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2013:34

Seismology – Post-glacial seismicity and paleoseismology at Forsmark

Initial review phase

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SSM perspektiv

Bakgrund

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

Projektets syfte

Uppdraget är en del av granskningen som rör den långsiktiga utvecklingen av bergmassan omgivande det tilltänkta slutförvaret i Forsmark. Detta uppdrag fokuserar på att studera SKB:s hantering av jordskalv som skulle kunna påverka slutförvaret och dess närområde. Fokus ligger främst på SKB:s konceptuella hantering och analyser relaterade till post-glaciala skalv, och deras tillförlitlighet.

Författarens sammanfattning

Metoden som SKB använder för att förutse seismisk risk för slutförvaret skiljer sig i två avseenden från gängse förfarande. För det första, förkastningsrörelser inom förvaret är beräknade utifrån numeriska bergmekaniska modeller i stället för genom en Probabilistisk riskanalys för förkastningsrörelse (PFDHA) som även rekommenderas av IAEA (2010). För det andra, uppskattningen av frekvensen för sådana rörelser baseras på långsiktiga töjningshastigheter eller från frekvens på seismisk aktivitet inom ett område med en radie på 650 km, i stället för att vara baserat på en seismisk zonering definierad i diskreta seismotektoniska provinser. Dessa två tillvägagångssätt som inte är standard-förfarande resulterar i att vissa aspekter av seismisk risk kan bli förbisedda eller undervärderade.

SKB medger att, under en glacial referenscykel på cirka 100000 år, kommer jordskalvsmekanismen att ändras under den pre-glaciala, glaciala och post-glaciala perioden. Men, för att förutse frekvens på olika magnituder på jordskalv inom en glacial referenscykel, använder SKB enbart data på nutida seismisk aktivitet, och anpassar dem inte för de lägre frekvenser som förutses under glacial period och högre frekvenser under post-glaciala perioder.

SKB:s beräkning av framtida stora jordskalv nära Forsmark baseras på sökande efter bevis på post-glaciala förkastningsrörelser i norra Uppland (Lagerbäck m. fl. 2003, 2004, 2005). De kommer fram till att det inte finns några bevis för stora post-glaciala jordskalv nära det tilltänkta slutförvaret, inte heller associerade med Forsmark-, Eckarfjärden- eller Singö-förkastningszonerna. Men, Mörner (2003 och senare), har publicerat resultat för samma område som står i konflikt med detta påstående. SKB har inte löst dessa motstridