic ridge. The glacially induced stresses as simulated are superimposed to the background stress field for later analysis of the fault stability. The magnitudes of stresses are estimated by assuming frictional equilibrium in pre-existing, optimally oriented zones of weakness by the Coulomb failure criterion at Byerlee's average friction and hydrostatic pore pressures. Comparison to the determined parameters and stresses as well as orientations yield some differences. Both a strike-slip (ss) and reverse faulting (rf) regime are assumed for the background stress field.

The superposition of the background stress field and the glaciation stresses was aiming at the analysis of the faulting potential for the locations Oskarshamn, Forsmark and Pärvie. It was shown that the use of a ss background stress field delivers no indication of faulting potential at the end of stadials, i.e. at the time the large seismic events were reported at the time of deglaciation. In contrast, assuming a rf stress field, the analysis yields instabilities at the end of stadials at all three locations. An updated analysis using the specific stress fields (rf at Forsmark and ss at Oskarshamn) yielded comparable results to the general respective stress fields. This implies that there is a potential for activation of fractures at Forsmark based on the above analyses, but less at Oskarshamn only under the unfavourable, currently not evident rf stress field conditions.

While the variations in magnitudes of the stress field are based on the earth model used, the ice model determines the rebound pattern and velocities. The discussion stresses the importance of the ice sheet model, and it is stated that studying alternative ice histories and ice sheet models would have been favourable. Also, the importance of the knowledge of the background stress field has been shown by the results. The elastic properties of the lithosphere have been identified being an important factor to change stress magnitudes in the models at the most surface layers.

It is suggested by the authors, that the pore pressure has a significant impact on the stability analysis and hence a better understanding of the hydrology during glaciation times is essential. It is also argued, that the lack of earthquakes below the ice sheets, as is suggested to be valid for Sweden by the geological observations, implies either that the pore pressure is considerably lower than the weight of the overlying ice sheet, or that the pore pressure lubricates the crust, so that accumulated strain is released aseismically. Finally the concept that the deglaciation triggers the earthquakes is supported.

It is concluded that if the background stress fields at Forsmark and Oskarshamn are strike-slip at seismogenic depths, then glacially induced faulting is unlikely.

Comments

The idea was developed in the discussion, that the pore pressure under the ice sheet is lubricating the crust and hence the accumulated strains are released aseismically. From a fracture mechanics perspective this concept may be supported. It is know that fractures in rock may propagate at loads that are only a fraction of the critical stresses for failure. The propagation of the fractures is slow and hence small energies are radiated only. The presence of a fluid promotes this so-called subcritical fracture growth, as the creation of the fracture is driven by chemical processes; pressurisation may even enhance those effects further. Hence, fractures may grow slowly under the increased stresses at glaciation and become longer aseismically. From the concepts of fracture mechanics it can be derived that the longer a fracture, the smaller the imposed load needed for propagation. Therefore, if a fracture becomes subcritically longer, it may reach at some point at constant loads a length suitable for critical, i.e. seismically detectable, fracture propagation. This could explain coglaciation earthquakes. Or the stress field is altered, giving way to critical fracture propagation. This is a possible scenario for deglaciational earthquakes.

As was stated in the discussion, the investigation of alternative ice models would have been instructive. Even more, the inclusion of earlier glaciations might give different results, as the simulated rebound patterns suggest. If a previous glaciation would have delivered remaining increased stresses and the uplift would not have been complete, the stress field as simulated under the assumed constraints of the Weichselian glaciation may have delivered different results (higher stress magnitudes and hence increased differential stresses at the end of glaciations?).

From 120ka BP to 80ka BP there was a period of permafrost without any significant ice cover. Permafrost without an ice cap is reported for some cases to reach down several hundred meters up to 1.5km. It should be studied if there was a significantly thick zone of permafrost introduced which might have an impact on the Young's modulus as well as the Coulomb parameters to be used. As it was shown that the thickness and the parameters of the elastic layers has some influence on the magnitude of stresses, this should be discussed.

The chosen magnitudes of Young's moduli need discussion. The magnitudes for the uppermost layer in some models are very high (factor of about 3 to laboratory values). Perhaps an increase of Young's modulus with depth could be implemented, giving different stress magnitudes in the simulation runs that might be considered more realistic input for subsequent stability analyses.
The topography is not represented in the geometrical model. It is stated that the erosion during the glacial cycles is neglected, which are estimated to be less than 4m. On the other hand the about 2,000m high mountains can be found in Sweden. 2,000m of rock may add a load (— 55MPa) to the system which might influence the results of the model. It was stated that the reduction of the lithosphere thickness has an Impact on the simulation results and it should be considered if the mountain areas do also, or if their contribution may be neglected.
This comment deviates a bit from the intention of the paper, but it might be interesting to look at. It should be clarified what the changes of stress field means for the stability of the openings in the repositories; especially as the ice sheet scenarios indicate the risk of tensile stresses. Depending on the orientation of a deposition hole or access tunnel this could cause tensile tangential stresses on (unsupported) excavations giving way to fracture generation. Example: A rough estimation of the stresses from Figure 7-17, page 63, Model T10 delivers Sv = OMPa, SH = OMP and Sh = -6MPa. The background reverse faulting regime (equation 8-4, page 71) delivers at 500m TVD S1 = 42MPa, S2 = 28MPa and S3 = 13,5MPa. The stresses at the sites are then e.g. approx. VN./ = 13,5MPa, S'H = 42MPa and S'h = 22MPa. This gives minimum tangential stresses on a circular opening of STmin = -1,5MPa and STmin = 24MPa and maximum tangential stresses of STmax = 112,5MPa and STmax = 104MPa. The stresses might be high enough to activate existing fractures near the excavations, especially if because of an earthquake the fluid pressure is locally increased. A fault activation potential analysis or a numerical sensitivity analysis of the fracture pattern might be helpful. A first approach to this was done in Figure 9-14 for the locations of Oskarshamn and Forsmark without considering the stress redistribution around excavations.
This report very clearly shows that one needs to know the actual background stress field before performing predictive work, as the results differ significantly for a static strike-slip or reverse faulting regime. The assumptions for the background stress field in the report need clarification.

10.1.6 Munier and Hökmark (2004)

Respect distances. Rationale and means of computation. SKB R-04-17, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.
Munier and Hökmark summarise in the first part of their study different simulation campaigns of similar layout. A fault is assumed that radiates a seismic event in terms of displacements and the reaction of a ‚target fracture' of 100m radius are studied. This fracture should not achieve displacements larger than 0.1m, as this is the maximum displacement allowable before canister damage might be achieved.
Poly3d was used to simulate the displacement of target faults of different size at a distance of 2km due to a static displacement equivalent to a M 6 earthquake on a rectangular fault. It was shown that the longer the fracture radius the larger the maximum shear displacement predicted. For a 100m radius frictionless fracture a M 6 earthquake gave a permanent static slip of about 15mm, which is larger than the allowable 0.1m.

A second simulation campaign using Flac3d defined a dynamic boundary condition history as generated from velocity records with the WAVE code. Different parameter settings were tested. The model cannot capture the static displacement effect due to the slip of the fault. The seismic response of the target frac-

tures yielded for frictionless horizontal fractures induced displacements that decayed with time. For frictional fractures the seismicity was attenuated and even showed permanent slip. An increased distance of the target fractures from the simulated fault showed reduced induced maximum displacements. All displacements were significantly smaller that the displacements simulated due to the static displacement of the fault.
Simulations with the WAVE code only could model the static and dynamic displacement of the fault predicting displacements on the target fracture the same magnitudes as for the static only Poly3d simulation. Newly presented data incorporated a Flac3d simulation incorporating both dynamic and static displacement of the fault, verifying the WAVE results qualitatively. The campaign is declared ongoing.

It is summarised from the simulation experiments that a M 6 event equivalent to a surface rupture length of 5km did not produce induced displacements >0.1m on a 100m radius target fault and the appropriate respect distance would be 200m. The induced displacements on the target fracture is governed by the static displacement of the fault rather than the dynamic effects.

In the following chapters it is speculated what the influence of larger earthquakes M > 6 might be, the influence of the process zone or transition zone of faults is deliberated, reference is made to the also reviewed study by Bäckblom and Munier (2002), and scaling considerations were discussed. A worked example completes the report. In the appendix the reports to the summarised simulations and a review of postglacial faulting are given.

Comments
The layout of the report is weak. The summary of the numerical results is too short for a comprehensive understanding and the reprints in the appendix are of the same style. However, the review of the postglacial faulting is very good.

In the definition section (page 8) it is stated that the ‚respect distance is the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited'. The definition ignores the fact that the fracture process zone (or transition zone in the SKB nomenclature) is created at the tip of a propagating fracture. Hence, not only the direction perpendicular to the fault should be considered, but also the zone parallel to the fault trace, i.e. in front of the tips. In the case of a reverse regime acting on the faults reactivated in relation to the deglaciation, the zone in direction of the fault trace is under Mode III loading and hence faulting and fracturing in that direction is also possible. Hence the respect distance should consider a zone around the fault.

The definition of the size of such a zone, which must be considered the minimum size of a respect distance, should include not only empirical evidence as from a plot of fracture width vs. fracture length in the style of Vermilye and Scholz (op. cit.) but also the incorporation of different theoretical fracture process zone models like slip-weakening or tension-softening.

The Poly3d analysis assumes a rectangular discontinuity (page 15). It needs to be discussed if there might be an artefact due to the stress concentrations at the edges of the rectangular. Further, the applied displacement needs specification. It does not become totally clear how the reinterpretation of the Poly3D analysis in Figure 3-5 (page 17) was performed.

In Table 3-3 a horizontal target fracture orientation is indicated. How relevant is this? What about vertical or steep dipping fractures in parallel with the fault? Then the fault and target fractures would be parallel and the shear displacement might give different results.

Fracture stiffness on target fractures was considered as a constant value. However, stiffness is load dependent. Also the stiffness of shear and normal loaded fractures are usually not the same as assumed in the FLAC3D models (Page 66). A sensitivity analysis might be interesting and possibly could show similar trends as the introduction of the friction. The WAVE models used more reasonable but still constant stiffnesses (page 129).

In Table 3-7 there seems to be a typo (Model Nr. 2, peak displacement 0.03mm?), otherwise the conclusion drawn that the differences in results is very small, may not be drawn (page 28).

All rock properties were assumed not to be depending on the dynamic loading. It should be evaluated if some of the parameters are rate dependent (like friction or Young's modulus), and if they alter the results of the studies significantly.

lt is stated that the results by La Pointe et al (2000) are based on fracture toughness values by Shen (1993) (page 47). Shen reports static values only, but it is well known that the dynamic fracture toughness is much higher, hence the conclusions on page 44, fourth paragraph and the study needs revisitation. Zhang et al (2000) report values of dynamic Mode I fracture toughness that are exponentially increasing above a certain loading rate (see figure D).

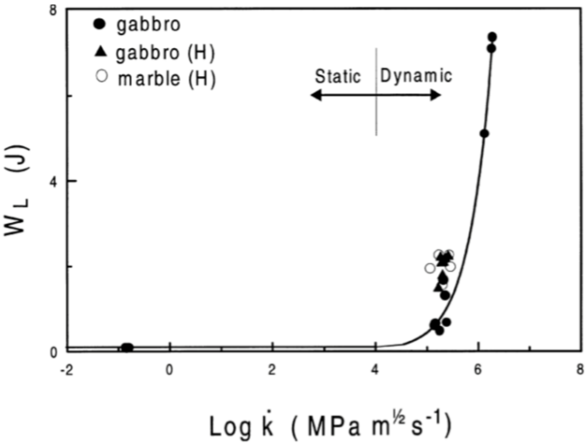
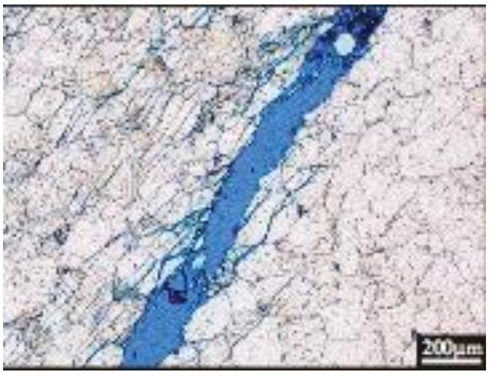


Figure D. Relationship between the energy needed for fracture propagation W_L and the loading rate k. The energy W_L absorbed by a specimen in static fracture is much less than that in dynamic fracture. The main reasons are that in the process of dynamic fracture both the macro-crack branching and micro-cracking damage within rock specimens, which are much more serious than in static fracture, must consume extra energy. (From Zhang et al. 200, figure 11).

Further it is stated that in the study by La Pointe et al (2000) the effect of fracturing at the fracture tips was studied and it was found that the maximum possible induced shear displacement was independent of the load of the fracture. The arguments for this conclusion are not comprehensively given and they are not obvious. It is not clear why propagation of a fracture should result in a back-bouncing of slip.

In the discussion (page 41) it is stated that the risk for earthquake damage can be significantly reduced if undesirable fractures are avoided in the canister holes. This ignores the fact, that fractures in the neighbourhood of deposition holes may be affected by the altered stress field (see figure E). In such configurations they do not intersect the excavations. It should be analysed in as how far the superposition of the

Figure E. Stress state and potential slip on fractures in the vicinity of circular openings. (from Brady and Brown 2004).



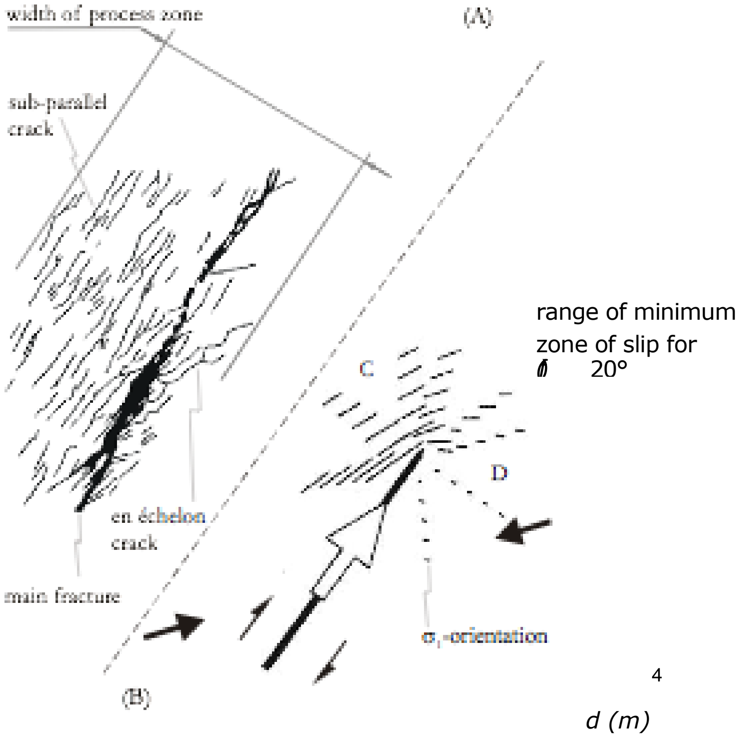


Figure G. (A) Schematic re-drawing of the main fracture and process zone from the above figure F. (B) Plot of the calculated maximum compressive stress directions surrounding the tips of a Mode II crack, showing rotation to lower angles with the fracture in the compressive quadrant, C and higher angles in the dilatational quadrant,. D, Open arrow indicates fracture propagation direction, solid arrows remote major principal stress direction. The small lines indicate orientation and magnitude (proportional to length) of major principal stress (after Vermilye and Scholz, 1998). (Backers 2005).

On page 37 it is reported that the ‚transition zone is asymmetrical'. This is what one should expect for shear fractures. This was shown by e.g. Vermilye and Scholz (1998) or Backers (2005). The reason may be derived from the non-symmetrical stress field ahead of shear fractures, which results in sub-parallel fracturing on the one side of the propagating fracture and inclined fractures on the opposite side (figures F and G).

The simulation results nicely show that a static slip on a fault generates slip on target fractures much larger than any seismic movement. No extension/propagation of the target fractures was assumed in the study. However, it was not discussed if the fracture slip is large enough for fracture propagation. The extension of the fractures not only gives way to connection of fractures and development of pathways to the biosphere. If the fractures were allowed to propagate, they become longer. The longer they become, /a/ the larger is the slip due to an earthquake as was shown by the Poly3D study, and /b/ the less energy/displacement is needed in the next seismic event to propagate them further.

A way forward to look at the DFN activation potential would be generating a simulation campaign, where the response of a DFN to a superimposed permanent shear displacement as generated by a fault slip is analysed. Further, in the repository the stresses around the deposition holes are magnified. What if a fracture is under influence of the increased tangential stress field and the seismic event adds additional static and dynamic displacements?

The static component of the slip of the fault might also introduce conditions for subcritical fracture propagation on target fractures. This needs to be studied as the repository will be in operation for considerable times which may relevant to subcritical fracture growth.

In chapter 7 it is concluded that for a M6 event, if one can detect fracture of radius >100m and the allowable slip is <0.1m, the respect distance is 200m. It is anticipated that this conclusion was drawn with the assumption of friction on fractures. In chapter 3.2 it is stated that a M6 event introduces a maximum static displacement of about 0.15m on frictionless fractures of radius 100m. As the effect of fluid pressure increase due to an earthquake is not explicitly addressed, a loss of friction cannot be excluded and the conclusion drawn needs explanation.

Altogether the conclusions drawn are not based on comprehensive studies but more on indicative assumptions. Analysis of more than some geometrical layouts of fault and target fracture would have potentially gained more insight into the mechanical behaviour of a DFN in a potential repository.

10.1.7 References

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10.2 Prof. Hilmar Bungum, NORSAR

10.2.1 Review of reports

In the following we will review these reports, in chronological order. Comments are provided throughout the text as well as in a separate section after the reviews.

10.2.2 Bäckblom and Munier (2002)

This report is essentially a fact-finding effort early in the SKB project on *Effects of Earthquakes on Underground Facilities*. Most of this is accumulation of background information where comments are not needed, except for a more general reflection that, since the compilation is now almost 10 years old, an update is clearly recommended. More seismological research results of interest to this project have been published during these years than in any earlier decade.

A minor comment here is that there is a distance metric error in Figure 2-1, where what is called "distance to rupture" should be "distance to top-of-rupture", while the often used "Joyner-Boore distance" is the shortest distance to the surface projection of the rupture surface. "Rupture distance", on the other hand, is the term used for the shortest distance to the rupture surface. Hypocenter distance is not really used as a distance metric for extended earthquake sources.

It could also be noted that since 2002 there have been considerable improvements in terms of development of ground-motion prediction relations (GMPE's, earlier often called attenuation relations) and their uncertainties, aleatory as well as epistemic (e.g., Bommer et al., 2005). The medians here have, however, not changed very much over these years, but our understanding of uncertainties and the behaviour of the extreme motions far out on the tail of the distribution (e.g., Strasser et al., 2008) has improved considerably, which we will briefly return to in Section 2.

An important safety criterion in the present report is the displacement level of 0.1 m, above which the canister is thought to be damaged. We cannot see where this number comes from and how it is justified, but it seems that the topic is addressed more thoroughly in the subsequent Munier and Hökmark (2004) report.
Similarly, the level of 2 m/s^2 is also not well justified, and for two reasons. Firstly, it is stated that "damage to underground facilities occurs, by empirical knowledge, when the Peak Ground Acceleration is greater than about 2 m/s^2". This is not the level of precision which would be expected for a project of the present importance. Secondly it is stated that "seismic hazard has been calculated for Sweden and it is concluded that PGA greater than 2 m/s^2 is very unlikely the next coming 50-year period, in which the repository is planned to be constructed and operated". This number seems to refer to the GSHAP project (http://www.seismo.ethz.ch/gshap/) which is now largely outdated, and in any case it will be necessary to discuss and determine the appropriate exceedance probability level and to consider what the appropriate confidence level should be. Even if a new pan-European earthquake hazard project (SHARE, http://www.share-eu.org/) is now under development we cannot really see that the needs in this case can be covered in any other way than through a new site-specific earthquake hazard study, preferably conducted within the frame of the SSHAC methodology (e.g., http://pubs.usgs.gov/of/2009/1093/;Hanks et al., 2009).

What is said in the report about respect distances is assumed to be outdated by the Munier and Hökmark (2004) report which is reviewed in the following.

10.2.3 Munier and Hökmark (2004)

The purpose of this report is to "discuss various aspects of the assignment of respect distances, propose a methodology for its assignment and apply the methodology to the Forsmark Site". The respect distance is defined in this report as "the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to anticipated, future seismic effects on canister integrity".

One initial problem with the concept of respect distance is that it is not intuitively understood what it could mean. More important, however, is the fact that there appears to be a discussion about what should be included in the concept, as reflected by the fact that Posiva (Finland) has written an 83-page report (Lampinen, 2007) only about the terminology. What Lampinen finds is that SKB's respect distance considers primarily the seismic risk, such that it overshadows other effects (hydrological and mechanical), while Posiva's respect distances consider the seismic, hydrological and mechanical properties of the deformation zones as the most important issues with respect to the risk to the canisters. It is not clear to us if one can conclude like SKB is doing about the balance between seismic, hydrological and mechanical properties, even if this is specifically tied to Forsmark and not intended to be generic. There are, after all, significant uncertainties tied to all of the different factors that are driving the risk to the canisters.

Munier and Hökmark (2004) are revisiting the issue from Bäckbom and Munier (2002) on the failure criterion for the canisters, finding that the level of 0.1 m seems to be conservative. Even so, they want to stay with the value, which may be justifiable if this is a threshold against which independent displacements assessments are compared, which seems to be the case here. Clearly, this is an important value.

The numerical analyses and assessments documented in Section 3 (and supported by several appendices) are thorough and solid, using a number of complementary approaches. What is found is that an Mw 6 earthquake and a 100 m radius target fracture did not produce displacements in excess of 0.1 m for any of the simulations. For a 200 m distance the displacement was close to the threshold (0.065 m).

This analysis is, however, somewhat limited in that uncertainties are weakly covered and also in that only some parameter combinations are modelled, including only one magnitude. This is addressed briefly in some reflections on future simulation work in Section 3.4.3, and in the discussion of large earthquakes in Section 3.5. One of the reasons for the limited analysis is the great computational demands of the numerical simulations. It is correctly stated in the report that an essential question is the way in which an earthquake grows to become larger, and if this implies any change in the stress drop and seismic moment per unit area of ruptures, which is not the case in the simplest models. This discussion of scaling laws is useful and important, but could have been better supported from more recent publications.

The discussion in Section 6 on conservatism is also interesting but raises in turn also other related questions. We would like to note here that during the last few years many tools for more advanced final fault modeling has been developed based on both kinematic and dynamic approaches (e.g., Song and Somerville, 2010), including also the near field and the influence of various nonlinear effects. For example, the rupture velocity is very important, and in general the variability of stress drop and thereby the 'patchy' distribution of slip across and along the fault. This even includes super-shear ruptures (e.g., Andrews, 2010), which now are considered to be less unlikely than what was judged earlier.

This increased understanding of fault complexity, even for intermediate-size earthquakes, has provided also a better basis for appreciating the great variation in amplitudes that is now appearing mostly as a result of an increasing density of deployed recording instruments. For these reasons it would be useful also in this case to revisit this work, given the rapid scientific development within this field and the fact that the Munier and Hökmark (2004) report is now about six years old.

The discussion about target fractures size seems to be hinging on the assumption that fractures exceeding 100 m radius can be detected in the deposition holes, and that respect distances have been calculated on that assumption. Surely this is discussed elsewhere but in this report it does not seem to be; it appears that this detectability is a critical assumption that should have been given more attention, including how it could be expected to be changing with time, thereby affecting also the respect distances.

The final comment in Section 6.5 on scale is more philosophical than really useful. The interesting thing with scale invariance (fractality) is not its existence (since it applies so widely) but where it breaks down (in both ends); barriers are often not effective since they are often jumped, and all long, continuous faults should therefore be considered suspect (Emile Okal, pers. comm., 2009; see also Kase, 2010). So the conclusion in the report is correct, to use regional models.

10.2.4 Hedin (2008)

In this paper a method is developed for assessment of the likelihood ε of a canister being intersected by a fracture of a certain size, derived essentially from the combination of fracture radius and fracture orientation distributions, respectively. While these two distributions are assumed to be uncorrelated it is not discussed how important this assumption is, which would have been useful, especially since the assumption does not seem to be justified.

We have not spent any time on the mathematical derivation of ε, essentially since the derivation is checked (the word ‘verify’ should be avoided in the observational sciences) through independent numerical simulations. An important part of the paper is the sensitivity analyses where obviously there is a large sensitivity to the maximum fracture radius. What is more surprising is the great sensitivity of ε to the exponent *k* in the fracture radius model, showing a variation in ε by almost two orders of magnitude from a variation in *k* of only ±20%. This is noted by the author but not discussed, which clearly also would have been useful, given that uncertainties are so essential is these discussions.

Otherwise the paper seems to be tied closely to and based on the Munier and Hökmark (2004) report; in fact, the author specifically states that “the meaning and physical reasonableness of the selected input parameter spans are not discussed here”. It would have been useful to know where these in fact have been discussed.

10.2.5 Lagerbäck and Sundh (2008)

This report is a summary of the work done over the last 40 years or so to map, understand and explain early Holocene faulting in northern Sweden, and we would like to emphasize some points in this connection:

The report provides the most complete and comprehensive overview of these subjects that we know of, and of particular importance here is the fact that data and observations, including the extensive paleoseismicity work, is well balanced by interpretation and discussion where a proper allowance is made for remaining uncertainties, which is not always the case in such work. The present seismicity and its possible relation to the mapped faults is also discussed, albeit without offering any model or explanation for the reported results (cf. Bungum et al., 2010).

A new and very important element is introduced when the authors suggest that the postglacial faults in northern Sweden during the last deglaciation were not typical for the previous glaciations. It is argued that the limited erosional impact of the Quaternary glaciations would not obliterate fault scarps several metres high. This would imply that the crustal stress state history and possibly also the associated fluid pressure (in terms of permafrost-related residual overpressures) were extraordinary during the last deglaciation. An alternative explanation is that these exceptional conditions occurred in other parts of the Fennoscandian Shield during previous de-glaciations and that the deformation consequently migrated through the region with time. Younger erosion and sedimentation could have obliterated these pre-Weichselian structures.

We consider the cold-based ice sheet and its associated effects on the pore pressure to be the most viable explanation here, but regardless of explanation these results do indicate that the assumption that the earthquake loading potentials following the next glaciation will be more or less identical to those following the last glaciation is less certain than earlier assumed (Hora and Jensen, 2005). This clearly is of great potential importance in a nuclear waste deposition context.

Another point of importance in this report is that it contains a reasonably thorough discussion of the claims that have been forwarded (e.g., Mörner, 2003) about postglacial M8+ earthquakes in more southern parts of Sweden. These claims are refuted by Lagerbäck and Sundh (2008) on various grounds, including the lack of solid bedrock manifestations, the scattered occurrences of the key soft-sediment deformations, and the ‘boulder caves’ claimed to be related to these large earthquakes. While these far-reaching claims earlier seem to have been largely ignored in the scientific literature we find the present refutal to be both solid and well supported.

Given all these positive impressions, we would however have liked to see a perspective in this report that was less ‘Swedish’ and more regional, especially in the discussion section, even if references are made to both Finnish and Norwegian research (cf. Bungum and Lindholm, 1996; Olesen et al., 2004) within the same field. One remaining issue of common interest is the single-event assumption, which could have been discussed more thoroughly in the report. It is hard to see how a fractal and log-normal distribution could be avoided even if this was a spectacular burst of energy release, in which case Bungum et al. (2005) find that a drop in magnitude by 0.4 units will reduce the slip only by a factor of 4, while Båth’s law with a magnitude drop of 1.2 units will lead to a reduced displacement by a factor of 60. As is well known, even with a normal frequency-magnitude distribution the largest events tend to dominate entirely the displacement field.

10.2.6 Lund, Schmidt and Hieronymus (2009)

This report is a new one in a series of reports and papers from Björn Lund and collaborators on numerical (finite element) modelling of glacial isostatic adjustments (GIA), now having extended this also to 3D. The report is admirably well organized and written, including purposes, assumptions, methodology, results, discussions and conclusions, and the many references to and comparisons with other similar studies provide a good frame-of-reference also for the less specialized reader.

Such a solid documentation is very important, given the well known level on non-uniqueness within much numerical modelling, in particular related to initial conditions. For example, depending on the selection of time for isostatic equilibrium, either before the onset of glaciations (Wu et al., 1999) or at glacial maximum (Stein et al., 1989), contradictory modes of faulting have been modelled. While Stein et al. (1989) predicted reverse mechanisms on the oceanic side, well supported by present observations (Byrkjeland et al., 2000), and normal mechanisms on the continental side (less so supported), Wu et al. (1999) predicted thrust faulting under the ice, in agreement with the existence of reverse late glacial reverse faults in northern Fennoscandia (e.g. Olesen et al., 2004), and normal faulting outside the ice margin (less so supported). The fact that (some) observations are found to support the modelling is not necessarily sufficient in order to ‘verify’ a model.

In a similar way the present modelling is also dependent on the underlying conditions and assumptions. This applies in particular to the ice sheet model, it applies to the Earth model used, to the pore pressure model, and to the background state of stress, where both a reverse and a strike-slip field has been used in the modelling.

These and many other assumptions are, in various levels of detail, commendably discussed in the report. For the ice history, the authors state that it is unfortunate that they have not been able to investigate an alternative ice history. Compared to the Earth model, which mostly affect the range of stress magnitudes, the ice model seems to be much more important, and they use the (much larger) Saalian and the Laurentide glaciations as examples here. In fact, this has wider implications since it not only concerns the modelling of the Weichselian glaciation but also the implicit assumption in the report that the next glaciation will be similar. In this contact it would have been interesting if the authors had discussed the important suggestion from Lagerbäck and Sundh (2008) that the Weichselian may have been special in terms of its end-glacial stress field and faulting; in fact, the report is not even referred to. In any case it would have been useful if the authors had discussed the documented ice sheet sensitivity in terms of the next glaciation, given that this is such a sensitive question for the issue at hand (e.g., Hora and Jensen, 2005).

The pore pressure model, defined as 50% of the local ice weight, is another sensitive and uncertain parameter. The authors show that increasing the pressure head to 90% of the local ice weight will cause wide-spread instability during ice covered conditions in a strike-slip background field, while in a reverse field instability is promoted earlier in the glacial cycle. Also, the high permeability assumed in this model may not necessarily be consistent with the potential implications from permafrost as discussed by Lagerbäck and Sundh (2008). While they discuss a potential sensitivity of landsliding from the distribution of permafrost the importance for the pore pressure model is likely to be even more obvious.

The background state of stress is thoroughly discussed in the report, and its sensitivity is investigated. The fact that a uniform stress field seems to be a computationally necessary assumption here, where reverse and strike-slip has been used, is likely to be a problem given that we know that there are large state of stress variations both at repository depth (as documented in the report) and at seismogenic depths (e.g., Hicks et al., 2000). It is interesting to note here that the authors find that the best fit would be for a strike-slip field in the south and a reverse field in the north, and also that the orientation of SHmax has a large impact on the resulting stability field. In general, however, the background stress field is also an assumption which ideally should have been determined from independent data, which in this case could have been more thoroughly justified and documented.

10.2.7 Concluding remarks and comments

The five reports under review here are quite different in purpose and nature, even though they are all aimed at supporting SSM in their long term efforts towards safe disposal of radioactive waste in Sweden. The purposes and goals of this review and also of the subsequent SSM workshop on March 23-25, 2010, have however not been well defined, and can only implicitly be assumed to cover in part the contents and the quality of the reports as such, and in part to which extent they can assist SSM in their efforts to store the waste safely and for a sufficiently long time. Since such a frame-of-reference has not been offered, thereby explaining how the different reports and recommendations are combined into a common perspective and solution, it is also difficult here to provide an overall assessment.

One reason for this is that the depository time frame appears not to be well defined for this assessment. The time frame was only implicitly referred to in some of the reports; in fact, in their summary Bäckblom and Munier (2002, p. 5) even use the term "foreseeable future" (whatever that means). In the same report there is, however, a figure (2.1) on page 13 which shows decay curves for the various nuclear elements contained in the waste. It can be inferred from this figure that the radiotoxicity is down by 4-5 orders of magnitude after about 100,000 years, but since there cannot be a sudden transfer from 'unsafe' to 'safe' it would have been useful to know if may be several time durations could have been indicated, each one referring to different levels of hazard and acceptable risk. This could be potentially important for the evaluation of the different loading factors.

A general problem with the reports is that they address in quite different ways the uncertainties, which some times are not discussed at all. In principle, uncertainties are either such that can be reduced thorough the accumulation of more knowledge (epistemic) or they are due to the apparent randomness in nature and therefore cannot be reduced (aleatory). In any case it is important to know how to combine uncertainties in cases when there is a chain of arguments and a potential situation for propagation of uncertainties. In such cases it becomes very important if conservative assumptions are used on the individual elements or if best estimates should be used instead, in which case the level of confidence (conservativeness) would have to be introduced at the end of the chain of arguments.

There is, admittedly, an effort to discuss the level of conservatism in Section 6 of Munier and Hökmark (2004), but mostly by reflecting on individual elements without any effort to discuss the resulting effects when the different elements are combined. To this end the practical example in Section 8 of the same report is very useful, but again uncertainties are not seen to play any role there. In fact, that section opens another important question, namely how the underlying deformations zones are assessed and evaluated. What is a lineament in this case and how are they mapped, in 2D and 3D? Which of these could be judged as potential zones for reactivation (faults), and on which criteria? How old are they and what are their possible levels of sealing? What are the chances that new fault zones can grow slowly over tens of thousands of years, starting with one that is below the present detection threshold? It may well be that all of these questions are addressed in separate reports, but since these are not known to us they appear as holes in a chain of arguments and reasoning.

One of the most important elements in this chain of arguments is the expected seismic loading at the end of the waste deposition period, which was addressed by Lund et al. (2009) and earlier by Hora and Jensen (2005), among others. This is a very challenging question and even if Lund et al. (2009) discuss properly both sensitivities and uncertainties, there are also (see above) aspects that are less covered, such as the potential implications of the Lagerbäck and Sundh (2008) results. A problem which should be easier to assess, albeit still challenging, is the seismic hazard at present, that is, during the 50 years or so when the depository will be under construction. It is not really satisfactory to base this important work on a more-or-less outdated European-scale earthquake hazard analysis (see above), especially since there has been such a major development within this field during the last decade.

A new seismic hazard assessment for the Swedish depository sites may not necessarily yield higher 500-years levels, which the GSHAP study refers to, but for the present project it will also be necessary to consider also other exceedance rates. For the Yucca Mountain repository the original assessment was for an exceedance rate of 10^{-4}/year (Stepp et al., 2001), but since the US Nuclear Regulatory Commission requires that the hazard be assessed at one chance in 10,000 of being exceeded in 10,000 years, the resulting exceedance rate became 10^{-8} per year. It is well known that the results for Yucca Mountain were (and are) controversial because they were so high, largely driven by the uncertainties. While this question is not finally resolved for Yucca Mountain it is worth noticing that in an independent study, based on paleoseismic data and dynamic modelling, Andrews et al. (2007) also found very high values (fortunately also much higher than possibly could be expected for central Sweden).

An issue that clearly comes into play here is the question of focal depths and of the way the top-of-rupture may vary with magnitude, which recently was discussed by Bungum et al. (2005) for the continental margin of Norway, identifying structures which would be able to accommodate M 6.5-7 earthquakes without reaching to top-of-bedrock. Clearly, for M 6, the changes for a complete burial are even greater. In the present case the depth question should be stated differently, however: what are the possibilities (stress and rock mechanics wise) that a magnitude 6 earthquake could nucleate high enough in the crust to intersect with the depository?

One very important development within this field is the great increase over the last decades and also the last few years in the highest ground motion that is observed from earthquakes (Strasser et al., 2009a,b), where the highest acceleration now is 3.9g (M6.9 Iwate-Miyagi, Japan, 2008). The extreme values cannot be explained by site effects alone; in fact, source and path effects seem to be more important, and the events come from a range of magnitudes, seismotectonic conditions and modes of faulting.

Another point that should be kept in mind here is the fact that so-called stable continental regions (SCRs) are also known for occasionally producing large earthquakes (Stein and Mazotti, 2007). In any given place, the return time for such events may be thousands of years, so in this case the principle of ergodicity (replacing time for space) is often used to explore these issues. In fact, we know of 15-20 historical M+7 earthquakes in SCR regions, and the most prone areas are rifted passive margins and failed rift zones (Johnston et al., 1994; Bungum et al., 2005). Even if such tectonic features, such as the Oslo Rift zone (Bungum et al., 2009) and the continental margin of Norway (Byrkjeland et al., 2000), are where many such rare events are known to occur, there also some that are more difficult to explain tectonically. No SCR region can therefore be completely ruled out in this connection, and in any case the choice of maximum magnitude will be influenced (e.g., Mueller, 2010).

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10.3 Dr. Conrad Lindholm, NORSAR

10.3.1 Introduction

The present “report” is a result of reading five reports. It is beyond the capacity of the present author to penetrate into the details of each of these very different reports and thereby challenge some key issues in methodology or parameters in each of the reports. Instead the reports have been read (and much enjoyed for their quality!), and the challenging questions triggered below are more of a fundamental character (and possibly due to lack of understanding). When reading the following pages one should therefore regard them as basis for discussion rather than a rigorous review.

10.3.2 Effects on earthquakes by Bäckblom and Munier (2002)

Bäckblom and Munier have a comprehensive discussion of how earthquakes may threaten the safe long term depository of nuclear waste. This study is the oldest and in many ways the basis for the “follow up” studies referenced below. The study highlights a number of basic observations in a straightforward and credible way. There are however a number of small but important issues that should be challenged:

- o It is stated that Sweden have experienced few M>4.0 earthquakes. It is true, but the observation period is so short that it does not lend much credibility in a 500 year perspective, and much less in a 100,000 year perspective.
- o Reference is made to a hazard study (seems to be GSHAP). In addition to being old and outdated, it never approached the quality needed as background for nuclear waste deposits (I know because I happened to be one of the main workers behind the study).
- o The PGA = (M,Distance) referenced should unconditionally be updated and revised.
- o Focus is put on sudden fault snapping through earthquakes. Slow displacements seem not to be of any concern. This simplification is not immediately obvious in view of the many slow movements that are observed (among others with recent GPS systems).

10.3.3 Respect Distances. Munier and Hökmark (2004)

Munier and Hökmark have a comprehensive discussion of the rationale and how this concept can be applied. This report can be seen in the perspective of the POSIVA report by H. Lampinen from 2007 on the same topic. It is defined as follows: *The respect distance is the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited due to anticipated future seismic effects on canister integrity*. The basis for this work is that leakage due to a direct seismic impact seems to overshadow mechanical, thermal and hydraulic impacts.

The respect distances have been estimated through a variety of modelling exercises:

- o Shear displacement on a frictionless fracture; FLAC3D modelling; M=6.0; Angles of fractures relative to causative fault: 0^o, 45^o; Distances: 2 and 10 km
- o Velocity-time histories modelling; Source variations; Free surface effects; Fault orientation; Shear propagation
- o Shear displacement on a fracture with friction; FLAC3D/WAVE modelling;
- o Numerical simulation...; WAVE modelling; Maximum displacement values ranging from 0 to 7.68 cm.

It is in conclusion stated that respect distances to mapped fractures of 100 meters may be regarded as safe.

10.3.4 Late Holocene faulting. Lagerbäck and Sundh (2008)

The content of the report is an overview of surface faulting manifestations in Sweden and northern Fenoscandia. The great structures of Pärvie and other faults in northern Sweden reflect an outburst of seismicity that seems to have been particular and which probably did not occur in association with the earlier glaciations (based on surface geology analysis). The burst of seismicity evidenced by surface marks seems to be concentrated both in time and space. It is furthermore reported on silt deformations have been found as evidence of large earthquakes in central Sweden.

The overview prepared by Lagerback and Sundh is comprehensive and detailed. While some details may be challenged a rather convincing evidence of a burst of active seismicity is presented.

The overview on the distances at which liquefaction can occur as function of magnitude seem too simple. My key questions are:

- o Is it possible that the liquefaction evidences could be caused by more frequent and more distributed and smaller earthquakes? The response to this question deals with the precision of the dating of the "mud-patterns".
- o The lack of "mud-pattern" far from surface faults may be a result of less focussed and more difficult search (undermining the assumption that this is connected to the surface faults.

10.3.5 Stress evolution and fault stability under Weichselian glaciation. Lund et al. (2009**)**

The presented work is an extensive modelling of the ice sheet load and unload generated stresses at 500 meters and 9.5 km depth. A number of scenarios with the same ice history model has been investigated. The modelling shows a reverse fault instability at the ice retreat period for compressive stresses, and the use of Pärvie is used as a reference. The possible weakness is:

- o Lagerbäck and Sundh seem to be clear on the fact that the Lapland faulting is one-of-its-kind while it is simultaneously clear that there have been repeated glaciations.
- o Glacio-isostatic modelling seem to slip on the fact that so many glaciations have not created any surface faulting. It is not convincing that they use the Weichselian ice sheet model, since there are so many other possible ice models.

10.3.6 Stereological analysis of canister-fracture intersections. Hedin (2007)

Hedin (2007) conducts a comprehensive statistical modelling aimed to quantify how many canisters that may be hit by unknown fractures through reactivation. The rationale behind the modelling is that not all the fractures in a given rock volume can be avoided, and hence it is practically not feasible to fully respect the respect distances (since some fractures will exist without being possible to map). About 2% probability of intersections are indicated.

- o Is this only the probability of intersection (not any movement)?

10.3.7 Conclusions, Comments and Questions

General on other issues**:** With little previous experience on these issues some related thoughts "pop up"... It is presumed that the following conditions are modelled and considered in other studies:

- A reference frame for the lifetime of the repository will be helpful. We do presume that 100,000 years is representative for getting radiation close to the background radiation (Bäckblom, 2002).
- Are the permanent vertical displacements combined with sea level changes always estimated to keep the storage above level?
- The likelihood of submerging the repository under sea level and the probability of water penetration into the canister vaults?
- The influence of tunnel collapse (if not 100% backfilled)?

From the reviewed documents it emerges an approach which can possibly be characterized as below:

- Only sudden ruptures that may corrupt canister integrity are considered. Slow and but systematic displacements seem not to be considered.
- The geological somewhat deterministic modelling of faults and ruptures are applied in context repeated glaciations and deglaciation periods.
  - Largely based on geology considerations and fault density and fault reactivation the concept of *respect distance* is developed.
  - The *respect distance* is developed on geotechnical considerations: A future earthquake will rupture pre-existing fractures (not pristine rock).
- The assumption of repeated glaciations/de-glaciations motivate the modelling of stresses induced by the ice loading/un-loading as basis for initiating M>= 6.0 earthquakes.
- It seems from the context that geological changes associated with glaciations (fault loading and sudden release) are used as the main scenario. I.e. the geology is basically very stable on a 100,000 year horizon.

Questions:

- From geothermal fields it is well known how small temperature changes cause significant earthquake activity (indicating changes in the rock fracture conditions). Since heat will be a key issue from the canisters a permanent changing temperature condition is introduced. How is this temperature influence modelled as basis for rock crack developments?
  - Are there empirical data with similarities that can be used?
- The Kaliningrad earthquakes in Sept. 2004 (M=5.2 and 5.0), The Skåne earthquake (M=4.7) on Dec. 2008 and the M=6.2 near Svalbard in Feb., 2008 are only a few recent examples of quite large and very unexpected (not in well mapped active areas) earthquakes occur in the Fennoscandian *present* geological conditions (i.e. no extra glaciation stresses).
  - Would it not be natural to conduct a high level earthquake hazard investigation, probabilistic and based on present day conditions at low annual probabilities?
- The Holocene faulting is given very high attention in the present depository context. As much as the findings are very intriguing the question related to hazard may be challenged:
  - The fact that surface manifestations are found should not be overemphasized. Most of today's seismicity occur at greater depth on blind faults. In terms of shaking power and reactivation of splays closer to the surface these may be as important. However: They can naturally not be similarly identified.
  - If it is correct that the Lapland faults represents a one-of-its-kind earthquake activity burst concentrated in time and space: Why? What were the underlying causes for this?

10.4 Dr. Jonny Rutqvist, Lawrence Berkeley National Laboratory

10.4.1 Introduction

This report is the results of a review of the work conducted by the Swedish Nuclear Fuel and Waste Management Company (SKB) regarding seismology in relation to the proposed site of spent nuclear fuel in Sweden. The review was conducted in conjunction with a workshop arranged by the Swedish Radiation Safety Authority (SSM) in Stockholm, March 23 to 25, 2010. Five of SKB's key publications were reviewed (Bäckblom and Munier, 2002; Munier and Hökmark, 2004; Hedin, 2008; Lagerbäck and Sundh, 2008; Lund et al., 2009). These were the publications available for review while there are some documents that are being finalized and not available for review (e.g., Fälth et al., 2010).

This report is focused on a few key results and issues that were identified in SKB's publications. The review was conducted from the viewpoint of geomechanics and related to a previous review on coupled thermal-hydraulic-mechanical (THM) processes in fractured rocks by Rutqvist and Tsang (2008). First a summary of SKB's approach and results are presented. Then two outstanding issues are discussed.

10.4.1 Summary of SKB's approach and results

SKB analysis indicates that the main risk related to seismicity would be that an earthquake taking place on a major fault at a certain distance from the repository would change the stress field in such a way that it could induce shear displacement along a secondary fracture/fault intersecting a deposition hole. If such shear displacement is sufficiently large it could jeopardize the mechanical integrity of a waste canister. SKB's strategy is to place the canisters at a sufficient distance from major faults and to not place canisters where observed major fractures intersect. In such a case, SKB's analysis indicates that the maximum possible shear displacement would not be sufficient to breach a canister. SKB's approach and results regarding three key items—seismicity and respect distance from a major fault, likelihood of a major earthquake, and shear displacement across a waste canister—are summarized in the next three subsections.

10.4.2 Seismicity and respect distance from a major fault

SKB has a strategy to not emplace waste canister in the immediate vicinity of major faults that cold host a major earthquake. The canisters will be placed outside a damage and transition zone (a zone of increased fracturing and deformation around an active fault) and at a certain so-called respect distance from major faults. The respect distance is related to dynamic shaking and static stress changes that might cause damage to the Engineered Barrier System (EBS) of the repository. In SKB's publications it is pointed out that in the event of a nearby earthquake, the EBS shakes as a solid body and the tunnels will be backfilled thereby preventing damage to the EBS (Bäckblom and Munier, 2002). SKB identifies possible shear displacement along secondary fracture/faults (socalled target fractures) intersecting a deposition hole as a possible event that could breach a waste canister. The shaking and static stress changes decreases with distance from a reactivating fault. Therefore, placing the canisters at sufficient distance from the major fault could assure that induced shear displacement on a target fracture would not be sufficient to breach a canister.

10.4.3 Likelihood of a major earthquake

In the documents, SKB acknowledge that shear reactivation along fractures/faults and associated earthquakes cannot be ruled out during the next glaciation. SKB identify the deglaciation—when the ice sheet is receding—as the most likely period for inducing shear reactivation (Bäckblom and Munier, 2002; Lund et al., 2009). However, depending on the evolution of fluid pressure and the background stress field at the site, shear reactivation is possible both during glaciation and deglaciation periods (Lund et al., 2009). Geological evidence indicates that the geomechanical behaviour during past glaciation cycles have been highly variable, with some glaciation cycles giving rise to major earthquakes in some regions, whereas other have not given rise to major earthquakes (Lagerbäck and Sundh, 2008). It has not been possible to determine the reason for the variability in earthquake response during past glaciation cycles. This shows that it will be difficult to predict the earthquake response for the next glaciation cycle. Therefore, the only option is to conservatively assume that major faults could be reactivated during the next glaciation cycle.

10.4.4 Shear displacement across a canister

In the SKB documents, shear displacement along a fracture/fault intersecting a canister is the most likely mechanisms that could breach a canister. SKB has adopted a criterion of a maximum allowable shear displacement of 0.1 m that according to SKB's analysis would assure canister integrity (Munier and Hökmark, 2004). In the documents, SKB analysed the possible shear displacement along a fracture/fault (called target fracture) intersecting a deposition hole subjected to static and dynamic stress changes from earthquakes taking place in a nearby major fault (Munier and Hökmark, 2004; Fälth et al., 2010).

SKB's analysis shows that stress changes induced around a reactivating major fault decreases with distance from the fault. As a result, the induced shear displacement on the target fracture decreases with distance from the reactivated fault. Over the years, SKB have evaluated the possible shear displacement on a target fractures using different kinds of modelling approaches (Munier and Hökmark, 2004). The most recent and direct approach is a three dimensional distinct element modelling (3DEC) in which the earthquake on a major fault is explicitly modelled and the mechanical response on the target fracture is evaluated. The target fracture is assumed to be a single fracture of a certain radius (e.g. 100 m) embedded in an elastic medium with intact rock properties. SKB claims that a linear elastic medium with intact rock properties is a conservative assumption with respect to maximum shear displacement (Munier and Hökmark, 2004).

SKB's analysis shows that the maximum shear displacement along a fracture intersecting a deposition hole would not exceed 0.1 m for a fracture with a radius less than 100 m. Thus, by not emplacing waste canisters in deposition holes that intersects identified fractures/faults that are larger than 100 m in radius, shear displacements across a canister will not exceed 0.1 m.

10.4.5 Some identified issues

In this section, two main issues related to the SKB's approach and results are discussed. The first one is related to the effects of the operational and thermal period and the potential for induced seismicity that could occur within tens of years after closure of the repository. The second one is related to the prediction of the maximum shear displacement in a fracture/fault intersecting a deposition hole.

10.4.6 Possibilities of induced seismicity during operational and heating phases

In a previous review of SKB’s work related to coupled THM processes within SR-Can, a number of issues related to damage and geomechanical changes in the fracture rock were identified (Rutqvist and Tsang, 2008). One issue closely related to seismology is the possibility of thermally-induced shear reactivation fractures and faults in the far field (Figure 1). The coupled THM analysis of Rutqvist and Tsang (2008) showed that the increased temperature will increase horizontal stress substantially (on the order of 15 to 20 MPa) in the repository horizon. This could lead to shear reactivation along shallowly dipping fractures across the repository.

Figure 2 shows a vertical profile of calculated stresses. The figure shows that increased horizontal stress occurs over a vertical distance extending several hundred meters above and below the repository horizon. Thus, fractures of a radius of several hundred meters could be reactivated by the thermal effects and such reactivation could cause seismicity that might be of concern to the local population.

Figure 3 shows the evolution of the stress path (maximum versus minimum effective stress) during the operational and thermal phase. The initial minimum principal compressive effective stress σ_3 is equal to the vertical effective stress (overburden stress minus the fluid pressure). The initial maximum effective stress σ_1 is the maximum horizontal effective stress. If the rock mass at Forsmark is initially critically stressed, the initial stress would be very close to failure. Neglecting cohesion, this would correspond to an initial coefficient of friction, μ= 1.0 on critically stressed faults. However, for a sparsely fractured rock such as that of the Forsmark, a substantial rock mass cohesion would exist. During the operational phase the stress initially goes to a more stable condition after the excavation. This is caused by the depressurization and associated increase in effective stress. After emplacement the fluid pressure is restored towards hydrostatic and thermal stress develops. Thermal stress develops preferentially in the horizontal direction and increases the horizontal stress by about 15 MPa. The high horizontal stress and the high shear stress are sustained for thousands of years.

In Figure 4, the stress path for the last glaciation cycle is added using approximate values of stress extracted from Lund et al. (2009). According to Lund et al., (2009), both vertical and horizontal stress increases during glaciation. Such an isotropic increase in stress provides confinement and increases stability of the rock mass. However, during deglaciation, the vertical stress decreases much more rapidly than the horizontal stress. Just after deglaciation, when the pre-glaciation lithostatic vertical stress has been restored, a net increase in horizontal stress of about 10 MPa remains. This is an unstable stress state, but is less unstable than during the peak thermal stress. On the other hand, the glaciation affects the entire crust around the repository, whereas the thermal effect is limited to within the repository horizon and a few hundred meters surrounding it.

In summary, the results in Figure 4, shows that the shear stress increases more during thermal period and that the estimated increases in the last glaciation cycle. Thus, it seems to be important to study the potential for induced seismicity during the thermal cycle.

10.4.7 Predicting the maximum shear displacement of target fractures

The maximum shear displacement that could be induced on a fracture/fault intersecting a deposition hole would depend on the cumulative effect of several types of loadings:

1) Thermal load for thousands of years (high shear stress)
2) High shear stress during deglaciation (aseismic slip over 10,000 years)
3) Effects by repeated earthquakes in nearby faults

Each of these events could give additional slip until the fault is fully reactivated (reach its slip limit depending on its length and stiffness of surround rock). Considering the assumption of a circular fracture embedded in a linear elastic medium, the shear displacement D for a certain change in shear stress (stress drop) can be calculated analytically as:

D = (24/7 t) At (r/G)

where At is the shear stress change, r is fracture radius and G is the shear modulus of the surrounding medium. For a stress drop At = 15 MPa, a fracture radius of 100 m and a shear modulus G = 30 GPa, D = 5 cm. G = 30 GPa is the shear modulus of the intact rock assumed in the analyses conducted in the SKB documentation (e.g. Munier and Hökmark, 2004). However, in a fractured rock mass, the displacement of the target fracture must be affected by nearby and intersecting minor fractures that would tend to soften the rock and thereby allow for larger shear displacement. Figure 5 illustrates the difference in the case of the target fracture embedded in linear elastic medium (Figure 5a) and the case of the target fracture located in a fractured rock mass (Figure 5b). Thus, it is not clear that the use of linear elastic medium with intact rock properties is a conservative case.

For predicting the maximum possible shear displacement it should be useful to study field observations of fault length versus fault displacement data. Figure 6 presents data compiled by Schultz et al., (2008). It is shown that for a fault length of 200 m (corresponding to a fault radius of 100 m) the maximum shear displacement is larger than a meter and could be up to 10 meters. This represents the upper limit of shear displacements for a certain fault length. Further shear displacement would make the fault to growth to a larger length. It is questionable how relevant the data in Figure 6 is to the rock types and conditions at Forsmark. However, it shows that the total shear displacement along a fault is a result of repeated slip events that might be both seismic and aseismic, and the shear displacement for a 100 m radius fracture could be substantial. Thus, there is a possibility that SKB's estimated shear displacement for the assumed target fracture could be underestimated.

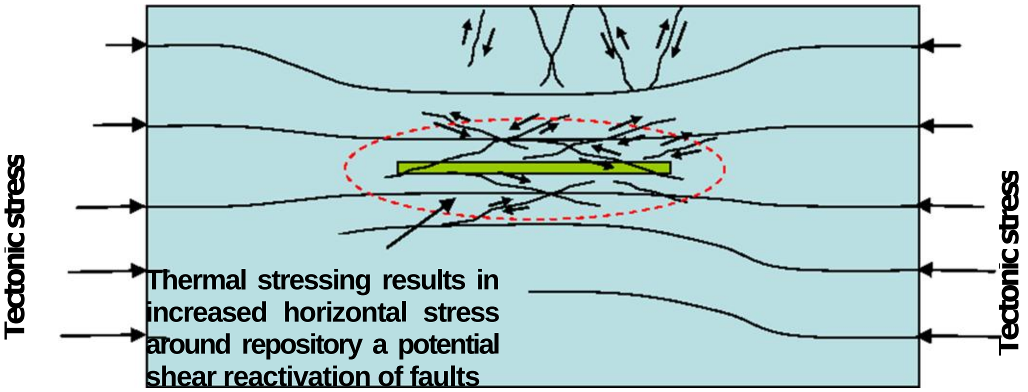
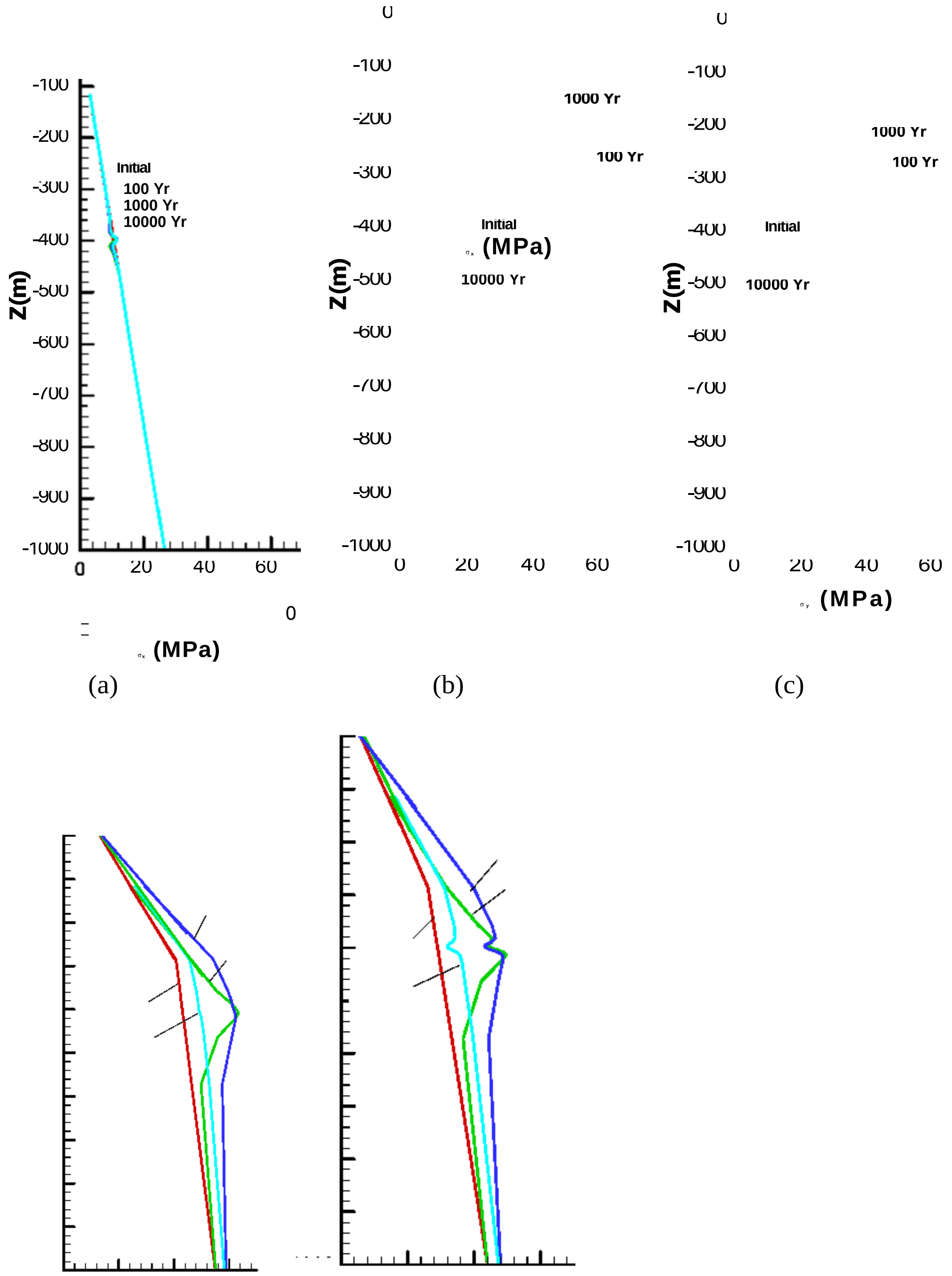


Figure 1. Schematic of potential massive shear reactivation in the fractured rock mass as a result of thermal stressing in a rock mass that might already be critically stresses for shear (Rutqvist and Tsang, 2008).



(a) (b) (c)

Figure 2. Profiles of vertical and horizontal stresses for a repository located at Forsmark: (a) vertical stress, (b) horizontal stress normal to the tunnel axis and (c) horizontal stress along the tunnel axis (Rutqvist and Tsang, 2008).

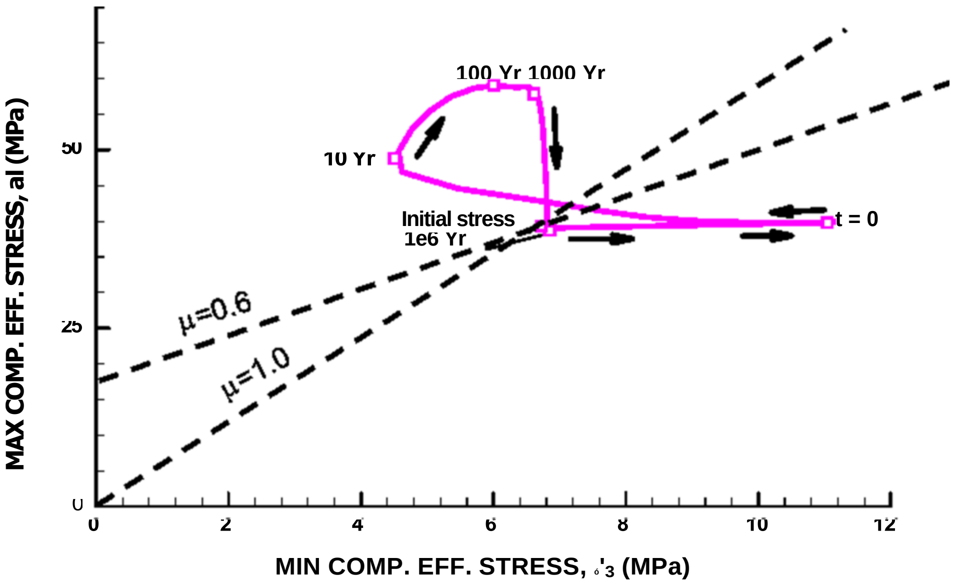


Figure 3. Evolution of the principal stress path in the rock mass at the depth of the repository in comparison to different frictional coefficients that are likely to induce shear slip along existing fractures (= 0.6 to 1.0), for a repository located at Forsmark (Rutqvist and Tsang, 2008).

MIN COMP. EFF. STRESS, .'3 (MPa)

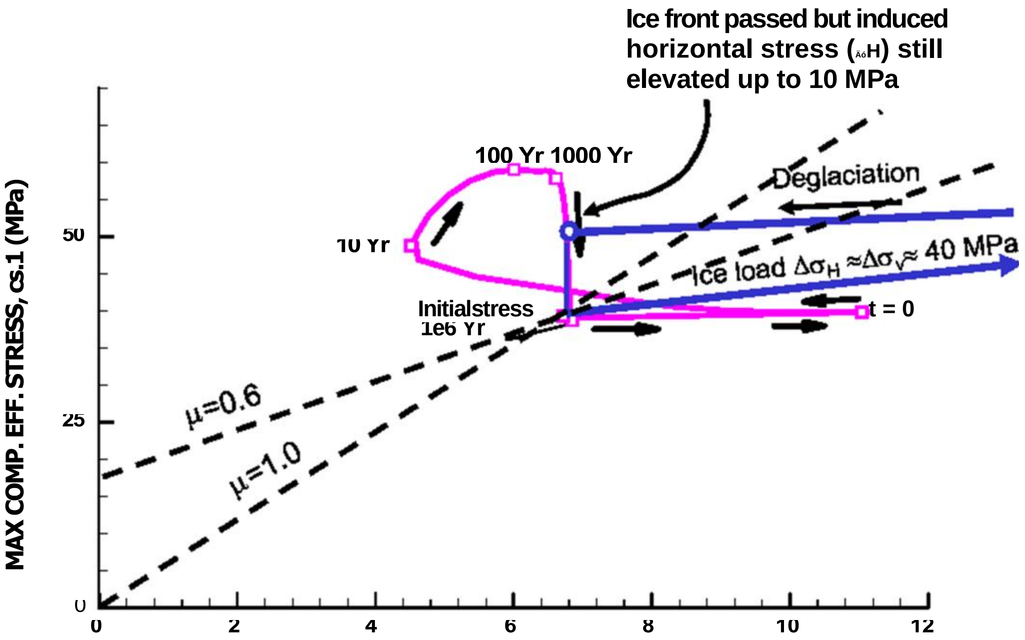
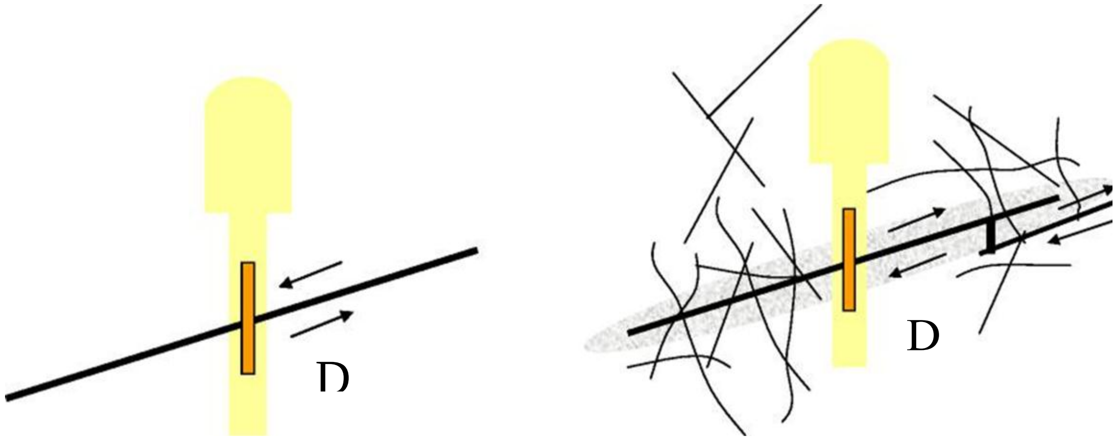
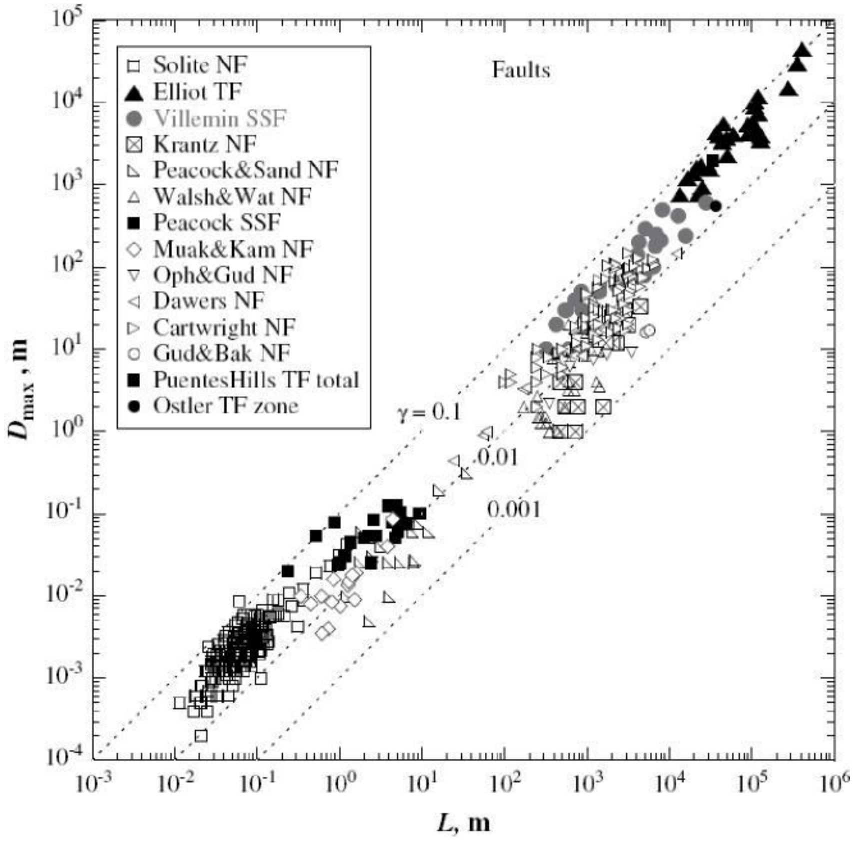


Figure 4. Evolution of the principal stress path in the rock mass at the depth of the repository with stress path during glaciation and deglaciation added (blue line).



(a) (b)

Figure 5. A major fracture intersection a deposition hole (a) in intact rock and (b) in a fracture rock mass.



10.4.8 Concluding remarks

This review of SKB work related to seismology was conducted from the viewpoint of geomechanics and related to previous work on coupled thermal-hydraulic-mechanical (THM) processes around a future repository at Forsmark. Two main issues were identified:

- The potential for large scale shear reactivation in the rock mass and associated induced seismicity during the thermal period has not been sufficiently addressed.
- The maximum possible shear displacement calculated for the target fracture might be underestimated, because cumulative effects of thermal, long-term ice load, and repeated seismic, and variability in rock mass properties surrounding the target fracture are not sufficiently considered.

Field evidence indicates that maximum shear displacement for a 100 m radius fracture/fault could be much larger than 0.1 m, and SKB needs to show that this could not occur at Forsmark.

10.4.9 References

Bäckblom, G. and R. Munier (2002). Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. SKB TR-02- 24, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.

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Schultz R.A., Soliva R., Fossen H., Okuba C.H., and Reeves R. (2008). Dependence of displacement-length scaling relations for fractures and deformation bands on the volumetric changes across

10.5 Prof. Ove Stephansson, Steph Rock Consulting Berlin

10.5.1 Introduction

In a letter by Swedish Radiation Safety Authority 2010-02-15 Steph Rock Consulting AB have been asked to present a review of the following reports and scientific articles and to present the results at the Workshop on Seismology in Stockholm 23-25 March, 2010:

1. Bäckblom, G. and R. Munier (2002) Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. SKB Technical Report TR-02-24.

2. Lagerbäck, R. and M. Sundh. (2008) Early Holocene faulting and paleoseismicity in Northern Sweden. Geological Survey of Sweden, Research Paper C 836, 80p.

3. Lund, B., P. Schmidt and C. Hieronymus. (2009) Stress evolution and fault stability during the Weichselian glacial cycle. SKB Technical Report TR-09-15, 106 pp.

4. Munier, R. and Hökmark, H. (2004). Respect distances. Rationale and means of computation. SKB Report R-04-17, 218 pp.

5. Hedin, A. (2008) Semi-analytical stereological analysis of waste package/fracture intersections in granitic rock nuclear waste repository. Mathematical Geosciences 40:619-637. DOI 10.1007/s11004-008-9175-3

10.5.2 Bäckblom, G. and R. Munier (2002) Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. SKB Technical Report TR-02-24

This report presents the main results from the SKB project *Effects of Earthquakes on Underground Facilities.* The fact finding with interviews, literature surveys, Internet searching, circular letters and study-tour started in 2001 and the final report was released in 2002. This is a very short time for such an ambitious programme and search activity of an important issue in the safety programme for the location of a repository. Published records from earthquakes and underground damage to openings in China, Italy, Japan, South Africa, Taiwan, USA and former Yugoslavia are compiled and presented. Of special interest to the issue of respect distance is the information presented in Chapter 3 and 4 of the report.

In Chapter 3 the authors present a countrywide overview of cases on earthquake influence on underground facilities for each of the countries listed above. From China, Italy and Taiwan one single earthquake and its effect on underground openings are described. From Japan and the other countries several events and damages are presented. One can raise the question if the number of earthquakes and underground construction damages studied are enough to reach valid conclusions about the effect of earthquakes on a deep repository for spent nuclear fuel. Many of the studies presented and discussed are located in rock types of little relevance for the deep repository in Sweden. The most relevant data are gathered from the Hyogoken-Nan-bu (Kobe) earthquake in an area of granitic rocks, January 1995, pp.53-55.

It is a well-known fact, and also supported by the presented case studies from the literature in the report, that damage from an earthquake is much less underground than at the surface. In Table 3-6 the authors present an overview of measured displacements observations close to re-activated faults and they claim that even for very strong earthquakes, deformations are confined to a few hundred meters from the re-activated fault.

One has to bear in mind that the width of the damage zone, or sometimes called process zone, is a function of the length of the faults. In Figure 1 is presented scaling data of the fracture (fault) process zone from laboratory and natural faults (Zang and Stephansson, 2010). The solid line in the double logarithmic plot of process zone width versus fault length is for natural faults from the classical paper by Vermilye and Scholz (1998) with a regression slope of 1/62 and the regression slope of 1/50 for laboratory faults by Zang et al. (2000). Note that the width of the process zone (and also the fracture toughness) scales with the length of the fracture. The diagram in Figure 1 scales over six orders of magnitude and the scatter of single data points is as large as one order of magnitude.

If we apply this diagram to the situation in Forsmark and to the mapped faults as presented in Figure 2-7 of the rock mechanics site descriptive model stage 2.2 (SKB R-07-31),Table 5-2 of the geological site descriptive model stage 2.2 (SKB R-07-45) and the Appendix B of the recent published Site Engineering Report (SKB R-08-83) we find that most of the data points for the faults in Forsmark fall slightly below the regression line presented in Figure 1 with a regression slope of about 1/45. If we limit the analysis to the most important faults in the target area and for the Singö fault we receive the results presented in Table 1. The table lists the major characteristics of the three major groups of faults of importance for the location of the repository. Like for all faults in the Forsmark site investigation area we find that most of the data points of the measured process zone width versus fault length fall on the regression line or slightly below. If we plot the estimated span of process zone width versus fault length
We find the scatter in fault width is of the order of one magnitude which is about the same as for the different data presented in Figure 1.

What can we learn from the data presented in Table 1 about Forsmark? There is a relationship between fault length and fault width which follows the general trend reported in a number of studies worldwide. This gives confidence that the fault tectonic situation at Forsmark follows the normal behaviour and is valid worldwide and for different geological conditions although the slope of the regression line is somewhat less than what is presented in Figure 1. Hence, the regression line for Forsmark with a slope slightly less than shown in Figure 1 is valid for the geological conditions in the region. The regression line for Forsmark can be used to put an upper bound on the selected respect distance for canister location in the vicinity of faults. This application of the result of the fault data demands a correct determination of the fault length.

SKB has stated in the Site Engineering Report (SKB R-08-83) that a respect distance of 100 m is required for major deformation zones with a trace length at ground surface greater than 3 km. If we apply this criterion to the presented results for Forsmark we find that the 100 m respect distance, corresponding to 100 m fault width, for a 3 km long fault fall just below the regression line for the majority of faults in Forsmark. If one considers the scatter in the data about the faults the selected respect distance is not enough. The information from the compilation can be used to define the best estimate fault width for each individual fault in the repository area once the fault length has been determined. This might be a better methodology than using the measured fault width which comes from a limited number of measuring points as suggested by SKB for Forsmark.

In section 4.2 the author raises the question “Can new fractures be created?” and he supports the main hypothesis put forward by SKB and several scientists that release of energy is dominated by shaking and by displacements along pre-existing faults and fractures rather than by creation of new fractures. Under normal rock condition with averaged fractured rocks and stress conditions the faulting is governed along pre-existing faults or within the existing process zone from previous

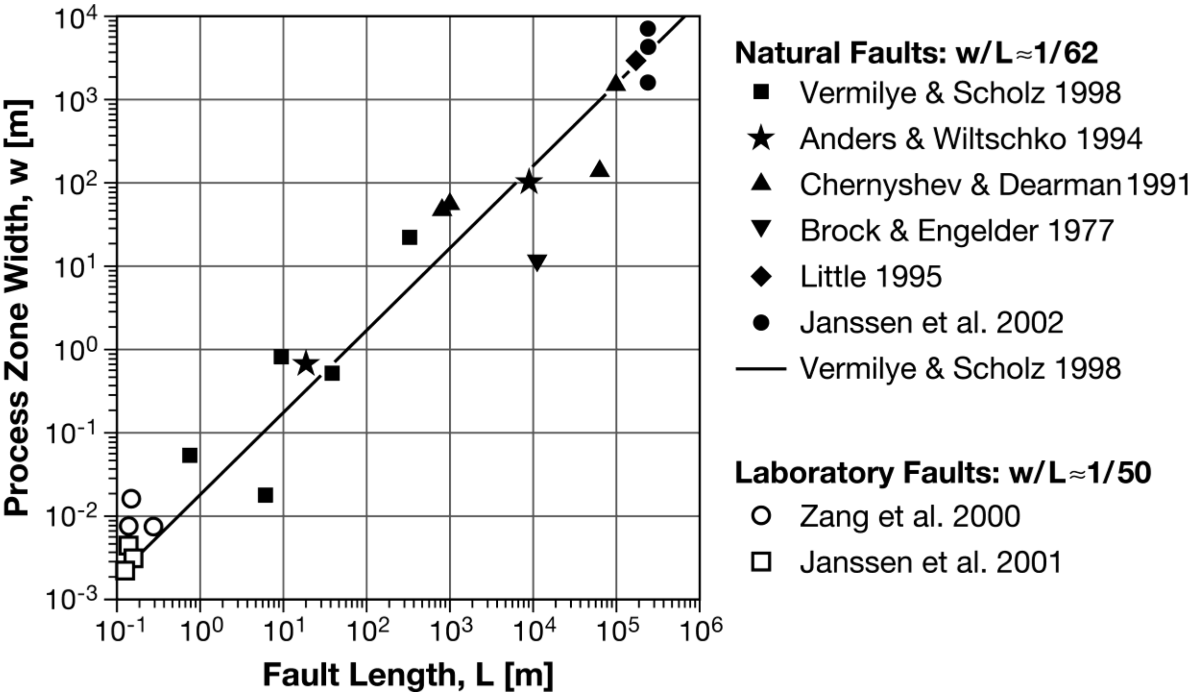


Figure 1. Fault-scaling relationship in rock. The width of the fracture process zone determined on natural and laboratory faults is plotted versus the length of fault. (After Zang and Stephansson, 2010).

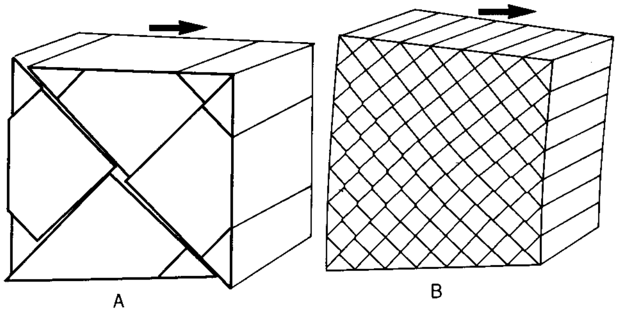
Table 1. Deformation zones of importance for the repository location at Forsmark

Name	**Number**	**Strike/Dip (^{o})**	**Length (m)**	**Measured Width (m)**	**Width Span (m)**	**Comments**
WNW- NW Striking Faults	ZFMNW0001 Singö Zone	120/90	30,000	165	53-200	Below regr. line in Fig.1
	ZFMNW1200	138/85	3,121	47	10-65	On the regr.line
	ZFMNW0123	117/82	5,086	52	10-64	On the regr. line
	ZFMNW0809A	116/90	3,347	25	10-64	Below regr. line
	ZFMNW1127	120/90	5,394	35	10-64	Below regr. line
ENE-NE Striking	ZFMNE0060C	241/75	1,161	20	3-45	On the regr.line
Faults	ZFMNE0062A	058/85	3,543	44	10-64	Slight below regr. line
Gently S, SE, and W	ZFMA2	080/24	3,987	23	9-45	Below regr. line

dipping faults						
	ZFMA8	080/35	1,852	32	6-37	On the regr. line

faulting. Later in the section the author is referring to the work by Ortlepp (2001) and his work about faulting in the deep South African gold mines. Ortlepp states and the author of the report agrees that the absence of faults and fractures is a less favourable factor in high-stress regimes because the mining-induced fracturing occurred at very high stresses in very good rock quality where there are no faults or fractures that could accommodate the stress build up. The work by the author of the report was completed about the time when the site investigations started in Forsmark in 2002. When the site investigations were completed in 2007 it turned out as a result that the rocks at the target area is of very good rock quality and very few fractures. Whereas the target area has high stresses or not is still an open question. SKB is of the opinion that the stresses are higher than normal for Scandinavian conditions while the INSITE group of SSM claims that the stresses are typical for Fennoscandia hard rock conditions. We have to wait for the final answer till the underground works have proceeded and reached the deposition level.

The issue about protecting the repository by means of deformation zones of different origin and size was very much discussed at the beginning of the location of a final repository for the spent nuclear fuel during the early 1980s (Stephansson et al.,1980). The idea is to locate the repository so that it is protected by a number of deformation barriers (faults) of different size, location and age. Any displacement related to an earthquake should be taken up by the barriers and the repository remains intact. At this time the author of this review advocated and still advocates that from a rock mechanical point of view a jointed rock mass with an intensity of 2-3 joints and fractures per metre prevents stress concentrations and the risk of brittle and semi-brittle fracturing within the repository, see Figure 2. The question still to be resolved is "What is the risk for new fractures to be created due to excavation and thermal loading on the near-field and far-field scale of the repository? This issue will be suggested to SSM for further studies.



Figur 3. Modell av berg med sprickor som deformeras. A, få sprickor i berget ger höga kontakttryck mellan blocken och risk för ny sprickbildning. Stora breda sprickor bildas som underlättar vattnets strömning. B, lagom mycket sprickor, 1–2 st per meter, ger följsam deformation och låga kontakttryck. Rotation av blocken ger små spricköppningar och låg vattenströmning.

Figure 2. Finite element model of jointed rock mass subjected to shear deformation. A, few fractures in the rock give high contact stress between the blocks and cause high risk for generation of new fractures. Large open fractures also enhance the groundwater flow. B, favourable number of fractures, 1-2 per meter, gives gentle deformation and low contact forces with less groundwater flow. (After Stephansson et al. 1980)

In Section 4.3 the author discusses the accumulated displacements of fractures by more than a 0.1 m at the location of canisters and concludes that deformations measured along faults in tunnels do not necessarily indicate slip along secondary faults and fractures and he gives reasons for that statement. The results from numerical modelling of displacements > 0.1 m over the deposition hole for the canister will be discussed in the review of the report by Munier and Hökmark (SKB R-04-17).

The discovery of post-glacial tectonic structures in Northern Sweden in the late 1970s has raised the question if similar events can happen in the vicinity of a repository in conjunction with future glaciations. In this Section the author readdresses the critical questions:

- Can new, significant fractures be created?
- Will accumulated displacements > 0.1 m occur in the rock where the canisters are deposited?
- Will post-glacial earthquakes behave like the earthquakes we can study today?

but no important and new knowledge is brought up. In respond to the question raised the following answers can be given:

- There is a risk that new fractures can be created in the near-field and/or in the far-field during the post-closure phase of the repository
- There is a potential risk that thermally induced fractures can develop during the post-closure phase and the likelihood for this has to be demonstrated,
- To answer this question SKB has to study seismicity in de-glaciation areas with hard rocks like the coast of West Greenland and this type of work is now initiated

In Section 4.8.1 of the report the authors bring up the issue “Can the repository itself induce earthquakes?” and refers to a study by Martin and Chandler (1996) which shows that the very low extraction rate (excavated volume versus total initial volume) of the order of 0.25-0.30 for a repository is not enough to generate earthquakes and damage. The author never considered the effect of the heating plus the excavation on the probability of earthquake generation.

“Can shaking induced by earthquakes before closure damage the repository?” is the title of Section 4.8.2. Damage of underground structures is known to result from earthquakes with a Peak Ground Acceleration (PGA) of 2 m/s^2 or more. The seismic risk analysis presented for the nuclear power unit Forsmark (Stephansson and Lande, 1976) gave PGA = 0.15 m/s^2 with a recurrence probability of 10^{-5}. The probability of damage of the underground facilities from an earthquake during the pre-closure phase is very small. This opinion is also supported by the author of this review.

In the Section about earthquake impact during the pre-closure phase in the Conclusion, the authors claim that it might be possible to experience local rock burst problems due to the heterogeneous rock strength and varying rock stresses. In this statement, the author has disregarded the additional loading of the rock mass from the heat of the waste and claims that in case the events appear they will take place when the tunnels are excavated rather when the spent fuel is deposited. Instead, it is more likely that the events appear after the closure of the repository and at the time when the rock temperature reaches the maximum after approx. 100 years. To what extent the risk of fracturing and seismic activity can appear during the pre-closure phase is also an open question that needs to be explored.

10.5.3 Lagerbäck, R. and M. Sundh. (2008) Early Holocene faulting and paleoseismicity in Northern Sweden. Geological Survey of Sweden, Research Paper C 836, 80p.

Robert Lagerbäck, the first author of the report, together with Gösta Lundqvist were the two scientists first describing the remarkable large Early Holocene faults and related sedimentary structures in Northern Sweden in a paper of Geologiska Föreningens Förhandlingar 1976. The discovery came at the time of the ongoing site investigations within the KBS project. It is not discussed in the report what importance the discoveries have had for the location of a repository for spent nuclear fuel, but certainly the results of the discovery has played an important role in SKB's decision not to locate a repository in the bedrock of the northernmost parts of Sweden. The SKB project, following the KBS project, has also supported the investigations of the fault structures and in particular the Lansjärv fault presented in the report published by the Geological Survey of Sweden.

For more than 35 years Robert Lagerbäck has been conducting a large number of reconnaissance and detail studies of faults and sedimentary structures emanating as a consequence of faulting. He is a quaternary geologist and specialist on analysis and description of quaternary deposits and his work has been extended to other parts of Sweden and in particular in the area of the two selected sites for site investigations (Laxemar and Forsmark) by SKB. From his studies over many years and all over Sweden it is clear that the fault structures are limited to the northernmost parts of Sweden. There have been attempts to interpret structures in southernmost part of Sweden as being Holocene fault structures but careful investigations by Lagerbäck and other experts show that the structures are not related to deep-reaching bedrock faulting. This information is of utmost importance for the suggested location of the repository to Forsmark far away from the known Holocene fault structures in Northern Sweden.

The authors of the report describe the fault structures in Northern Sweden thorough and with great detail and they also show the location of the known Holocene faults in Finland and Norway. The few structures known in these two countries could have been included in the report and the study extended to cover Northern Fennoscandia.

The fast land uplift from the deglaciation is thought to generate the Early Holocene faulting in Northern Sweden. The sandy-silty sediments formed in low elevation at the time of the ice recession were liquefied due to seismic activity from the faulting. The saturated glaciofluvial sediments formed large landslides and it is striking how the landslides are located close to the border of the highest shoreline, see Figure 2 of the report. There are exceptions around Storuman and at a few sports east of the Pärvie fault. The dating of the large land slides is still a problem and it seems that additional efforts has to be done to reach a final conclusion about the genesis of the landslides and their relation to the seismicity from the faulting. Another issue to be resolved is the genesis of the landslides entirely dominated by glacial till and located above the highest shoreline. Such till deposits are not expected to slide or flow under normal conditions and in particular in the gentle slopes often existing in the area surrounding the faults above highest shoreline. In addition tills are normally not expected to generate liquefaction structures.

In Figure 80 of the report the authors present a typical ice tectonic structure in the form of a fold. The structure is found at Östansjö 7 km south of Forsmark. This raises the question if some of the structures existing in the soft sediments in Northern Sweden also are triggered and generated by forces governed by the retreating or advancing ice at the late stage of deglaciation.

In the section about paleoseismic records in the Discussion Chapter of the report the authors mention that the apparent absence of landslides in the vicinity of the Pärvie, Lainio-Suijavaara and Merasjärvi faults is somewhat obscure. From reading the report one does not get a satisfactory explanation for this situation and the statement disagree with the first sentence in the section saying that the faulting in Northern Sweden is strongly supported by the regional distribution of the paleoseismic records, landslides as well as soft-sediment deformation features.

Heavily disrupted bedrocks like the one found at Bodagrottorna (Fig.86) and boulder caves like Trollberget (Fig. 87) have not been reported from the Late Holocene faulting areas in Northern Sweden. The authors of the report also take a strong position against the idea that these structures are of paleoseismic origin. The author of this review is of the same opinion.

About the timing of faulting the authors of the report and other scientists studying the faults are of the opinion that the fault scarps in Northern Sweden formed in close connection with the deglaciation about 10,000-9,500 years BP. Professor J. Lundqvist has presented a model of deglaciation where the faults developed successively during the ice retrieve. If this model is correct it can most likely be verified only by additional dating of organic objects in the sediments. So far it is only proven that the faulting occurred as a single episode from the trenches excavated across the Lansjärv and Röjnoret faults. The difficulties to reach the remote Pärvie fault with trenching equipment prevent a thorough analysis of the displacement event and associated sedimentary structures.

More detailed seismic analysis from Northern Sweden during the last century shows that ca 50 % of the recent earthquakes is associated with the Late Holocene faults (Fig.91). These ´aftershocks´ are with a few exceptions located on the hanging wall of the faults and gives a clear indication that the faults are deep reaching with an easterly dip in the Earth’s crust. If we apply the plot of width of the process zone versus fault length as presented in Figure 1 of this report we obtain the result presented in Table 2.

The result from applying the plot in Figure 1 to the most important faults in Northern Sweden clearly demonstrates the impressive dimension of the structures. This is also supported by the large magnitudes and focal depth of the seismic events as demonstrated by Bödvarsson and Lund (2003) and Lund et al. (2004). Of special interest are also the results of the stress evolution during the Weichselian glacial cycle recently presented by Lund et al (2009) where the orientation of the horizontal maximum stress during ice maxima and after ice melting is directed perpendicular to the strike of the Late Holocene thrust faults. Also the region with maximum shear stress in the models coincides with the area of Late Holocene faulting

Table 2 Estimated widths of the Late Holocene faults

Fault	**Length (m)**	**Width of Process Zone Vermilye & Schulz (m)**	**Scarp Height Lagerbäck & Sundh (m)**
Pärvie	155,000	1,100	3 - 10
Lansjärv and Lainio	50,000	900	10 - 20
Bastuträsk and Röjnoret	35,000	600	5 - 15
Merasjärvi	8,000	100	4 - 8

10.5.4 Lund, B., P. Schmidt and C. Hieronymus. (2009) Stress evolution and fault stability during the Weichselian glacial cycle. SKB Technical Report TR-09-15, 106 pp.

Björn Lund and co-workers have presented a series of technical reports and a few publications in international journals about the state of stress in the Fennoscandian Shield during a glacial cycle. The purpose of the modelling is to increase the understanding of the stress variation in the Earth's crust during a glacial cycle and to provide regional and local stresses to different earth science site descriptive models for the repository sites. In performing the analyses they have been using the commercial finite elements software ABAQUS. In this report the team is modelling a series of benchmarks to illustrate the results from different assumptions regarding GIA models and modifications of the treating material properties at layer boundaries. In addition they have studied relationships between 2-D and 3-D models constrained from using GPS data. The main parts of the report deals with glacially induced stresses for different stratified models and fault stability during glaciation for the two selected sites at Forsmark and Oskarshamn and the postglacial faults in Northern Sweden.

For the benchmark tests the group has been using four different existing benchmark models of type axisymmetric, flat-earth spectral model, viscoelastic half-space axisymmetric models and some of the previously developed benchmark models by Lund. In developing the GIA models for Fennoscandia the group has omitted the influence of sea-level variation during glaciation as no water is simulated in the models except pore pressure. Effects of other large scale ice sheets and previous glaciations are also omitted. Finally, the model material compressibility does not include internal buoyancy. All these omitted effects and processes are likely to have minor effects on the results.

In previous studies by Lund and his group, 2-D profiles of the glaciation models were used. In Chapter 3 of this report the group is presenting the comparison in stresses between the two modelling approaches at fixed time intervals. It is clear that there are substantial differences in calculated stresses for the two different models. The authors reach the conclusion that previous presented 2-D models are not suitable to derive at correct stress state for a particular ice model and site. This is an important information from this study.

In simulating the stress evolution during the Weichselian glaciation the group has been using the thermo-dynamic ice sheet model by Näslund 2006 which is also the model used by SKB. The solid Earth model is a finite element model with 8-node infinite solid elements and spring elements for simulating the gravity forces at the layer contacts, a total of 260,000 elements. The large 3-D model is a half-sphere with infinite elements at the boundary. The ice model forms a box in the large model and this allow analysis of different sub-models for the uppermost 15-20 km of the crust. The uppermost elements are 1km thick which allows determination of stresses in the vertical direction per 500 m distance. In principal three different lithosphere models have been simulated; a uniform 100 km thick layer, a three layer model and a three-layer model with varying lithosphere thickness. Six different horizontally stratified models were analysed and four models of laterally varying lithosphere thickness.

GPS data from Fennoscandia and countries along the Baltic and North Sea coasts and relative sea-level data have been used to calibrate the models. It turns out that models with a mantle viscosity of $1x10^{21}$ Pas produce the best fit with the velocity data from the GPS measurements although the elasticity of the overlying lithosphere is too high relative known data from seismology and rock mechanics.

The modelling team presents glacially induced stresses in the models for two different times, at the ice maximum (18,5 kyr BP) and when the ice sheet has disappeared (10 kyr BP) (Chapter 7). The region of high stress due to glaciation generally follows the shape of the ice sheet and the maximum horizontal stress varies from over 70 MPa to 30 MPa depending on the model geometry and stiffness of the elastic lithosphere. The higher elasticity the larger stresses. The fore-bulged areas outside the ice sheet generate tensile stresses in the upper part of the lithosphere. The presented results of maximum and minimum stresses, stress orientation, maximum shear stress and stresses versus depth for the two sites Oskarshamn and Forsmark for the two types of crustal models studied provides an impressive and very interesting reading and the conclusions drawn are solid and well founded. In addition, the results from the modelling supports many of the field observations presented for the neo-tectonic fault structures in Northern Sweden and it provides valuable data for the interpretation of the change in the stress field due to a glacial cycle at the Forsmark and Oskarshamn site. Based on the evaluation of the evaluation of the ten studied models the authors have selected models 2, T9 and T12 as the most appropriate models for the subsequent fault stability analysis. As a reader of the report one would also like to have the results about stresses in the models at present time. This would allow one to assist in the calibration of the different models and also provide interesting data about magnitude and orientation of the stresses in the Fennoscandian Shield.

In Chapter 8 of the report the authors describe the background stress field that is later used in the fault stability analysis for the different earth models. As stated in the report the data about the orientation of the maximum horizontal stress as presented by the World Stress Map project is far from uniform in the Fennoscandian Shield and the variation in direction is the most in northern part of the Shield. In the most recent version of the World Stress Map data base there is an option to statistically resolve the maximum horizontal direction by means of a smoothing routine. This can be used to try to find a possible border of the strike-slip and thrust faulting regimes for Sweden. However, it is clear that there is a need for more stress data in the Fennoscandian Shield to be able to confirm the different stress regimes and to obtain magnitude and orientation of the principal stresses.

The authors have developed two synthetic models of the stress field to be used as background stress field in the stability analyses, one strike-slip model and one reverse (thrust fault condition) stress state. For the direction of the background maximum horizontal stress the authors have been using the Euler pole for the Eurasian plate. In deriving the vertical stress and the horizontal stresses the authors derive equation (8-3) in the report. However, it is not clear why the authors have left out the pore pressure terms for the vertical stress component for the two stress models and for the intermediate (least horizontal stress) for the reverse stress model (see eq.8-3).

Zoback et al (2003) have presented a stress model according to Andersson faulting for hydrostatic pore pressure and the same friction coefficient μ=0.6 and a rock density of 2.3 ton/m^3 of similar type as done by the authors of the report and that is shown in Figure 3. The models in Figure 3 are valid for a rock density of 2.3 tons/m^3 compared with the 2.73 tons/m^3 used by the authors. The two horizontal stresses used by the authors for the strike-slip and reverse models are is much larger than the horizontal stresses used in the model presented in Figure 3.

The much lower stresses for the model in Figure 3 will certainly lead to other fault stability maps than those presented by the authors. The selection of background models and its application to fault stability for the selected glaciation model will certainly modify the fault stability maps for Fennoscandia and the fault stability at Oskarshamn and Forsmark and the stability of the Pärvie fault. This issue was discussed at the Workshop and later the first author of the report has in full explained the method used and also that the two models are congruent when using the same rock density.

The authors have used the Coulomb failure criterion to the combination of the background stress field and the glacially induced stress field. The criterion is widely applied in geophysics and rock mechanics and is also relevant for the problems studied in the report. For the indication of stability the authors are using the well-known term Coulomb Failure Stress, CFS, (equation 9-2) which means that if CFS is positive the shear stress is larger than the frictional force and the fault will fail in frictional sliding. The situation that CFS = 0 has been used to define the background stress as shown in Figure 8-3 of the report. As pointed out above, it is not fully clear how the authors derive the equations used to define the background stresses. Therefore an alternative model as shown in Figure 3 of this report is presented. The use of the friction coefficient μ = 0.6 and the omission of cohesion when defining stresses at great depth is acceptable. Of utmost importance is the pore pressure for determining the background state of stress and the stability. The authors have been using pressure head of 50, 90 and 100 % in the stability analysis. The 50 % pore pressure mode means that the pressure reaches 50 % of the local weight of the ice column due to the resistance from slow pressure diffusion. In simulating the stability conditions for the ice model during a glacial cycle the authors have considered the influence of the intermediate principal stress and have used R = 0.5 (equation 8-2). The selection of this value for R needs further explanation.

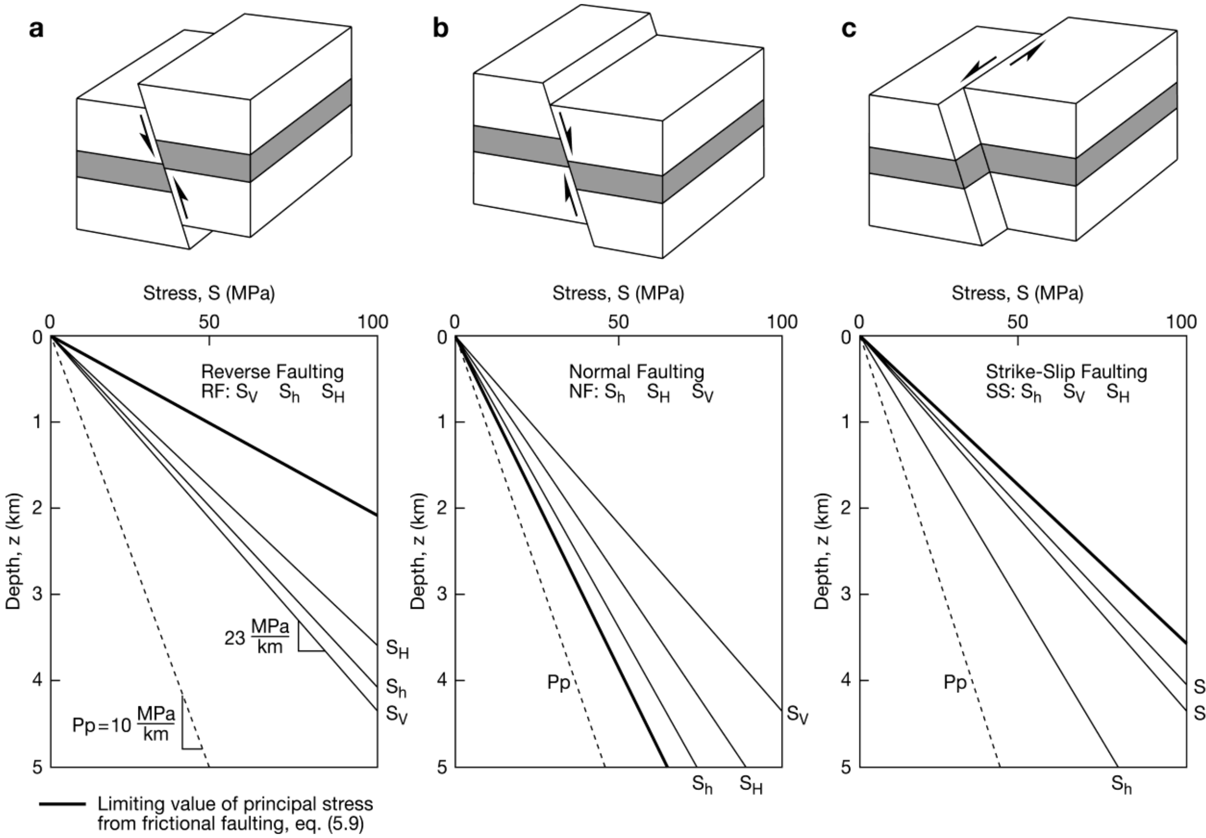


Figure 3. Variation of stress magnitudes with depth for three different faulting conditions RF **a**, NF **b**, and SS**c**. Assumption are μ=0.6 for friction coefficient, 23 MP/km for the depth variation of S_v and pore pressure of 10 MPa/km. From Zang and Stephansson (2010) after Zoback et al (2003).

The authors are presenting maps of the modelled fault stability field over Fennoscandia at 10 km depth in the Earth's crust and a pore pressure at 50 % of that at ice maximum at 18.5 kyr BP and at the end of the glaciation 10 kyr BP. As expected the weight of the ice at ice maximum will enhance the stability of the Earth's crust over Fennoscandia and instability is appearing at spots in areas of the forebulge at the border of the ice sheet. When the ice has melted the assumption of strike-slip faulting result in remained stability over central Fennoscandia. The assumption of reverse faulting condition causes failure over large areas in central Fennoscandia with a maximum in the northernmost parts where the late Holocene faulting appears. So for example the Pärvie fault is located just at the edge of the highest faulting potential. The presentation of the fault stability maps in plan view and as depths profiles illustrate in an excellent way the stability conditions at the selected time spots. As a reader of the report one would have liked to the same presentation of the stability like in Figures 9-1, 9-2, 9-5 and 9-6 for the present time, i.e. 0 BP. However, the results presented clearly show the importance of selected far field stress conditions for the final results about stability and it emphasis the need of obtaining better understanding of the regional extension of the different far field stresses in Fennoscandia.

In Section 9.3 of the report the authors present the temporal evolution of fault stability at 9.5 km depth for the two sites Oskarshamn and Forsmark, again for the assumption of strike-slip and reverse faulting conditions, respectively. The CFS for instability versus time clearly shows that independent of pore pressure assumptions the fault instability at the two sites will appear for reverse stress conditions at the end of the glaciations (Figure 9-7). For strike-slip faulting condition the instability appears during the inter-stadials and at the initial phase of the glaciations. With a few exceptions, these general trends are valid independent of the assumption of pore pressure. The results presented in the report are conclusive and on the whole of high interest and value for the understanding of the effects of the glaciation on fault stability.

In Section 9.4 of the report the authors are presenting the optimal orientation of faults for causing failure and earthquakes at the depth of 9.5 km for the two sites Oskarshamn and Forsmark with the assumption of 50 % pore pressure and R = 0.5. As expected the optimal fault direction for generating slip is governed by the orientation of the synthetic far field stress.
The presented results also show that at the time of maximum instability at the Forsmark site (11 kyr BP) and with the assumption of reverse faulting condition, the instability of faults at 500 m depth is governed by a set of NE striking faults with moderate dip to the SE and NW (see Figure 9-14). With the assumption of strike-slip faulting condition at Forsmark at the time of maximum instability at 32 kyr BP, the risk of slip is highest for the steep dipping NW-SE faults.

The temporal evolution of the stability field of the Pärvie fault shows that faulting takes place when the ice is melted and only during reverse faulting synthetic stress field and for all tested pore pressure conditions and variation of the direction of the maximum horizontal stress field (± 45 degrees). This modelling result is in direct agreement with the field observations at Pärvie. The modelling results also gives strong support to the neotectonic field studies in the area of Oskarshamn where no indication of Late Holocene bedrock tectonics is found.

In conclusion, the results presented in this report show a major improvement in the modelling of stress evolution during the Weichselian glacial cycle. The introduction of 3-D modelling and the generation of the FE models are very much improved compared with the 2-D models. The idea to superimpose the present day stress field in the post-processing stage is another improvement. The authors have used the SKB = Näslund glaciation model. As pointed out by the authors, there is a need to use other glaciation models to get confidence in the results. The reviewer agrees with this statement. Apart from the synthetic regional stress field the authors have demonstrated that the modelling results are sensitive to the pore pressure. There is certainly need for more information about the hydrogeological conditions beneath and at the edge of an ice sheet. The authors have demonstrated the sensitivity of pore pressure to the resulting CFS but the analysis need to be repeated for other ice models.

The results presented in the report clearly illustrate the lithosphere properties and thickness and the viscosity of the mantle have minor influence on the stress-time history during a glaciation cycle. This is partly new and interesting results. The conclusion reached in the report is that glacially induced faulting is unlikely at Forsmark and Oskarshamn based on the assumption that strike-slip faulting condition exists in the Earth's crust and that the direction of the maximum horizontal stress is NW-SE and corresponds to the direction of the plate movement of the Eurasian plate and that the sub-glacial pore pressure head is 50 % of the weight of the ice column. Our present knowledge of the orientation of the maximum horizontal stress is not conclusive for Fennoscandia although the orientation of the stresses down to approx. 1000 m in Forsmark and Oskarshamn support the orientation NW-SE. We certainly need additional deep stress data from seismic focal plane analysis to confirm the far field stress model. In addition we need to have better understanding and data about the prevailing sub-glacial pore pressure from glaciated terrains.

10.5.5 Munier, R. and Hökmark, H. (2004). Respect distances. Rationale and means of computation. SKB Report R-04-17, 218 pp.

This report dates from 2004 and the content gives a summary of SKB's knowledge about respect distance at that time. The report consists of a summary of computation results of respect distance performed with the FLAC3D and WAVE computer codes. The summary is based on results presented in four different reports which are attached as appendices to the main report. The summary is followed by a presentation of the transition zone (process zone) around faults followed by a chapter about Empirical knowledge and a Discussion on conservatism. A Summary, discussion and recommendations is followed by a chapter about Worked example from Forsmark. In Appendix 4 the authors present a review of postglacial faulting. The review, which is very well formulated and covers all the major aspects of postglacial faulting, is written by R. Munier and C. Fenton. The latter author is one of the leading experts in this field of research. The organization of the report is poor and the large number of appendices, the several summaries of results from numerical modelling and the overall style makes it difficult to grasp the main ideas of SKB's approach in defining respect distance.

In Chapter 3 about Computation of respect distance the authors define some of the key relationships regarding earthquake magnitude and fault dimension. In modelling of respect distance between a major deformation zones and the target fault in the repository the main hazard stems from a postglacial earthquake which mimic the geometry of a postglacial fault. The fault is assumed to be oriented perpendicular to the orientation of maximum tectonic stress in the region. The rupture of the deformation zone originates from the centre of the zone towards its boundary with a velocity that is about 70 % of the shear wave velocity. The orientation of the target fault varies and no friction is assumed. The static analysis of a vertical earthquake fault generating a M6.1 strike-slip event and the response on a population of target fractures located at a distance of 2 km from the earthquake fault was studied in the earthquake scenario risk analysis in SR97 with the Poly3D computer code. The maximum displacement of about 2.2 mm occurs for a fracture with 40 m radius. For a friction free fracture with radius 100 m the maximum displacement was found to be ca 15 mm.

Following the series of static analyses, SKB continued to perform dynamic calculations using the FLAC3D for dynamic analyses and WAVE for velocity records for all source to target distances analysed. Displacements were small for all analysed cases with a maximum value of 6 mm on the horizontal target fault. The WAVE code was also used directly to calculate the displacement on the target fault which resulted in about 16 mm displacement (Figure 3-13). The static component in the analysis overshadows the dynamic component and the results from the WAVE analysis is in agreement with the static analysis using Poly3D. In a third step of the dynamic analysis, SKB has performed more realistic earthquake simulations with FLAC3D where the shear movements are looked first and thereafter subject the fault to a given stress field, typically 15 MPa. The target fracture properties were given zero tensile strength and shear stiffness equal to the normal stiffness (10 GPa/m). The shear stiffness might be too high for this type of analysis since shear stiffness of rock discontinuities usually is less than the normal stiffness. The analysis is limited to M6 earthquakes and simulation of larger magnitudes is at the moment limited by the capacity of the computers. One of the important conclusions of the WAVE/FLAC3D simulation is that the static part of the analysis gives the major input to the calculated displacement field. Therefore, a fracture mechanics approach to the stability and displacement calculations might be a way forward to gain additional knowledge about the displacement field around the target fracture.

Chapter 4 of the report presents SKB’s opinion about the transition zone on each side of the core of the deformation (fracture) zone. A schematic cartoon of the different components of the zone is presented in Figure 4-2. The composition of the zone is slightly different from the most recent model of the brittle deformation zone according to Caine et al (1996) and presented in the SDM for Forsmark stage 2.2 (SKB R-07-45). The authors conclude, and I fully agree, that respect distances should be defined such that the width of the transition zone constitutes a minimum respect distance from the core of the fault.

In this chapter, Chapter 4, the authors describe their extensive searches in databases with the aim to find studies that directly relates the size of the transition (process) zone to the size of the deformation zone. The authors found the work by Vermilye and Scholz (1998) as reported in text to Figure 1 of this review, but they never made use of the plot of length of deformation zone versus width of the zone in double logarithmic diagram. The diagram shows proportionality constant of the order of 10^{-2}. As stated in previous reviews of this document, SKB is recommended to make use of all fault zone data collected from the site investigations and generate a plot valid for Forsmark bedrocks.

In Chapter 5 of the report a summary of the content of the report by Bäckblom and Munier (2002) is presented. This report is reviewed in this document and the conclusions will not be repeated here. Munier and Hökmark in their report stress the view that the respect distance between the source fault and the target fracture may not have to be very large because the distance over which dynamic oscillations are known to propagate and cause damage to surface structure is not relevant to deep underground structures like a repository for spent nuclear fuel.

The main concern of SKB about earthquakes is glacio-isostatic faulting during or shortly after the next glaciation and in particular faulting along pre-existing large deformation zones that can generate too large displacements (slip >0.1 m) along target fractures intersecting a canister hole. SKB has assumed that fractures exceeding 100 m radius can be detected in the deposition holes and assumes that fractures with a radii exceeding 50 m can be detected using standard mapping techniques. This assumption is most likely correct. However, the assumption that the additional fractures around the target fracture will absorb some of the strains and cause less strain to the target fracture itself is not very likely. The almost fracture free rock mass in the target area of Forsmark prevents this redistribution of strains around a target fracture.

The fracturing around the tip of the slipping fracture is an important mechanism for the development of the target fracture. In the analysis by La Point et al. (2000) the slip and fracture propagation were uncoupled and slip without friction was assumed. In reality the slip along the fracture will cause changes of the stresses at the fracture tip and the propagation can proceed out from the tips in a direction and at a length governed by the stress field. Knowing the stress drop or displacement of the source fault, the induced stress at the target fracture with a given radius and stress field can be calculated and the probability, length and orientation of fracture propagation from the tip can be determined. Such a rock fracture mechanics analysis must consider the friction along the target fracture prior to and during propagation. The rock fracture mechanics code FRACOD is able to model such situation for a given stress field and different orientation of the source fault and target fracture. In the FRACOD analysis of this type of problem at small distances between the source and target the dynamic effects can be omitted.

In Table 7-1 of the report the authors are presenting respect distance based on numerical analyses and width of the transition zone for different size of the zones. The analysis and the illustration in Figure 7-1 of the report show that short target fractures are not allowed within the distance of the total width of the respect distance of the fault. As a consequence SKB has to define the respect distance for each individual fault in the target area. For some situations of source and target length the field observation is determining the respect distance, for others the results of the numerical analyses as presented in Table 7-1. In Chapter 8 of the report an example of respect distance computed for Forsmark is presented. The result presented is based on the site descriptive model version 1.1 for Forsmark that was presented at an early phase of the site investigations.

Appendix 3 of the report is a review of postglacial faulting with the title “Current understanding and direction of future studies”. The review is written by R. Munier, SKB and C. Fenton now senior lecturer at Imperial College, London. It is a well-written and comprehensive review and state-of-the-art about postglacial faulting with ample examples from different glaciated terrains and Fennoscandia in particular. Of special interest is the list of criteria for recognition of postglacial faults (Section A3-6) based on information collected by C. Fenton and co-authors during the 1990s. Reading these criteria and applying them to the situation in Fennoscandia as described in the literature gives confidence to the (right) interpretation about the genesis of the Late Holocene faults in Northern Fennoscandia presented by Lagerbäck, Lundqvist, Muir Wood and others. At the same time the established criteria presented in the Appendix A3 provide support to the sceptical and sometimes wrong interpretation of alleged postglacial rock and soil structures in Southern Sweden.

10.5.6 Hedin, A. (2008) Semi-analytical stereological analysis of waste package/fracture intersections in granitic rock nuclear waste repository. Mathematical Geosciences 40:619-637. DOI 10.1007/s11004-008-9175-3

This international journal paper by A. Hedin at SKB presents an interesting analytical and numerical application of DFN modelling to the problem of secondary shear slip along target fractures intersecting canister deposition holes in the repository. The presented model uses the combination of the fracture radius distribution and the distribution of fracture orientation from the results of the mapping during SKB’s site investigation at Forsmark. Cylindrical canisters are oriented vertically and a mean intersection zone width (L) is calculated. From the calculated total critical fracture area (a) known from the mapping and the width of the intersection zone the volume of rock within which canisters would intersect fractures of critical radius is calculated. The product $a \cdot L$ is the fraction of the total volume for which positioning of canister centre-points should be avoided. This product is also the mean number of fractures intersecting a canister in the repository and this number follows a Poisson distribution. Therefore, the probability of a canister being intersected by a discriminating fracture, ε, can be written in the form $\varepsilon = 1 - \exp(-a\,(L))$.

The author has applied the stereological analysis to the deposition of 4500 canisters in Forsmark which results in 1.91 % of the canisters - 86 in number - are intersected by discriminating fractures. For this analysis the authors is using 4 sets of steeply dipping fractures and one set of sub-horizontal fractures from the presented DFN model of the target area for the repository in Forsmark. The smallest fracture considered has a length of
r_0 = 0.318 m. The exponent in the power law size distribution for the five fracture sets varies between 2.81 and 3.02. Additional data about the fracture sets are presented in Tables 1 and 2 of the article. Additional input parameters for the calculation are maximum and minimum fracture radius r_{Max}.= 500 m and r_{Min}.= 100 m, respectively.

The sensitivity analysis performed with the given data in Tables 1 and 2 clearly show minor increase in probability of failure for r_{Max}.> 500 m (see Figure 7). If the critical shear distance at deposition hole is doubled to 0.2 m compared to the assumed allowed maximum displacement of 0.1 m the likelihood of a canister being intersected by a fracture is down to 0.005 (Figure 9). The same likelihood is obtained when using the ratio *b* of fracture radius versus displacement (Figure 8). The results of the sensitivity analysis confirm the correctness of the model and the simulations performed.

In Section 6.2 of the report by Munier and Hökmark (2004) about respect distance the authors claim that fractures exceeding 100 m radii can be detected in the deposition holes and that respect distance used by SKB in the calculations have been based on that assumption. Also, the authors claim that it is reasonable to assume “that fractures with radii exceeding 50 m can be detected using standard mapping techniques, with adequate accuracy” (cit. p. 43). What will be the result of using the suggested model by Hedin if SKB assumes r_{Min}.= 50 m instead of r_{Min}.= 100 m? Minimum fracture radii, r_{Min} enters equations (11) for the assumption of power-law distributed fracture radii so that the total critical fracture area per unit volume of rock, *a*, is increasing when reducing the minimum radius. Therefore, inserting a lower value of fracture radii into equation (24) will reduce the value of ε and the likelihood of fracture intersection will decrease. An assumption of log-normal distributed fracture radii and r_{Min}.= 50 m, equation (15), also will result in a higher value of a_{LN} and a higher probability of intersection compared with r_{Min}.= 100 m. Hence, if SKB can prove the ability to detect fractures underground with a length less than 100 m the modelling results indicate that the likelihood of fracture intersections in the deposition holes will increase. The amount of reduction needs to be calculated by SKB and the results compared with data presented for r_{Min}.= 100 m in the article. Also, the importance for SKB to gain confidence in the description of fracture statistics in the interval from tens up to a few hundred metres is fully supported.

In the Discussion and conclusion, Section 8 of the article, the author mention that results of the sensitivity analysis prove that the model is more sensitive to uncertainties in parameters related to fracture radii distribution than those related to orientation distribution. This can be an effect of the fact that four of the fracture sets applied in the simulation for Forsmark have sub-vertical plunge and one set is sub-horizontal. An application of the model to a site with more gently dipping fractures might show that orientation distribution is also sensitive to the results. Orientation of the deposition tunnel axes with respect to the trend and plunge of fracture sets will enhance the importance of orientation relative fracture radii and increase the probability of fracture intersections in the deposition holes.

10.5.7 References

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10.6 Sven Tirén, Geosigma AB

10.6.1 Introduction

The organization of this document is as follows. A brief introduction of each report is given together with the references in the report. This is followed by a somewhat more extensive summary of each report and finally the notes (some parts of the text are rough and some are more structured) taken during the reading of the report. Before the more detailed notes are presented some information about personal experience is given.

10.6.2 Reviewed reports

In this type of study it is natural to start with the detailed field data for which there is well-established knowledge of geological setting, extent and geometry of the studied structures (Lagerbäck and Sundh 2008).

The second step is to go underground and study effects of earthquakes on underground constructions. Such facilities are preferentially located relatively close to the surface in urban areas or at deeper levels in mining areas. However, most existing tunnels or shafts are relatively young and earthquakes are unevenly distributed and such studies may be possible only in areas with seismic activity (Bäckblom and Munier 2004).

The third report considers modelling of instability in the Fennoscandian Shield based on assumptions of the character of the crust, regional stresses and stresses associated with a glaciation cycle (Lund et al. 2009).

Displacements in the bedrock occur along faults, which frequently occur in the crust, and it is most likely that a future distortion will take place along an existing zone of weakness. Thus, the next step is to ensure that structures that might be harmful for an underground construction, such as a repository for nuclear waste, are avoided and especially those of such length that a displacement of 10 cm can occur (Bäckblom and Munier 2004).

Using statistical methods one can calculate the distribution of potentially harmful fractures (called discriminating fractures) and one can try to calculate the risk of a discriminating fracture intersecting a deposition hole in a repository. In order to do this calculation several statistical parameters describing the population of fractures in the rock are needed. Such information can be obtained, to some level of detail, during the construction of a repository. Obviously unsuitable positions of deposition holes can be avoided when deposition tunnels are excavated, but some discriminating fractures may be missed. The number of missed fractures is of interest in the safety evaluation (Hedin 2008).

Full references to the reports are:

- Lagerbäck R, Sundh M, 2008. Early Holocene faulting and paleoseismicity in northern Sweden. Research Paper C 836. SGU - Sveriges Geologiska Undersökning.
- Bäckblom, G. and R. Munier (2002). Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. SKB TR-02-24, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.
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- Hedin, A. (2008). Semi-Analytic Stereological Analysis of Waste Package/Fracture Intersections in a Granitic Rock Nuclear Waste Repository. In: Mathematical Geosciences, DOI 10: pp 008-9175.

10.6.3 Lagerbäck and Sundh (2008)

The report by *Lagerbäck and Sund* is unique and well written. It summarizes the knowledge obtained during an extensive period of field studies mostly in the northern part of Sweden, where the most outstanding late- to postglacial fault escarpments exist. The report also provides a short summary of other areas and especially the search for indications of late displacements in the regional surroundings of the SKB sites at Forsmark and Laxemar. Observations of late displacements made by others are revisited and evaluated.

At sites where late- to postglacial faults are indicated trenches have been dug, some exposing the bedrock and some very extensive. All trenches are systematically and carefully documented and in many cases new information about the glaciation history were obtained. However, the documentation of the initial phase, the search for potential sites, is not so well documented and there is no list of criteria for finding sites for potential late faults, except for the occurrence of landslides. In densely forested areas, landslides are not easy to identify except in area where the forest have been cut down. On the other hand, on a site scale the indication are listed and the description of distorted sediments is very good. However, all structures described involve deformation of soft sediments. However, the largest postglacial fault, the Pärvie fault, is located above the highest marine level and it does not fit the criteria for other faults. Criteria for fault-related distortion of sediment in, e.g., permafrost areas are missing.

C. Talbot (1986; SKB TR-86-20) has made a structural analysis of the pattern of post-glacial faults in northern Sweden. All faults are reactivated. Seismic data from the SNSN network (2002-…) indicate that the root-zone of the late- to postglacial faults dip eastwards. Lagerbäck and Sundh report that the location of late faulting in Sweden is in the northern part. The reason for this is not given.

A very important contribution by Lagerbäck and Sundh is the geological maps showing the location of the late- to postglacial faults in relation to pre-existing system of faults and discontinuities in the bedrock. The maps indicate that the late- to postglacial faults are reactivations and especially partial reactivations of existing structures. The latter implies that the late- to postglacial faults could be linked from one structure to another at fault junctions. This may cause a post-glacial fault to shift its orientation. This have been observed in faults outlining the Åland deep east of Forsmark, where the active/reactivated fault is linked along a system of existing faults and thereby has become a curved structure shifting its orientation from N-S to E-W (cf. Tirén and Beckholmen, SSM report 2009:21). A minor comment is that the assessment of some features (balancing blocks and table-like blocks sheets along fault, in Lagerbäck and Sund) being related to lack of seismic events or indication of seismic events can be questioned.

10.6.4 Bäckblom and Munier (2002)

The outcome of the *Bäckblom and Munier* study (2002) is that the damage caused by faulting is indicated to decrease with increasing depth. Direct observations of wall rock displacement were in many areas not possible as the tunnels have linings. In general, circumstances that cause the observed/reported distortion and the type of geological terrains (most of them) are not prevailing in the Fennoscandian shield. However, the descriptions given by Bäckblom and Munier are interesting and give a perspective on the issue. With references to modelling presented in SKB reports it is stated that no fractures were displaced "*more than 0.1 m if they were located more than 3 km from a magnitude 7 earthquake (Fault length > 45 km). …In fact, no displacement exceeding 0.1 m could be demonstrated, in the simulations, on target fractures with radii less than 100 m*." The report is to some degree a precursor to the report on "*respect distance*" by Munier and Hökmark in 2004. A new search (cf.

googling) for references should be done because several new publications have become available after 2004. The coast of Norway show enhanced seismic activity compared to Sweden and along the coast there are lots of tunnels built in granitic and gneissic rock. Experience from tunnelling projects in Norway is probably published and available.

A general note, not related to the reviewed reports, is that earthquakes in Sweden are systematically recorded by SNSN (http://snsn.geofys.uu.se/) and the data is stored by SKB in their database SICADA. Seismic parameters stored in SICADA are location, time, magnitude and depth. There is so far no systematic calculation of fault-plane solutions based of SNSN data available, i.e. orientation of the plane along which the seismic slip has occurred. This information is essential when relating seismic events to basement structures or when using the seismic data to refine our knowledge about the regional stress field. Furthermore, the record of present seismic events reflects the existence of structures along which displacement can occur, i.e. the structures are not locked or sealed. The present seismicity may be used to locate late- to postglacial faults, but may not be used to predict future large scale earthquakes.

10.6.5 Lund et al. (2009)

The *Lund et al.* (2009) report is well structures and gives an important contribution to the understanding of late faults. It gives information about the locations of late- to postglacial faults in northern Sweden and that late- to postglacial faults are not to be expected in all glaciated areas. This they show by various types of modelling of the crusts, regional stresses and stresses related to the glaciation. They also discuss faults, within SKB sites, that might have been unstable during deglaciation. Although a variety of crustal models were adopted in the modelling, none of them did have a soft structure resembling the fracture system characterizing the east coast of northern Sweden (Norrlandskusten). It is astonishing that the area where postglacial faulting occur is located NNE of the centre with highest uplift and greatest relief. Results obtained by Fjeldskaar et al. (Fjelskaar, Lindholm, Dehls & Fjeldskaar, 2000: Postglacial uplift, neotectonics and seismicity in Fennoscandia. Quaternary Science Reviews, 19, 1413-1422) may be compared with Lund et al. regarding indicated areas with significant positive deviations (1.0 mm/yr) between the observations and the calculated glacial isostatic uplift.

10.6.6 Munier and Hökmark (2004)

A respect distance to a structure with a certain extent was applied in KBS-3, but at that time it was to avoid fracture that could form short pathways for circulation groundwater from the repository to an extensive structure. The new concept of respect distance, presented by *Munier and Hökmark* in 2004, is related to shearing that may occur along a fracture located outside a deformation zone and induced by a distant earthquake. In other words, the respect distance is a ‘protection area’ outside which shearing (induced by a seismic event along another structure) is unlikely to occur along a fracture of a certain size. Estimation of the magnitude of the respect distance along a deformation zone requires knowledge about the length of the deformation, its character (core+influence zone) and how the zones are connected to other structures (cf. linked late- to postglacial faults above). The report is reviewed by INSITE (SKI-INSITE TRD-05-09) and the review is not repeated here. However, there is no discussion about the possibility that a seismic event could affect the aperture of fractures and thereby open up pathways for circulating groundwater that may erode the buffer material. In the R-04-17 report, there is a section (a separate report) treating neotectonics and a section about criteria for identification of neotectonic structures. It is somewhat surprising that these criteria are not presented in any of the SKB reports treating investigations for late fault movements in the surroundings of Forsmark and Simpevarp. An overview of the concept respect distance, the usage in SKB and Posiva, is given by Lampinen 2007 (Posiva WR 2007-69). The respect distance concept is also used to outline envelope surfaces to embrace not fully planar deformation zones, i.e. to locate them inside tabular domains that will be considered in the layout of a repository (cf. R-08-83 Fig. 2-5).

10.6.7 Hedin (2008)

There is a missing link in the chain of reviewed reports and that is the report defining discriminating fractures by Munier 2006 (SKB R-06-54), i.e. fractures not allowed to intersect a deposition hole in a repository. These fractures, in relation to canisters in a repository, are modelled by *Hedin* (2008. The modelling of fractures needs a fairly good knowledge about the fracture characteristics (distribution of orientation, length and spatial distribution). In the confidence assessment report for Forsmark (R-08-82), SKB admits that surface outcrop statistics regarding fractures are not relevant for properties at depth. Appropriate data will be obtained from tunnel mapping, i.e. when the tunnel has truncated the upper fractured domain in Forsmark. Generally, the type of work presented by Hedin is essential and needed in the safety evaluation.

10.6.8 Personal contribution

My own experience can be briefly described to be within the fields of structural geology (incl. deterministic 3D modelling on various scales), characterization of deformation zones (internal geometry and character, relation to other structures, and reactivations), characterization of fractures and fracture pattern, and relating earthquakes with the faults and block faulting.

10.6.9 Notes taken when reading the reports

Review SGU RP C 836

Robert Lagerbäck and Martin Sundh, 2008: Early Holocene faulting and paleoseismicity in northern Sweden.

The report is focused on structures in the northern part of Sweden with a short review of recent findings in parts of eastern Sweden. One conclusion from the report is that there is a causal correlation between the deglaciation of the northern parts of the Nordic countries and large scale earthquakes (up to M_w>8). The displacement along a fault is indicated to be formed during one single episode. The faulting is mainly characterized by extensive faults trending NNE-SSW (most common orientation of all late- to postglacial faults), while minor, shorter, faults trending NNW-SSE are subordinate. All of the extensive faults are reverse faults, east side up, and inclined moderately to steeply eastwards. East of the most extensive fault, the Pärvie fault, there are minor faults with the west side up. The vertical throw along the extensive faults generally exceed 10m with a maximum about 25m. The smallest offset along a mapped fault is about two metres. All investigated late- and postglacial faulting have occurred along existing faults by reactivation. It is stated that structures occurring close together may be connected at depth (cf. Talbot 1986, SKB TR 86-20: A preliminary structural analysis of the pattern of post-glacial faults in northern Sweden/not included in the reference list).

The authors express that it is possible that late- to postglacial faults may have occurred south of Västerbotten (Umeå), but they have not found any indications as evident as those found in the northern part of the Nordic countries.

The report is structured and logical. The applied methodology is described and criteria for identification of late- or postglacial faults are generally well documented (a better description of the remote studies of aerial photos and maps could have been given). Interpretation of aerial photos used to identify possible sites with late faults and landslides was followed up by field studies, including excavation of trenches. Structural features in sand and gravel pits were documented. References from countries outside the Nordic countries are few. In some cases the given reference gives a more open view than presented in the Lagerbäck-Sundh report (e.g. Brune et al. 1996, see below).

The report is important and serves as a very good catalogue of features related to late- and postglacial faulting. The strength of the report is that it describes features on all scales from the character of the bedrock, the actual fault, structures in the soil cover to the trace of the fault line.

However, the report shows several relationships between bedrock structures, distribution of earthquakes and late- and postglacial fault that are not (or only slightly) described in text; relationships of importance for the understanding of fault reactivation/fault propagation. Missing is also information about the distribution of the present rock stress regimes and relation to the ongoing post-glacial uplift.

The bedrock maps (Figs. 13 14, 15, 16, 17) and the map of quaternary deposits (Fig. 42) give relations between late- and postglacial faults to old deformation zones in the bedrock. In the bedrock map mainly extensive structures are displayed or structures that offset thinner rock units. It is often pointed out in the report that the late- and postglacial faulting represent reactivation along older structures. However, this is not always obvious from a visual inspection of the bedrock maps in the report. Still, the late and post-glacial faults may occur along old structures, but reactivated structures may not be prominent enough to appear on the geological maps.

Some examples:
1. *The Pärvie fault (Figs. 13 and 14)*. It is only indicated on the bedrock map that this fault lines up with an existing fault in its southernmost parts (Figs. 13 and 14). Furthermore, the Pärvie fault shifts, in some cases, its position sideways when crossed by other faults (sections of strike slip may be missing along the Pärvie fault). A low angle relationship between the late Pärvie fault and old faults exist, like a splay. The somewhat irregular form of the trace of the Pärvie fault is due to the inclination of the fault (moderate to gentle near the surface) and the topography.

2. *The Lainio-Suijavaare fault (Fig 15)*. The trace of the late fault indicates partial reactivation of an existing fault as it shifts its NNE-SSW orientation as it intersects and line up with an existing NNW-SSE trending deformation zone. The late fault stops at the intersection with a NW-SE trending fault. However, the late fault is a reverse fault (thrust) and the displacement causing the reverse faulting may have a strike slip component along the NW-SE trending fault. What is the length of a fault?

3. *The Lansjärv fault (Fig. 16)*. The fault appears to have a complex geometry. A three-dimensional model would help to understand the relationships (cf. Talbot 1986, Fig. 13 and 14).

4. *Röjnoret and Burträsk faults (Fig. 17).* Large parts of the faults are located along old structures and some parts are not. Are these parts connected (at depth or at surface)?

5. *Quaternary map 23H Stensele* (Fig. 42). The indicated NW-SE trending late- or postglacial faults most probably line up with the structural grain in the bedrock. The bedrock structures are sub-parallel with the terrain forms (drumlins). Displacements along these faults would be predominantly strike slip.

Figure 10. Precariously balanced rock. Under certain conditions such rocks can occur (also be frequent) in seismic areas (M7), e.g. in California (Brun et al. 2006). Compare also to monumental buildings, e.g. Greek and Roman pillars.

Figure 26. "*A sharp and fragile plinth that protruded from the steep slope of the Merasjärvi fault..*" Such uplifted sheets of rock are found in, e.g. Lillsjödal, Småland, and it is clear that these are formed by frost heave.

Figure 90. The crack in the ice, Lansjärv. Note that there is another crack further to the right in the picture. Interesting picture, but it arises some questions: 1. Do these cracks occur even during periods without pumping? 2. Does the lake have an outlet? 3. What is the bottom topography? 4 Before the pumping started there was apparently no connection between the aquifer in the rock below the lake and the lake. What type of water was found in the borehole after the formation of the crack? Or, what

was the source of the water that went into the fault zone? 5. Is it possible that the drilling affected the sediments in the lake allowing warmer water to rise along the fault? and 6. If shear occurred in the bedrock, why should the crack in the ice mimic the trace of the fault (deep frozen?)?

Fig. 58. 'Sorting in moraine by vibrations'. Is this found anywhere else? Any alternative interpretation?

An analysis of the locations of late- and postglacial faults in relation to existing faults (shown on bedrock maps) should be performed in more detail. This is of importance when considering linkage of faults, i.e. how long is a fault? Notable is that no indication of earlier displacements (during previous glaciations) along the late- and postglacial faults have been found. This is a bit strange as it is often stated that reactivated faults have a higher ability to reactivate again. One question that arises is: What do offsets of the landforms, especially the sub-Cambrian plane, represent?

Concluding remarks: The report describes structures along which late- and postglacial movements have occurred and points out that the possibilities of finding new faults in Norrbotten and Västerbotten are relatively small. The report gives no information why late- and postglacial fault appear in this area. The report does not provide tools for finding late faults, i.e. all landform breaks should be investigated (?). However, the report gives a very good description of sediment distortion (water saturated) in close connection to late faults.

The statement that the late- and postglacial faults are single events and that minor earthquakes along these faults are frequent, i.e. creep occur today, could have been elaborated a bit further. Furthermore, it is surprising that no late- and postglacial faults have been found in areas with the highest density of earthquakes and largest postglacial uplift (along Höga Kusten).

Bäckblom G. and Munier, R., 2002: Effects on earthquakes on the deep repository for spent fuel in Sweden. SKB TR-02-24.

The SKB project *Effects of Earthquakes on Underground Facilities (Reported in SKB TR-02-24)* aims to:
1. recompile field evidence of seismic damage on underground facilities (displacement >0.1 m given the highest priority),
2. shed additional light on the matter of friction loss in bedrock due to water-level changes and
3. find suitable ways to inform concerned Swedish citizens.

Input to the study:
1. about 150 published papers (how many site reports, not published, have been available? These may give more detailed information)
2. 60 circulars sent out (not presented how many answered – did those who answered have experience of severe deformation of distortion of bedrock at repository level?)

Why visiting Japan and Taiwan? Quite different geological environments and tectonic realms compared to the Swedish sites. No circular sent to South Africa? No European (except for Swedish) scientists are acknowledged.

The information about distortion in backfilled tunnels due to vibrations in relation to type of backfilling/buffer (swelling material, compaction of loose material?), water saturation and water composition is very briefly treated (two references) and results (low possibility for liquefaction) are mainly based on numerical simulations.

Nine compilations of data regarding earthquakes and damage (cf. Table below) have been chosen for the study. One of the authors of these reports has personally contributed (personal communication) to the study. The reports listed are published during the period 1959 to 1998. It appears likely that more updated reports exist today.

Table: Outcome of internet search www.google.com

Key words	Outcome 2001 July 12th 2001	Outcome June11th 2002	Outcome 2010 April 25th 2010 (search in seconds)	Difference 2001-2010
Earthquake	1 320 000	1 680 000	56 500 000 (0.11s)	> 54 000 000
Earthquake + damage	224 000	282 000	12 600 000 (0.14s)	> 12 000 000
Earthquake + damage + underground	26 400	30 600	3 680 000 (0.11s)	> 3 500 000
Earthquake + damage + tunnel	10 900	12 900	1 117 000 (0.26s)	> 1 000 000

A new search on, e.g., **www.google.com** will contribute to further information about the subject. However, the search strings have to be more precise. Information about the effect of vibrations on buffer and backfill can also be obtained.

Some comments follow below:
Table 1-1. SNSN is not included (was not in operation 2001) and neither the Norwegian nor Finnish data bases.

"The 71 cases involved earthquakes with Richter magnitude 5.8–8.3 and focal depths in the range 13–40 km, concluded that there were not even one report on falling stones in unlined tunnels, or cracking in lined tunnels, up to 0.19 g and only a few incidents of concrete cracking in lined tunnels for up to 0.25 g (p. 32)." It is not only a description of the bedrock that is missing, missing is also information about geometrical relation of zones (e.g. angles of intersections) and character of the prevailing stress regime. The report states that "*there are only five cases reported for moderate or heavy damage at levels below 300m"* (p. 35).

Why not use the same classes in Fig 2-2 and Table 2-3 (about peak ground acceleration in relation to seismic events/distance to faults)? In Table 2-3 it is indicated that most of the formed fractures within a depth interval of 300 to 1000 m show deformation associated with tunnel construction. This does not seem to be the case for deeper levels (few data, however). In Table 2-4 the damage is related to rock type. The sample size is small and there is no data on depth and stress regime. There is no information on how to identify a structure along which there has been no damage within fractured rock, except when the tunnel is lined. Despite this, it is indicated that distortion in soft surface sediments is more common than bedrock damage. Interesting is the indication that igneous rocks are more frequently damaged (heavy to moderate) than metamorphic rocks or other rock (labelled "*Rock(?)*" and "*Unknown*" in the table).

Fig. 2-3 (relation between peak ground acceleration and distance to faults) is of general interest. However, the amount of background data used to construct the diagram is not obvious. Table 2-5 gives an example of heavy damage at a distance of 1km from a M3.7 earthquake and moderate damage at distances of 25 km from M5 earthquake.

A general comment is that it sometimes is hard to know where the presented data come from (location and geological setting) and distance to epicentres, e.g. the enormous Alaskan earthquake (i.e. Anchorage in 1964, M= 9.2, cf. p. 37).

It is stated that earthquakes have *less influence in the sub-surface than at the surface*. However, there is very little information presented about deformation of old landforms. Distortion of alluvial fans or colluvium, often semi-stabile, may not be used as a reference for Swedish sites.

"*Large part of damage locations coincided with locations of existing faults and fracture zones that had been identified during construction"* is a statement and not shown in the report.

"Mountain tunnels in sound rock and lined without material and structural defects are less affected by an earthquake even if it is very large." Would this indicate that in tunnels located in flat areas with very smooth topography the distortion would be less (is a mountain tunnel equal to a tunnel going through a mountain?)? However, *"Mountain tunnels may suffer some damage if the tunnel is located near the epicentre of the earthquake fault, i.e. within 10 km for a magnitude 7 earthquake and 30 km for a magnitude 8 earthquake".*

Concluding remarks: In section 4 several questions about the effect of earthquakes (natural earthquakes and earthquakes caused by the construction and drift of a deep geological repository) may have on the safety of the repository. It is generally concluded that the "*effects on the rock is basically governed by the magnitude and distance from the seismic event*", respect distances has to be site and fault specific (detailed knowledge is needed; numerical modelling may overemphasise the distortion of rock adjacent to brittle structures) and the possibility of future multi-reactivation of structures should be considered.

The information to the public is treated in only very general terms and cover about a fifth of a page.

Munier, R. and Hökmark, H, 2004: Respect distances, Rationale and mean of computation. SKB Report SKB R-04-07

The definition of respect distance (p. 8) is *"the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to anticipated, future seismic effects on canister integrity*". This implies that the respect distance is related to the definition of deformation zones, especially brittle deformation zones. Furthermore, the uncertainty in the location of a brittle deformation (the core and the width of its transition zones) will affect the uncertainty of the position of the respect volume (p. 7), i.e. the closest distance between an "*earthquake fault*" and the repository. What type of fault is then to be considered as an earthquake fault? "*The respect distance can have a fixed value, for a given size of a fault, but only if coupled to the maximum acceptable size of fracture intersecting a canister position*" (p.9). This implies that the respect distance is given by two parameters related to the brittle deformation zones (width and length) and that the width of respect distance may be decreased if the detection limit for fractures (target/discrimination fractures) can be decreased. Of these parameters the size of deformation zones, and also the size of discrimination fractures, can be most intricate to determine.

The size of the respect distance will affect the available rock volume for a repository. "*If it will be feasible to reject canister positions intersected by 50 m radius fractures, the respect distance can be reduced from 200m* (for fractures of 100 m radius) *to be approximately 100 m*" (p. 47) for brittle deformation zones greater than 3 km (Table 7-1) and for M6 events and larger. Decreasing the radius of discrimination fractures to 25 m radius "*would not automatically result in a reduced respect distance"*(p. 49). On the other hand, the number of target/discrimination fractures will increase with decreasing size of the target/discriminating fractures (negative power-law size distribution) and this may affect the utilization of the available repository volume; cf. optimisation (size of discrimination fractures versus respect distance).

The size of the deformation zone (> 3 km, Table 7.1) that should have a respect distance is due to the indication that displacements along shorter structures do not exceed 0.1 m and, e.g., M5 correspond to a c. 3.5 km long zone (p. 51; cf. Wells and Coppersmith , 1994, Bull. Seism. Soc of America, 84, 974-1002; 3km zone may hold M6).

"the numerically calculated induced displacements along reference target fractures probably are representative also of larger events, such that the computed respect distance does not need to be larger for M7 and M8 events than for M6 events" (p. 47). This has to be proven. If so, it may role out the scenario for tectonic earthquakes.

The size of the respect distance related to earthquake risks is of the same order as the respect distance applied in the KBS-3 report (based on transport resistance).

Fractures of such size that they are not allowed to intersect a canister position are called discriminating fractures (cf. target fractures).

In the introduction (p. 5) of the report it is stated that it considers seismic displacements along exiting faults. The existence of aseismic creep is treated very briefly in Appendix A 3.6 (p. 195-6) without discussing the effect of such creep on a repository.

Earthquakes and associated displacements were treated in the KBS-3 report (part II Geology, section 8.7) but the effect of such events was considered for the entire repository volume rather than related to distortion along a fracture adjacent to and in connection with a displaced extensive fracture zone (are there any differences?).

Section 2 Definition

In page 8 the following question is formulated: *"a fault that is large enough to create an earthquake of a given magnitude M, what is the maximum size of a repository host rock fracture that can be allowed to intersect deposition holes?"* Even if the size of such a fracture is determined, how may the fracture be identified at a depth of 500 m with a relative disperse arrangement of boreholes (before deposition tunnels are excavated)? The deterministic part of the SDM contains only zones that are larger than 1 km. An alternative is to characterize fractures that have been reactivated, especially fractures that are open today. Such fractures could presumably be identified within the vicinity of the repository, especially in the deposition drifts and deposition holes.

"Based on these investigations SKB used a failure criterion of 0.1 m shear deformation across the canister in the safety report SR-97 and subsequent modelling efforts."(p. 10)
It is presented that a displacement of 20 cm of the wall of the deposition holes along a fracture, perpendicular to the deposition hole, does/may not reach the breaking threshold of the canister (not a function of the deformation rate?). What magnitude of a single seismic event does such displacement correspond to at a depth of 500 m? How many minor earthquakes are needed to accumulate this displacement? Is aseismic creep along a single minor fracture zone or fracture able to distort a canister probable within a time interval of c. 10^6 years? On the other hand, if a minor zone or fracture is reactivated, opened up or kept open due to finite incremental slips, without reaching the failure criterion of the canister, the question arises: Is not the KBS-3 definition of respect distance more appropriate than the new definition from a SA point of view? What is the general knowledge about displacements at depositional depth related to earthquake magnitude?

“*We anticipate that the main hazard stems from post glacial earthquakes. We therefore find it necessary to mimic the geometry of known post glacial faults (see Appendix 3 for an exposé). The predominant strike of mapped postglacial faults is perpendicular to the orientation of the major (tectonically accumulated) horizontal stress. This is consistent with dip-slip motions on steeply dipping faults. In our models we therefore orient the earthquake–generating faults accordingly” (p. 11).* The described faults are reactivated. In the report by Talbot (SKB TR 86-20), one of the neotectonic faults in northern Sweden, the Pärvie fault, is described as a palm-tree structure, i.e. a symmetrical structure that in its upper parts has horizontal to sub-horizontal zones (dipping towards the centre of the structure) and with increasing depth the structures become steeper and converge, forming a single root-zone. However, the Pärvie fault shifts in character southwards and becomes a sub-vertical zone. Actually, this may indicate that increasingly deeper parts of the zone are exposed along its trace. This implies that the Pärvie zone is reactivated in all its parts and that neotectonic movement may occur also along sub-horizontal fracture zones. Furthermore, strike-slip movements are not easily identified by analysis of landforms and the existence of such neotectonic displacements can not be ruled out.

One should distinguish between model configuration of fractures and the natural geometries of fractures in the rock. The sub-fracture (target fracture) will with an increased probability be reactivated if it represents an off-shooting fracture related to the formation of the main structure along which faulting occurs (the rupture zone). The target structure could be genetically related to the main structure (cf. Kim et al. 2004: Fault damage zone. Journal of Structural Geology, 26, 503–517) in the sense that it constitutes a part of the damage zone (alternatively, the target structure could be a structure that is overprinted or overprints the rupture zone). This implies that the schematic presentation of the different components of fracture zones expressed in Figure 4-2 (core and transition zone) should be extended to also give a genetic interpretation of the zone geometry in accordance with Kim et al (in order to guide the layout of the repository).

Section 4. Out-of-plane growth; the transition zone.

Page 36. The identification of the disturbed zone (SKB terminology: transitional zone) needs good exposures plus a generic interpretation of the fault/fracture zone. Kim et al. 2002 separate between three types of damage zones: wall damage zone, tip damage zone and linking damage zone. The last two are not discussed by SKB (though important in SKB lineament studies: lineament coordination and linkage). There is no interpretation or visualisation of genetically related fracture patterns in the SKB site descriptions (Laxemar and Forsmark), i.e. there are no site-related reference structures presented yet.

Section 7 Discussion and conservatism

Page 43. “*We have assumed that fractures exceeding 100 m radius can be detected in the deposition holes and the respect distances calculated so far have been based on that assumption.”* This assumption is not proven to be correct. In the Grillby study (not published SKI study), it is found that it is difficult to correlate fractures across a 25 m wide road even when the road cut is about 10 m high. It is even harder to correlate structures across an unexposed section, 50 to 150 m wide, located between two separate sub-parallel road cuts. It is not obvious how SKB will be able to identify 50 to 100 m large fractures at a depth of 500 m. So far the SDM only contain structures larger than 1 km, see comments for page 8.

Page 44. 6.4 Single versus multiple events. If slip occurs along a certain fracture then the probability for reactivation of that fracture, further slip, is much higher than for other fractures. Certain fractures may accommodate most of the deformation in the bedrock (see comments above for pages 8 and 43).

In the KBS-3 study gneissic rocks were favoured because individual fractures were smaller and that the well yield was found to be lower than in granitic rocks (the fractures are less connected in gneissic rocks?).

Section 7 Summary, discussion and reconstruction

Page 47-48. The arguments in the summary clearly aim for recommendations for planning the layout of a repository. However, it is stated on page 48 "*Since the transition zone is here considered an integrated part of the deformation zone, deposition of canisters within the transition zone is prohibited by SKB design policy."* A plan is needed how to distinguish between structures that are overprinted by a zone, overprint the zone and structures related to the zone (located within the disturbed/transitional zone). As it is today the subject is hypothetical.

Section 8 Worked example

Page 51- 53. Worked example. Gently inclined structures do not appear to be included in the model.

Appendix 3 Review of postglacial faulting

Page 157. Current understanding and direction for future studies. This Appendix is apparently a summary of Munier's efforts in conjunction with the planning of the seminar on neotectonics (cancelled, too few participants). Regrettably, the review is "*hidden*" as an Appendix in a report considering respect distance.

Page 188-189. Criteria for recognition of postglacial faults. Twelve (7 + 5) criteria for recognition of postglacial faults are listed. These criteria are not presented in the method descriptions for the study of postglacial faults (SKB MD 133 001) or in corresponding activity plans.

Page 202-218, A 3-9 References. It is an impressive list of references. However, I miss some references on deformation of the bedrock surface, especially fracturing of small hills (stress concentration; sheet fractures and rock burst by e.g. Twidale et al. 1996 and 2000) and fault structures in permafrost areas Bihong Fu et al. 2004: "Surface deformations associated with the 2001 Mw-7.8 Kunlun earthquake, northern Tibet: geomorphic growth features along a major strike–slip fault". International Journal of Remote Sensing
Vol. 27, No. 20, 20 October 2006, 4461–4470).

Lund, B., Schmidt, P., Hieronymus, C., 2009: Stress evolution and fault stability during the Weichselian glacial cycle. SKB TR-09-05.
Focussed on large late faults, e.g. Pärvie. Does their study exclude late- and postglacial faulting in other parts of Sweden (reference to Lagebäck and Sund 2008 is missing)?

Modelling of fault stability is based on six conditions. However, the inhomogeneity represented by the framework of structures in the rock is apparently not considered or is it included in item 2?

A large set of rock models are tested: including alternative horizontal layering in the crust and also lateral variation. However, the large scale structures, the structure trail along Norrlandskusten, is apparently not inferred as an inhomogeneity (representing a zone of weakness – soft or stiff).

What is the memory in the crust of previous episodes of loading, e.g. previous ice ages?

"*Over Fennoscandia and in northern Europe, the difference between the maximum configurations of the Saalian and Weichselian ice sheets is considerably smaller*" and "*There is no reason to believe that a future ice sheet over Fennoscandia would be fundamentally different than previous Late Pleistocene Fennoscandian ice sheets*." This should also be considered when discussing the late- and postglacial faults in northern Sweden.

Page 28. The relation between the Lambert and Näslund ice sheet models is only briefly described. The time of loading and how load affects distortion of the crust could be clarified. Do the two models balance, i.e. cause the same effect (descending/uplifting) on the crust? The answer given is that significant differences could be expected and further modelling is needed. Such modelling would give information about the uncertainty of the effect of the ice sheet on crust deformation. Note that there is a coupling between the ice model and the rock model (p. 18). It is pointed out that the results of importance are related to the ice model and that the different Earth models show similar evolution. In the discussion it is mentioned that it is unfortunate that an alternative ice model have not been used. Calculations performed by others give for the Forsmark area an induced stress magnitude of about 40 MPa, which remained in place for more than 30 Ka before the onset of deglaciation, and shear stress magnitudes reach 20 MPa. The presented model based on the Näslund ice model indicates that induced horizontal stresses at 500m depth (p. 67) do not exceed 40 MPa in Forsmark and less than 30MPa in Simpevarp.

Page. 35. Uplift 11mm/year (other sources give about 8-9 mm/year and an accumulated uplift of 286m) and horizontal displacement velocities of about 1-2 mm/year. The fact that the centre of maximum ongoing uplift moves NNE-wards is not mentioned. It is pointed out (p. 39) that the maximum uplift rate does not coincide with the location of step-formed increase in crustal thickness. Why should it? It is located just to the west, i.e. the thinner crust may have reacted in a more pronounced manner (thin crust: less to depress – the ice form a higher relative load ??).

Page 45. The areas of tensional Shmin are more pronounced than those of SHmax, outlining the forebulge region.

Page 47. I note that at 10 Ka ago the largest Shmin/largest shear stress was located in northern Sweden and Finland, north of the Bothnian Bay.

Page 49. In northern Fennoscandia all models predicted SHmax directions approximately perpendicular to the strike of the large "*end-glacial faults*", in agreement with the direction of fault slip.

The expression "*tensional minimum horizontal stress*" is not a commonly used in the literature (google=0 hits).

Section 5.
Could the regional stress field (assuming that there have not been any glaciations) cause displacement along existing faults (aseismic creep or seismic events)?

Section 7.
The areas of increased shear are in agreement with observation of late faulting (late- to postglacial). About 10 Ka ago the largest Shmin was north of the Bothnian Bay (Bottenviken). "*The high shear stress regions coincide with the areas of maximum flexure*." (p.49) – If the maximum flexure refers to landform, this is not correct because the area of maximum uplift is located further to the south (downwarped 800 to 900m), along Höga Kusten (cf. Figs.7-6 to 7-8)

Why do we not have any indication of shear along Höga Kusten. Should one look for other types of structures?

Page 67. A very good summary of the stress evolution at 500m depth in Forsmark and Oskarshamn. The character of the stress field changed during the evolution of the glaciation and deglaciation. Could there be a period of strike slip movements? Reverse faulting may be associated with strike slip faults (at least minor strike-slip faults). Tensional stress may be associated with the glaciation (during much of the glaciation at Simpevarp and at the onset of the glaciation in Forsmark) and may affect the groundwater transport in the rock.

Page 71. Orientation of the regional stress, main horizontal stress is 123° in Forsmark and 121°in Simpevarp. Angular relationship between regional faults in Forsmark is 65-33=32 degrees for Singö and Forsmark fault zones and 45-37=8 degrees for the Eckarfjärden fault zone.

Page 84. The water pressure in faults is very important. The higher water pressure is, the more unstable faults may be. "*In a strike-slip background stress field, very high induced pore pressures are difficult to stabilize".* Such destabilization is not in agreement with observations (p. 96). Where these observations are made is not presented. Furthermore, high pore pressure causes little additive effect on the instability of the reverse faults (Table 9-2).

Page 90-91. Reverse background stress field. The gently inclined faults at Forsmark were unstable at about 11 Ka ago, and in Simpevarp most fractures/faults are steeply dipping so the effect was less even though the "*region*" (spread in orientation) of unstable faults is larger. However, if gently dipping faults in the Forsmark are displaced they have to be accompanied by displacement along vertical WNW-ESE to NW-SE trending faults as most of the gently inclined faults terminate against such faults. In strike-slip stress state the orientation of unstable faults vary with time during the glacial cycle as it is related to the geometry of the ice sheet. Important is also the state and orientation of the background stress field. However, it is not clear whether the background could cause distortion, aseismic or seismic, in the bedrock; the processes behind large-scale earthquakes could have been treated. Is it accumulation of stress?

Concluding remarks: The outcome of the modelling show good agreement with the occurrence of post to late glacial faults in northern Norway-Sweden-Finland. However, the area of maximum uplift and the enhanced density of earthquakes along Norrlandskusten is not explained or discussed. However, it is stated "*The rebound pattern is determined by the properties of the ice sheet while the magnitude of the response depends on the earth model"* (P. 95). As mentioned above, the area is located just west of the contact with thicker crust and the thinner western side has been elevated more.

Review of Hedin, A., Semi-analytic stereological analysis of waste package/fracture intersections in granitic rock. Math. Geosci.

The paper presents an approach to calculate the utilization of a repository volume.

Forsmark

SKB admit in the summary of the SI in Forsmark that the uncertainty in the fracture statistics is embarrassingly high. The reason for this is that the upper part of the bedrock has different fracture characteristics than what is observed at deeper levels, i.e. at repository level. This implies that the use of this type of exercise to describe the characteristics of the Forsmark site have to wait until the construction of the access tunnel and possible the central hall at repository level.

About the use of fracture data

The model is based on simplified structural data, for example:
1. The shape of fractures is generalized to be described as discs, circular in shape. Related to the shape of fractures is the termination of fractures (blind and/or against another fracture). The latter is not considered in the applied fracture model.
2. The fracture population can be divided into sets. Each set has its own variation in orientation (described by a Fisher distribution) and length distribution (power law). It is unclear in the text how the data are used (cf. lower part on page 3 – "*The calculation model consists essentially of two factors. One is related to the fracture radius distribution and the other to the distribution of fracture orientations. The two are then combined to form the model"* and on page 4 "*assuming (i) that the radius and orientation distributions are independent").* Each set of fractures has its own length distribution – cf. the two parameters dip and strike of fractures are not independent; the same holds for orientation (sets) and fracture lengths.
3. Termination of fractures is not considered. The termination and intersection/crossing of fractures affect the linkage of displacement along fracture planes and also affect the definition/measure of the present day fracture length. Linkage together with partial reactivation of fractures affects the length/extension of fractures/zones.
4. Reactivation may not involve the full length of a fracture/zone. Partial reactivation is common and this is an example where the maximum displacement may not be at the centre of a fracture/zone.
5. Information about fractures within the length interval 10m to 3/400 m are generally missing or not well sampled during the SKB site investigation. These fractures include the discriminating fractures.

The general outcome of this study

The outcome of this study is to test an approach to statistically estimate the relative proportion of intersections between discriminating fractures and canister positions (discriminating fractures are actually not allowed to intersect deposition holes).
Input to PA must include an estimate of the relative proportion of discriminating fractures that are not identified and intersect deposition holes. To get this information a methods for identifying discrimination fractures have to be developed. Such development does not only entail development of instruments but also development of strategies. The latter also includes the order of excavating different parts of the repository volume and the order of performing different types of investigations. The definition of discriminating fractures, fractures not allowed to intersect deposition holes, must at the same time be firm and flexible, including 'all' varieties of possibly structures. At an early stage of the excavation of the underground facilities, the criterion for discriminating fractures must be tested and evaluated. This is an interactive process which should be carried out during the excavation of the access ramp and before excavation of transport tunnels at repository level.
Furthermore, SKB may refine the definition of the respect distance. In order to do this, data on the character of deformation zones and related disturbed zones (cf. SKB transition zone) are needed.

Concluding remarks: The main problem with Hedin's approach is the idea of a critical fracture radius, which is based on a theoretical assumption of an isolated disc-shaped fracture with zero displacement on the perimeter. The reality is that many fractures at the SKB sites terminate at intersections with other fractures, so there can be displacement at the edge of the fracture. This means that the "*critical area*" of a fracture is generally larger than Hedin's analysis allows for, so this method of estimation isn't conservative.

The presented methodology may give important contribution to PA. However, appropriate data describing the modelled rock volume are needed. A methodology to record such data must be presented.

10.7 Prof. Kurt Lambeck, The Australian National University, Canberra

10.7.1 Overview

I have examined the five papers in the following order:

1. Lagerbäck and Sundh (2008)
2. Lund et al. (2009)
3. Bäckblom and Munier (2002)
4. Munier and Hökmark (2004)
5. Hedin (2008)

Together they provide much insight into the understanding of rock stability on the scale of a waste repository and in the presence of nearby earthquakes. They provide a body of quantitative information that is central to making rational decisions about the suitability of sites for safe storage. I have reviewed the five reports here as I would review papers for publication in a scientific journal. Thus if there are critical comments at times they are made in the spirit of how the particular report could be improved. Normally I would expect some of these points to be challenged by the authors but I make them here in the context that they may reflect aspects of the work that are not clearly expressed or that may warrant further work. The specific comments are contained in the following individual reports and the comments in this overview are general comments only.

Lagerbäck and Sundh present an outstanding review of palaeoseismicity of northern Sweden. It is based on a lot of work that has been published in the open literature and has been widely assessed and used by other researchers. It is therefore widely recognized as very reliable quality work.

The work by Lund et al. is important in several ways – not least because of the experience that he has gained in finite element modelling using he ABACUS package. This puts him in a very good position for further modelling of the evolving stress field under the growth and decay of ice sheets. I believe that it is important to do this further work because I am not convinced that it is valid to extrapolate from the field evidence from locations near the centre of former ice sheets to locations nearer to the margins of these ice sheets. This is based on my own limited work published at this stage only in technical reports. The quality of the work presented is unquestioned.

The report by Lund et al. has to be considered as a technical report rather than as a scientific paper that has been examined by the larger community of researchers. But the quality of the work is consistent with that of the lead researchers other published work and I would expect him to turn this work into publishable material.

I purposely read the Bäckblom and Munier (2002) paper before the Munier and Hökmark (2004) paper. The latter builds very much on the first and some of the questions I had initially were at least partly addressed in the second. A problem that I have with both papers is that they are almost entirely built on SKB reports and little of this work, if any, appears to have entered into the peer-reviewed literature. This may be because of the local interest of the outcomes but it means that it has not received the critical analysis by other users of the reports as is usually the case with successful papers published in scientific journals. Thus there is not a body of ‘confidence’ about it as there is with, for example, the Lagerbäck and Lund led work. This is not a critique of the authors but SKB should consider how to turn some of the report material into formal papers. It would lead to greater credibility of the work I am sure.

My own areas of recent research have been such that I am much more aligned with the work in papers 1 and 2. Past work has been closer to rock mechanics at ANU (I was the successor to J. C. Jaeger at ANU, and I was for ten years Director of the School that continued Jaegers work).

What I sense in reading papers 3 and 4 is that they may not capture some of the more recent developments in fracturing in rocks. I could be wrong but if SKB has not already done so, it may be useful to bring in an outsider(s) from an established laboratory to look at some of the operations: possibly someone from an ‘academic’ area and/or someone with extensive tunnelling experience in different geological environments.

Throughout the discussion of the papers 3 and 4 a recurring thought is, is it not possible to actually establish whether fractures have been re-activated and to approximately date these fractures. I am not up-to-date on the latest developments in this area of structural geology but I can make some enquiries about this if desirable.

Paper 5 presents a quite different approach to assessing the stability of a repository but it is not linked by any mechanism to the actual earthquakes. Thus this approach somehow needs to join up with the outputs of the other four studies. This leads to the general comment that the studies 1, 2, (3 and 4), 5 have all been carried out quite independently of each other and that little attempt has been made to link them up to give a coherent story. Perhaps it is premature to attempt this but I think that it must be done because of the importance of the SKB work and to reduce the impact of some of the more ‘maverick’ views on the subject (not represented by these papers). Perhaps this is the purpose of the current SKB evaluation of these studies in which case I withdraw this remark.

10.7.2 Lagerbäck R, Sundh M, 2008. Early Holocene faulting and paleoseismicity in northern Sweden. Research Paper C 836. SGU - Sveriges Geologiska Undersökning.

This is a review of evidence for palaeoseismic activity based on some 35 years of quite monumental fieldwork by Lagerbäck in northern Sweden. I have been in the field with him in Norrbotten and have seen some of the features that are described and I had previously drawn the conclusion that his work is very thorough and that he does not over interpret the data.

The evidence discussed can be grouped into primary and secondary. The first is the fault data concentrated mainly in northern Sweden and of Lateglacial or postglacial age. It should be emphasized that large earthquakes do occur in old geological cratons away from plate boundaries, as in the Proterozoic and Archaean terrain of Australia, but the association of these events with the last deglaciation of Scandinavia is an obvious one and is wholly consistent with models of stress evolution of the region during the deglaciation phase. This includes the work of Patrick Wu and my own investigations.

The secondary evidence consists of landslides and deformation of sediments that are attributed to the vibrations in water saturated sediments generated by earthquakes. Such deformations are known to occur elsewhere and the association made here is reasonable. In particular Lagerbäck and Sundh emphasize that this is an inference only. That the occurrence of these secondary effects occur in greatest concentration near the large faults in northern Sweden gives added strength to this inference. They report on quite extensive and detailed surveys in four regions of Sweden and find that these secondary features occur “at almost every site in the vicinity of the recent faults where contemporary liquefiable sediments were present, while in areas without evidence for such fault movements, similar deformation structures are much rarer and less extensive” (p.42).

Of potential importance is that in both the Uppland and Småland areas, “short escarpments were noted but....these features proved to be....formed prior to the last deglaciation” (p.60 and p.63). Their significance is that the ice movements across southern and central Sweden have not been the same during each ice advance and the stress field likewise can be expected to differ. This was shown in my preliminary study (in SSI Rapport 2005:20).

The authors note that the first recognition of the fault scarps as being triggered by the last ice retreat occurred some 35 years ago and that the subsequent extensive mapping of other comparable features means that it is unlikely that there remain numbers of undetected faults (p.66) although they do point out that low-angle normal or strike-slip faulting is less likely to be detected by the aerial mapping methods used than the high-angle reverse faults of northern Sweden (p.66) This is again potentially important since the style of faulting will change with location (c.f the studies by Wu and my own. *Loc. cit.*).

Also of note is that the secondary features appear to be more ambiguous in central and southern Sweden, with a number of them being attributed to local instabilities (e.g. p.63, p.65). I am less familiar with the central and southern Sweden localities and cannot comment on this from personal knowledge but in view of the care that Lagerbäck takes in his interpretations I would accept this in the first instance.

The small number of the secondary features in the central and southern areas, compared with the north, is consistent with an almost absence of post-glacial faults and with the assumption that the primary and secondary features are causally related and that, by inference, there is no strong evidence for faulting triggered by the last ice retreat across southern-central Sweden.

The authors address the alternate view of Mörner and some others who argue that disrupted bedrock outcrops are indicative of large (M>>8.0) earthquakes having occurred in southern Sweden after deglaciation. They dismiss this interpretation and instead attribute the features to ‘intense glacial quarrying during a late stage of deglaciation’. I am not familiar with these features nor have I seen the Mörner 2003 report but the arguments presented by Lagerbäck and Sundh appear the more reasonable: the absence of such features in northern Sweden in the vicinity of the known faults; the fact that these features are not seen elsewhere in the world outside of areas of glaciation; and the negative correlation with the frequency of surface boulders.

Lagerbäck and Sundh raise two additional questions:

- Are there recent movements along the faults?
- Are the faults recurrent phenomenon or unique events?

The first is better answered by seismologists working with the Scandinavian seismic network data. In the absence of clear field evidence for movements on these faults during earlier glacial cycles, the second question is probably best addressed by models of stress evolution (magnitudes and directions of the stress field) during a full glacial cycle using realistic models for the ice advance and retreat over the areas in question.

10.7.3 Lund, B., P. Schmidt and C. Hieronymus (2009). Stress evolution and fault stability during the Weichselian glacial cycle. SKB TR-09-15, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.

Lund et al. give a concise summary of the problem: of how two effects that are well understood in theory, namely the stress cycle due to the time dependence of the ice load and the change in the water pressure in the rock below the ice (increased pore pressure) can combine to cause crust to fail. To evaluate this a critical input is the ice history, its spatial variation through time.

Their report is a quantitative study of the first part of this problem. They use a flat Earth model which has some limitations in that it does not include

- self gravitation,
- the water loading of the concomitant changes in loading by the changes in ocean volume,
- the effect of Laurentide ice sheet which adds a regional character to the stress field over Scandinavia.

These limitations are recognised by the authors and their approach is probably sufficient for the first order stress modelling in view of the uncertainties in the ice history information. They will not be adequate, however, for high accuracy modelling of sea level change.

For the complete stress field need the complete displacement field (u_r and $u_{(,\square)}$. The horizontal displacements are more strongly E dependent than u_r and this will mean that knowledge of the Earth's rheology will be important. These are all current research topics and the work by Lund et al. provides a good basis for examining these additional issues.

The finite element modelling approach used here represents a major investment in time and effort but one that should pay off in the long term because of the ability to deal with lateral variability in crustal and mantle structure and with faults or other zones of weakness.

The authors have carried out some benchmarking, including against theoretical models. Other than the anticipated high spatial frequency edge effects, agreement is reasonable and shows need for high-resolution grids/elements if the outcomes are to be relevant to specific locations.

In their Chapter 3 both 2D and 3D models have been considered and their report represents an important step in going from 2D to 3D. Chapter 4 deals with ice models. The assumptions made about starting with ice-free conditions before the MIS4 glaciation is reasonable and will introduce less uncertainty than the assumptions made about the LGM ice itself. The Naslund model gives a better representation of the lead in to the glacial maximum than the Lambeck (2005) model (but see Lambeck, Boreas, April 2010), but the glacial maximum occurs too late and the ice is too thick to produce a realistic rebound for Late glacial times. I also suspect that this model does not have enough ice on the Norwegian shelf and this may become important for the stress calculations in northern Sweden near the Norway border. At this preliminary stage of stress modelling these are not important issues but worth keeping in mind when interpreting the outcomes.

Chapter 5 describes the earth models and how they are implemented in the finite element FE) code. This illustrates the value of FE modelling in that it is possible to take detailed crustal and upper mantle lateral structure into account that analytical methods such as my own cannot do.

As an aside, I note that the crust is taken to be elastic but it would be worthwhile to consider non-elastic components as well to represent stress relaxation within the crust over the time scales of the ice load (~ 60,000 years).

A problem in dealing with lateral earth structure occurs when the ice model used has been inferred from glacial rebound modelling itself in which lateral uniformity has been assumed. That is, the earth model (E) assumption will map into the ice sheet (I) model. In so far as stress in the second derivative of displacement, this should not matter greatly if the E-I combination gives a good prediction of the observed displacement fields.

Chapter 6 deals with observational constraints, including geodetic data. I have previously noted that the limitation of the modelling method is the neglect of self gravitation, water loading and the deformational influence of the other (particularly North American and Greenland) ice sheets. These limitations are recognized and I do not think that the outcomes are over interpreted.

Chapter 7 deals with the glacially induced stress field and its dependence on E models. Generally the surface stress patterns are very similar for the range of E models considered and suggests that the principal features of the stress field are well captured. As expected, the depth dependence on E is greater. As noted by the authors, the ice models are a greater discriminator of stress magnitudes. The effect of lateral variability in E also follows expected behaviour and indicates that the FE code is behaving well.

Chapter 8 deals with the background tectonic stress field. Uncertainties in the knowledge of this field are acknowledged and the adopted fields are used primarily to examine the consequences of different scenarios. This is a valid process. Chapter 9 deals with the fault stability during glaciation.

Together this work provides a very sound basis for further work in understanding the stress cycle in the crust during glaciations and has the potential to deal with important local problems, including the lateral variability in crustal and upper mantle structure. This raises some interesting and important points on what are the appropriate mantle/crustal properties. Are, for example, seismic properties of the crust relevant on the much longer time scale of glacial loading. These issues will have to be addressed at some future stage.

10.7.4 Bäckblom, G. and R. Munier (2002). Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. SKB TR-02-24, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.

This report is a literature/interview/internet survey of seismic damage on underground facilities. It draws a number of conclusions about possible impacts of earthquakes of a repository site during both the pre-closure and the post-closure phases. The distinction between the two phases is principally one of damage that may be caused by rock fall and damage to equipment used for the transport of spent fuel in the pre-closure phase, and damage caused by high stress-fields by shaking/faulting during the post-closure phase. This latter also includes possible failure of the bentonite protective barrier and the possible changes in groundwater circulation and chemistry.

The introduction provides the technical background. It includes a discussion of the ‘KBS-3 solution’ with which I am not familiar, and I assume that this is correctly reported. It appears to be consistent with methods developed elsewhere such as by NAGRA.

The concept of 'respect distance' is introduced. This is the distance from a fault to the nearest container to ensure safety of the latter. Experimental observations of this function are extracted from experience in mines/tunnels where movements on faults have occurred.

Section 1.3 reviews the level of seismicity in Sweden in modern times, and of the expected ground acceleration. The authors use published peer-reviewed results to establish that peak accelerations are likely to be small for much of Sweden and well below the level at which ground damage will occur in a solid-rock environment. This conclusion has the proviso that no new glaciation occurs and is appropriate for the pre-closure phase and the early part of the post-closure phase. The results of this study would have to be compared with the results of the Lund study on the stress fields in the case of a renewed glaciation over the region.

Section 1.4 summarizes tunnelling technology used in Sweden. Again, I am not familiar with Swedish practice but I do not detect anything unusual in this brief section.

Sections 1.5 and 1.6 outline the process used in this report. I am unusually wary of using the internet as a source of information unless it comes from peer-reviewed material and reputable sites. The table 1.1 in this case is useful as it provides some guide to the more important and reliable sites.

Chapter 2 summarizes previous compilations of seismic damage to underground facilities. From these useful conclusions can be extracted that are relevant to a range of below-ground environments. An interesting note of possible construction importance is that where damage to concrete lining of tunnels has been reported that these may be related to construction weaknesses (p.33).

I am a little surprised by the small number of cases reported of damage at depths below 300m (p.35) because of the occurrence of rock bursts in mines down to considerable depth as, I understand, occur regularly in deep South African mines. There is an extended discussion on rock bursts in these mines in Chapter 3 (section 3.5) and this does discuss more deep events (p.63).

This may be a naïve comment but with the extensive tunnelling experience in Norway (and in Sweden) I am somewhat surprised to see no reference to such experience. Possibly there are good reasons for this that I am not aware of but if not it may be worth following up on.

Chapter 3 provides overviews of earthquake influence on underground facilities in selected countries. This provides a useful reference base from which conclusions can be drawn, particularly about the distances from the fault over which damage occurred. The authors' conclusions are collated in section 3.9 and I consider these to be appropriate and to provide a realistic measure of the distances away from the fault over which damage occurs, for different rock environments and for different magnitude events.

Chapter 4 attempts to translate the background material collected in Chapters 2 and 3 to a repository environment. A number of good first-order questions are asked in successive sections (4.1 to 4.6). It is probably fair to say that first approximation answers are provided to these questions and that fuller answers may be possible using more rigorous formulations. It should be noted that the materials used in this report mostly date back 10 years and that there will no doubt be more recent information available such that a new appraisal may be in order. Having said that, I think it unlikely that the principal conclusions of this report will be changed.

Section 4.7 addresses the question of whether present-day experience is relevant for understanding a situation of glaciation and deglaciation (actually only the latter is considered). Glacial cycles are typically of 100,000 year duration with the early part consisting of relatively small amplitude advances, followed by retreats but with successive advances becoming greater, peaking in the maximum such as occurred ~20ka BP followed by the rapid deglaciation before entering into a new interglacial. We are currently in the late part of an interglacial if past interglacials are representative. Thus the next glacial maximum is some 100,000 years into the future, which is about equal to the time required for the decay of spent fuel to normal background levels.

It is noted here that it is high uplift rates that cause changes in the stress field (p.81). It is actually the other way around, the rebound occurs in response to the stress field induced by the load. This part of the discussion would be more convincing if it was accompanied by some realistic modelling. The report by Lund and earlier published work is more helpful in this regard.

I do not understand fully the discussion on hydraulic jacking and how the authors go from the 60m depth attributed to Lindblom (1997) to 800m depth and how this is relevant to the remainder of the argument. Since this is a 2002 report I assume that later studies have followed up this point.

The discussion of the "third" issue (p.83) is also not clear, mainly because it is poorly written. What is meant by "It appears that reverse faultings have created magnitudes around 6.5 for all the data points"?

Is it true that SKB is not concerned with the pre-closure period (p.83)?

Section 5 gives the conclusions. There are nine in total which I have numbered such. The first three deal with earthquake impact during the pre-closure phase. These conclusions are valid on the strength of the evidence presented, particularly as any repository is presumably in more competent rock than most mining operations or many other tunnelling projects, and because critical components of the infrastructure can be placed well distant from any identified faults. (Underground mining is carried out where the ore is and ore bodies usually are the result of fluid flow along faults. Thus they are not the best environment for stable settings and I am not sure that mine data is particularly relevant.) I imagine that there must be a lot of information available from other tunnelling sites, as in Switzerland, including from the SKB repository site, that may be more relevant.

The next six conclusions (4 to 9) deal with the post-closure phase. I will deal with these sequentially.

C.4. The implicit assumption throughout this report is that only the stress field during deglaciation is important. I disagree with this because it ignores the importance of the evolution of the stress field outside of the ice sheet on the flexural bulge. With semi-realistic ice models for the last deglaciation significant destabilisation can occur at sites such as Oskarshamn when rapid fluctuations occur in the location of the ice margin to the north of the site (see SSI Report 2005:20 p.97). Failure, were it to occur would preferentially be by normal faulting. Thus this first part of conclusion C4 needs to be revisited using more realistic ice models. The second part of this conclusion is reasonable.

C.5. I concur with this conclusion particularly as the repository will presumably be in reasonably competent rock rather than the usual environment of a mine.

C.6. This conclusion is reasonable and I see no reason to disagree with it although no quantitative information is presented to back it up. There must be a body of literature dealing with this?

C.7. I agree with this conclusion, but it begs the question, what is an appropriate "respect distance". The field evidence presented is not convincing and I can't help thinking that there must exist better examples from tunnelling operations elsewhere. But I do not know this part of the literature.

C.8. I agree with this conclusion in so far as the available information permits.

C.9. This uncertainty in the respect distance is important but I note that this matter is treated in the more recent report R-04-17 so I will dwell no further on it here.

10.7.5 Munier, R. and H. Hökmark (2004). Respect distances. Rationale and means of computation. SKB R-04-17, Svensk Kärnbränslehantering AB (SKB) Stockholm Sweden.

This report follows on from the earlier 2002 report (Bäckblom, G. and R. Munier, 2002) dealing with the effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results. In examining the ‘respect distance’ concept and amplitudes - the distance from a primary deformation zone at which no further significant deformation occurs in the event of earthquake movement in that zone - ‘significant’ is defined as being safe for canister emplacement. This is not a very quantified definition since it also implies properties about the canisters themselves.

Different definitions have apparently been used in the past three decades of KBS/SKB reports to include the different factors that could influence the distance from a fault at which canisters can be safely located, including thermal, hydraulic and seismic factors and a revisit of an operational definition is useful. In section 2 the authors conclude that the seismic factor “overshadows” the other factors but the evidence for this is not strongly argued. For example, it is stated (p.7) that “the thermal aspects were partly addressed in Hakami and Olofsson (2002) and [they] conclude that thermal aspects, though locally important, would not have any significant impact on respect distance...” I do not find this reassuring. What is meant by “partly addressed” – what has not been addressed? What is “locally important”? In so far as one is dealing with a single repository, will it not always be a local problem? What is meant by ‘significant impact’? Some quantification of these statements surely is required if decisions are to be based on them. Likewise the brief discussion of the hydraulic factor is not adequate to dismiss it as unimportant. This is not to say that the overall conclusion is wrong. But it has not been justified here.

It does not help in assessing these other factors by the fact that the references cited are all SKB reports and have not received the scrutiny that peer-reviewed journal articles would have. I recognize that this may be the nature of this kind of research, that it is rather project specific and not of broader interest, but I would feel more comfortable about the conclusions if I knew that these subjects had received a greater airing in the open literature.

Section 3 discusses the computation of respect distances, considering only earthquake risk. It is recognized that this function is dependent on many factors, each of which has be parameterized to reduce a complex bit of physics to a manageable numerical solution. Canister failure criteria are based on previous SKB studies and I cannot comment on their validity.

I concur with the discussion on p.11 in which it is concluded that no canister would be damaged (what probability is associated with the choice of the word “would”?) for small earthquakes (small here presumably means magnitudes ≤ 5). I note, however, that there are different forms of equations 3.1 and that there is considerable uncertainty in the constant term. I recall that Hanks and Kanamori (1979) for example give 10.7 rather than 6.07 but I haven’t checked further.

In the Introduction (p.5) of a report written in 2004 it is noted that only 6 events larger than M=3 have been recorded since 2001.

This is far too short a record to draw the inference that is made there, and a more realistic picture of the seismicity is given elsewhere. Bungum (in SSI Report 2005:20) for example shows three >5 magnitude historic events. In other cratonic areas, well away from plate boundaries large magnitude earthquakes (M=7) do occur, as in Australia, but with a very long repeat time.

I recognize that it is not said here specifically, but on reading the report from the beginning, I would have to reach the conclusion that (i) earthquakes are limited to only small magnitudes in the postglacial phase, and (ii) that there will be no canister damage. On the strength of the evidence presented here I would not agree that this has been demonstrated.

Further, on page 11, it is noted that "We anticipate that the main hazard stems from post glacial earthquakes". I presume that since we are in a post-glacial phase now, that what is meant is Late glacial.

Host rock stresses (p.12/13): I think that different situations need to be considered since the repository site may not be beneath the centre of the ice load and that the stress field may be determined by flexural stresses in the lithosphere. In particular, it is not obvious that the predominant failure will be by thrusting at locations away from the centre of the ice load. Discussion with Björn Lund would be beneficial here.

A quite extensive set of different modelling approaches and results has been described (section 3.1.4), backed up by more detailed analyses reported in the appendices. This provides a useful cross-section of results. I am not familiar with the numerical codes used but have no reason to doubt their validity in view of the origin of these studies. The conclusions drawn from the static models are duly cautious/conservative and reasonable. I note, however, that the results are based on a 1997 study and since then there has been much improvement in numerical methods and computer capability and I wonder if it is worth revisiting this problem, particularly in that it should be possible to run the model under many different conditions.

I am not familiar with the dynamic models but the discussion of the methodology, assumptions and parameters is reasonable and the conclusions drawn are internally consistent. The maximum displacements occur for zero friction fractures and the results show the expected major reduction in displacements once friction is introduced.

The third level of sophistication of the models combined the static and dynamic effects and from this it appears that the static analysis is largely adequate. The fourth level introduces a more realistic modelling of the stress field during the earthquake cycle but this also suggested that the static model was largely adequate. This is not an unimportant conclusion in that this simpler model can be more readily used to explore other parameter spaces if necessary. But as noted in their summary (section 3.4.1) the dynamic response model does become important when considering shear velocity ranges.

In discussing the validity of their results (section 3.4.2) the authors note that an extension to the study of large (M=8) earthquakes "will probably exceed current computation capabilities". I doubt that that is the case today, some 5-6 years later. The future simulation work suggested is reasonable. But because the outcomes are very much computer-code dependent, and I am always wary of numerical outcomes, it may be worthwhile to explore whether there are other codes that can be used for comparison purposes.

Section 3.5.1 raises some interesting points concerning the dependence or not of stress drop on seismic moment. This is based on work by Scholz in 1990. I must admit that I am not familiar with the more recent literature but I would suggest that this point is revisited in terms of what may have been learnt since. Overall, I do not find the treatment of the consequences of large earthquakes convincing. Nor do, I suspect, the authors, and this part of the study is worth returning to, particularly in light of what may have been learnt in the past decade and faster and larger computers.

Section 4 deals with the definition of the geometry of the deformation zone. The difficulty of a precise definition is made clear and a conservative definition, in terms of a fraction of fracture length is adopted for cases where direct observations cannot be made.

Section 5 is a brief summary of Bäckblom and Munier (2002) and does not add to the information.

Section 6 deals with the trade-offs between conservatism in the assessment of the likelihood of canister damage and the scale of repository required. Increased conservatism reduces the number of suitable canister locations and increases the total volume of rock required to hold a fixed number of canisters. In the following subsections specific issues are explored that influence this trade-off.

Section 6.1 deals with site-specific stress fields during a glacial cycle. Since this report was prepared there has been more work done on this as reported in SSI Report 2005:20, that may answer the questions raised here. I recommend that this section be revisited in terms of new information.

Section 6.2 is confusing and this may be the result of the sentence “However, a 200 meter wide fracture is fairly large.” I presume that what is meant is radius rather than width.

In section 6.3 qualitative statements are made about test outcomes. If these are outcomes of numerical tests it would be more convincing of the actual results are shown. Quantitative results are always more convincing than vague statements!

Section 6.5 is unconvincing. The conclusion is drawn that computations of respect distances should be based on regional inputs rather than local inputs. But what is regional and local in this context? This needs more discussion.

Section 7 provides a summary of the preceding sections. I will comment on each paragraph sequentially:

1. This is a reasonable and convenient conclusion as already noted.
2. With the evidence presented in the report this is a conservative outcome.
3. As noted, I find the conclusions about large magnitude events unconvincing and suggest that this be revisited.
4. Agree.
5. This appears reasonable. It is based on a study by LaPointe that has not been published in the open literature, so I do not know what credence can be given to this study. This is not to say that it is not a valid study.
6. (Starting Table 7.1) This provides a useful summary table. I would suggest that the word zone size is changed as it may be confused with transition zone. I presume that it is used here in the sense of fault length. The cautionary words below the table are appropriate.
7. Agree.

8. Last paragraph – page 49. This is a useful example of the trade-off discussed above.

The example illustrated in section 8 is informative and possibly its' greatest value is that a useful tool has been developed for characterizing a site in terms of its suitability for canister emplacement from seismic considerations alone.

10.7.6 Hedin, A. (2008a). Semi-Analytic Stereological Analysis of Waste Package/Fracture Intersections in a Granitic Rock Nuclear Waste Repository. In: Mathematical Geosciences, DOI 10: pp 008-9175.

This paper provides a clear exposition of the role of fractures within host rock in evaluating the long-term safety of canisters in underground storage. The role of fractures is at least threefold – as pathways for fluids, as affecting the mechanical stability of the host rock, and shear movements along fractures triggered by earthquakes located on nearby major deformation zones.

This paper deals with the third of these, using a statistical approach. In so far as full knowledge of fracture distributions is unlikely to be achieved, even for a restricted volume of rock appropriate for a repository, this is a very constructive approach. An attractive feature of the approach is that it is an analytical formulation, free of numerical limitations and uncertainties. In fact, it can provide special analytical examples that can be used to test numerical methods. It provides estimates of the probability of a cylinder being intersected by a fracture assuming certain radius and orientation distributions of the fault surfaces. In particular it can calculate these probabilities of fractures that exceed a certain size. These fault characteristics are stated to be consistent with the distributions reported in SKB site descriptions.

This approach provides a powerful method of evaluating the 'security' of potential sites in a statistical way. I am not sufficiently familiar with the history of the subject to establish whether this is a truly original approach but I note that on the important question of whether the assumed distributions are realistic the assumptions are consistent with quite independent studies reported in the quality peer-reviewed journals of JGR and Water Research.

The model is described as the set of three steps: the fracture radius distribution, the fracture orientation distribution, and the combination of the two. Each step is developed in considerable analytical detail. There are aspects of this development that I simply have to assume are correct, such as the appropriateness of the $_{P32}$ definition but I note that other studies have used similar approaches in different situations. The mathematics all appears to be correct although I have not checked some of the more complex integrals (e.g. 19). (I note a minor error, of no consequence in the model or analysis, on page 2 of the paper where it says "canister deposition holes should not be intersected by fractures exceeding a certain size, typically larger than 0.1m." I presume that what is meant is that displacement on the fault should not exceed this value.)

Accepting, therefore, the formulation for the critical fracture area per unit volume of rock and the average intersection zone with over a fracture set, the author obtains an estimate of the number of fractures intersecting a canister and the probability of a canister being intersected. An example calculation gives a probability of ~2%. I cannot comment on how realistic the assumed parameters are, but I believe that it is the methodology delivered here that is the most important.

The author, in section 6, does carry out a sensitivity study on some of these parameters, and these show the utility of this approach. It is noted, for example, that assumptions about fracture radius distributions are important, and as noted, it “is essential to gain confidence in the description of fracture statistics.” The author has also made a series of numerical simulations that yield consistent results with the analytic analysis.

Finally the paper addresses some of the limitations of the method as developed here. This is a realistic assessment. Some of these limitations would appear to lead to the method providing upper limit estimates of the probability. Others I cannot readily assess. This may therefore be worth exploring these further, in conjunction with numerical methods, to obtain further insight into these probabilities

11. Conclusion

Together the reviewed reports, the oral presentations and the discussions provide much insight into the understanding of rock mass stability on the scale of a waste repository and in the presence of nearby earthquakes. They provided a body of quantitative information that is central to making rational decisions about the suitability of sites for safe storage of the spent nuclear fuel in Sweden. We the experts have reviewed the five reports presented to us as we would review papers for publication in a scientific journal. Thus, if there are critical comments at times they are made in the spirit of how the particular report could be improved or additional work is needed.

Some of the works presented by SKB are innovative and of high quality which puts SKB in the absolute frontier of research and development as for example the work by B. Lund and co-workers about the evolving stress field under the growth and decay of ice sheets. Other innovative work is related to the issue of respect distance, i.e. the minimum distance between a fault and major fracture with the ability to generate damage to the canisters and its content of spent nuclear fuel. Also the discovery, study and reporting of the late-glacial major faults and related structures in the young sediments in northern Sweden are certainly highlights in the work initiated and supported by SKB. The expert group is also of the opinion that more of the work presented by SKB in technical reports should reach scientific publications with peer-review.

Two of the technical report were eight (effect of large earthquake on KBS-3 repository) and six years old (respect distance) at the time of review related to lack of newer publications. During the Workshop SKB gave up-to-date presentations and the new information is also available in recent technical reports as SKB support documents for the licence application. A general problem with the reports presented to us is that they address in quite different ways the uncertainties. Often uncertainties are not discussed at all.

In the safety analysis SR-Can, SKB analysis indicates that the main risk related to seismicity would be that an earthquake taking place on a major fault at a certain distance from the repository would change the stress field in such a way that it could induce shear displacement along a secondary fracture/fault intersecting a deposition hole. If such shear displacement is sufficiently large it could jeopardize the mechanical integrity of a waste canister. SKB's strategy is to place the canisters at a sufficient distance from major faults and to not place canisters into deposition holes where observed major fractures intersect. In such a case, SKB's analysis indicates that the maximum possible shear displacement would not be sufficient to breach a canister. It still remains to be demonstrated that the approach is valid for earthquakes larger than magnitude M>6. So far SKB has not considered the cumulative load from several types of loading 1) thermal loading over thousands of years, 2) high shear stress during deglaciation and 3) effects from repeated earthquakes from nearby faults. In addition there are recent compilations of data about target fractures that shows that a target fracture of the radius 100 m can have a displacement exceeding the failure limit of the canister.

Several of the experts have reached the conclusion that the maximum possible shear displacement calculated for the target fracture might be underestimated. The temperature increase in the repository leads to thermal stresses that exceed the stresses generated by the ice sheet and this stress increase is able to generate fracture propagation of the target fractures in the vicinity of the deposition holes and tunnels. Therefore the potential for large-scale shear activation in the rock mass and associated induced seismicity during the thermal phase of the repository need further studies. Also the risk for subcritical crack growth at the tip of target fracture has not been sufficiently addressed.

The stress models of the Earth`s crust and mantel developed by SKB and the research team of Lund at Uppsala University is certainly a major step forward in the understanding of the basic mechanisms of the stress changes during a glacial cycle. Still remains to obtain a better understanding and simulation of the gravitational and tectonic stresses in the Fennoscandian Shield.

The seismologists in the expert group have brought up the need for a modern seismic hazard study of the repository site at Forsmark. They claim that it is not satisfactory to base the important work of the large underground repository construction on a more-or-less outdated European-scale earthquake hazard analysis. We have to keep in mind that so-called stable continental regions (SCRs) are also known for occasionally producing large earthquakes. Fennoscandia is a typical SCR region and therefore large earthquake events cannot be ruled out.

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Appendix 1 Minutes of meeting

Written by:
Prof. Hilmar Bungum and Dr. Conrad Lindholm

23 March

Lena Sonnerfelt: Opening

Bo Strømberg: Long term radiation safety project

- Two reviews: SR-Can (finished) and SR-Site (starting 2011 and estimated for ~2 years). SR-Site review will be iterative and ~25 experts estimated to participate.
  Expert commissioning expected in fall 2010.
- Two identified risks: a) Corrosion and b) Shear failure
- Compliance criterion: 10^{-6}/year
- Short term seismic hazard should also be addressed (fixing to M=6 insufficient)

Mikael Jensen: Short review of expert panel elicitation of seismicity following glaciation in Sweden

- Issues on scientific approaches, political influence.
- A elicitation was conducted in 2005 (SSI Report, 2005:20). Question to be responded: “What will be the frequency of M=6 or greater earthquakes within 10 km of Forsmark and Oscarshamn during and after the next glaciation?”
- *Recommendation/Comment: The SHHAC methodology implied the use of expert teams that are expected to voice the center body and the range of the informed scientific community on the issue at hand (avoiding proponent roles). SSHAC methodology may be applied also to other fields than seismic hazard.*

Raymond Munier: Respect distances

- Evolution of the respect distance concept was described.
- Documented that tunnels are practically resistant to damage/effect from earthquakes (more than 300 reports and papers).
- Deformations from earthquakes rapidly decrease laterally, and are hardly found beyond 100 meters from the fault.
- Deformation is rapidly decreasing with increasing depth.
- The concept is based on the fact that local fractures above a minimum size are well mapped.

- Use of several proxies for identification of fracture size.
- Present earthquakes are small and infrequent. The worry is glaciations.
- *Comment/question: Difference between stable/unstable faults? This is subject to a given stress field which may be disputed.*
- *Comment/question: Growth of faults from outside the region into the region was possibly not sufficiently regarded.*
- *Comment/question: The safety limit of 100 meters from the boundary of the damage zone to the target is subjective and not based on modeling. A quantitative differentiation was reported on later (Høkmark).*
- *Comment: The rock types referenced in the 2002 report are not relevant for the Forsmark rock types. Surface investigations were dominating in the used dataset.*

Bjørn Lund: The effect of advancing/retreating glaciers

- The 3D modeling is based on increased stress due to a) ice-load, b) tectonic stress and c) crust flexuring.
- The 3D ice model of Näslund (2006; climate driven) was used.
- Several earth models with lateral variations in elastic thickness were used.
- Model tested against BIFROST GPS data.
- Two types of modeling: a) Effect of ice-load on regional scale, b) fault stability using background stress field.
- Sub-glacial pore pressure is critical and not well controlled.
- Sensitive also to background stress field.
- *Comment/question: The stresses computed by Lund et al. (2009) are very much higher than Zoback (2003).*
- *Comment/question: There are huge differences between the Näslund (2006) and the Lambeck ice model. This was admitted as an uncertainty.*
- *Comment/question: The modeling explained a difference in fault stability between north and south Sweden, and as such "explained" why we have Lapland surface faulting in the north and not in central Sweden (conditional on the chosen stress field).*
- *Comment/question: The difference between Canada and Fennoscandia can be explained by differences between ice sheets (lateral extent) relative to the earth model (elastic thickness).*

Harald Høkmark: Effects of large earthquakes on a KBS-3 repository.

- 3DEC modeling of effects of M=5.5, 6.2 and 7.5 reverse earthquakes on a complex distribution of target fractures.
- Results include cumulative distribution of target fracture slip.
- Slip velocity is correlated strongly with target fracture slip (limited by Chi-Chi fault slip velocity).
- Magnitude is not very important for target fracture slip.
- *Comment/question: The faulting model is homogeneous and simple, and the effect of a more complex and realistic rupture model with high stress drop patches was suggested.*
- *The statement of M=6.0 as representative for larger earthquakes needs to be better justified.*

Raymond Munier: Full perimeter intersection rejection criteria.

- The models attempt a complete mapping of potential reactivation structures. The talk described methods that with high probability can identify “dangerous” positions.
- Description of the Full Perimeter Intersection Criteria (FPC) and Expanded FPC criteria (EFPC).
- Detailed explanation of the mapping procedures for fractures intersecting with canister-holes.
- Probabilities for escaping detection of fractures were presented.
- The characterization of active and passive structures is subject of the underlying stress field.
- *Questions were raised regarding possibility of fracture growth/development of new fractures beyond current limits and intersecting barriers.*
- *The possibility of liquefaction due to shaking was raised (and rejected).*

Alan Hedin: The earthquake scenario in SR-Site.

- The calculations were based on the compliance criterion of 10^{-6}/year probability.
- Two significant effects: Corrosion and shear
- Results: For 5 cm shear after rejection criteria has been applied.

- The modeling result indicated only one complete canister failure in 100,000 years, however, this resulted in a radiation pollution that alone reached the regulatory limit. This was based on a number of conservative assumptions.
- Handling of frequencies of large earthquakes remains to be established.
- *Question/Comment: Probability distribution of fracture slip related also to intermediate magnitude earthquakes may also be an issue.*

24 March.

Hilmar Bungum

- The hazard investigations are outdated and inadequate. The PGA_{max}=0.2g is unsubstantiated. Stable Continental Regions (SCR) may have infrequent large earthquakes which is important for an adequate seismic hazard analysis.
- Magnitude scaling models were questioned (M=6.0 as representative for larger).
- Earthquake complexity, variability and extreme ground motions have not been accounted for.
- Propagation of uncertainties to the final results is apparently not conducted and should be considered.
- The underlying stress model in the Lund et al modeling is important and poorly known.
- Is the Weichselian glaciation representative for future glaciations?

Conrad Lindholm

- The singularity of the Wechselian postglacial faults and the possible inadequacy for the Forsmark site.
- Slow (systematic) movements that may corrupt canister integrity are not well understood or handled.
- Hidden faults: Large postglacial earthquakes are likely also in the Forsmark area, but with ruptures on blind faults. This has not been discussed.
- Influence of thermal effects: Earthquake generation and triggering.
- Recommended a seismic monitoring system before, during and after repository construction (is now in progress).

Sven A. Tirén

- The presentation was thematic.
- Examples from Lapland on postglacial fault crossing of older faults/lineaments (barriers?). The "fault arrest" concept used by SKB is thereby questioned.
- Examples of "flower structures" in Lapland.
- Examples with precariously balanced stones in seismically active areas (California) document that similar features in Sweden can not be used as argument against the existence of large earthquakes.
- Brittle deformation zones: Questions raised about the fracture density concept.

Ove Stephanson

- The Bäckblom and Munier (2002) report was quickly done and covered many regions of less relevance.
- Effect of heating is important and must be addressed.
  - This may induce seismicity
  - Growth and development of new fractures.
- The relation between process zone width vs. fault length is important. It has been cited, but not used by SKB.
  - Which fault zone width should be used when there is a range?
- Deformation zones around the geological lens can act as a protection against deformation within the lens.
- Lund et al. (2009): Better synthetic stress models (stress vs. depth) are needed. The current stress maps (regional and local) are poorly resolved.
- Fracture mechanics and fracture growth at the tip of the fractures need to be better addressed.

Tobias Backers

- The additional stress generating mechanisms generated by heat and excavation needs to be addressed.
- A reworking of the data in Bäckblom and Munier Table 2.3 showed a significantly different (and less optimistic) picture of damage at depth (e.g. in tunnels) from earthquake shaking.
- What is the proper respect distance: The Vermilye and Scholtz (1998) relation between fault process zone width and fault length is referenced but not used.
- Lund (2009): Permafrost and pore pressure, Youngs moduli, topography, the background stress field and alternative ice models needs a better discussion.
- Wash-out of bentonite may lead to canister-rock contact ➔ reduced sealing effect.
- The stress concentration at the tip of a fracture rupture may be important and has not been discussed.

Jonny Rutqvist

- Modeling tools used by SKB has been compared to results using alternative modeling tools (ROCMAS and TOUGH-FLAC). The comparisons showed that some issues of importance were not captured in the SKB modeling (example on tensile stresses in the tunnel and canister walls).
- The modeling of glacial stress magnitude relative to thermal generated stress clearly demonstrate that thermal stresses are larger (factor of 2).
- How much can a 200 meter fracture slip? The lower bound was assessed to 0.2 meters, and best fit to 10 meters. These values are quite different from the SKB model. Reference to Schlische et al., (1996) for an extensive empirical dataset.
- Increased shear stresses on fractures is over time may generate induced seismicity.

Appendix 2 Workshop agenda

Workshop on seismology
Elite Hotel Marina Tower, Stockholm
March 23-25, 2010

Agenda

<u>Tuesday March 23</u>

09.00	Opening, Lena Sonnerfelt
09.15	Long term radiation safety project, Bo Strömberg
09.35	Short review of Expert Panel Elicitation of Seismicity Following Glaciation in Sweden, Mikael Jensen
10.00	*Coffee*
10.20	The effect of advancing/retreating glaciers, Björn Lund
11.00	Respect distances, Raymond Munier
11.40	Effects of large earthquakes on a KBS-3 repository, Harald Hökmark and Billy Fälth
12.20	*Lunch*
13.15	Full perimeter intersection rejection criteria, Raymond Munier
13.50	The earthquake scenario in SR-Site, Allan Hedin
14.30	*Coffee*
14.50	Impressions from the SKB presentations, plenary discussion
16.30	Summarize day 1
19.00	*Dinner*

Wednesday March 24

09.00	Hilmar Bungum
09.20	Conrad Lindholm
09.40	Sven Tirén
10.00	*Coffee*
10.20	Ove Stephansson
10.40	Tobias Backers
11.00	Jonny Rutqvist
11.20	Discussion
12.00	*Lunch*
13.00	Discussion
14.30	*Coffee*
14.50	Discussion
16.30	Summarize day 2
19.00	*Dinner*

Thursday March 25

09.00	Discussion
10.00	*Coffee*
10.20	Discussion
11.30	Summarize workshop
12.00	*Lunch*
13.00	End of workshop

Appendix 3 Workshop participants

Workshop on seismology
Elite Hotel Marina Tower, Stockholm
March 23, 2010

List of participants

Dr. Tobias Backers	GeoFrames GmbH
Prof. Hilmar Bungum	NORSAR
Dr. Conrad Lindholm	NORSAR
Dr. Jonny Rutqvist	Lawrence Berkeley National Laboratory
Prof. Ove Stephansson	Steph Rock Consulting AB
Dr. Sven Tirén	GEOSIGMA AB
Prof. Kurt Lambeck	The Australian National University, will evaluate the articles, will not participate in workshop

Billy Fälth	Clay Technology AB
Allan Hedin	SKB
Harald Hökmark	Clay Technology AB
Björn Lund	Uppsala Universitet
Raymond Munier	SKB
Olle Olsson	SKB

Katriina Labbas	STUK
Ari Luukkonen	STUK
Paula Ruotsalainen	STUK

Patrik Borg	SSM
Björn Brickstad	SSM
Björn Dverstorp	SSM
Mikael Jensen	SSM
Jan Linder	SSM
Virpi Lindfors	SSM
Georg Lindgren	SSM
Jinsong Liu	SSM
Maria Nordén	SSM
Karin Olofsson	SSM
Lena Sonnerfelt	SSM
Bo Strömberg	SSM
Shulan Xu	SSM
Peter Segle	Inspecta
Öivind Toverud	Bromma Geokonsult

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

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

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

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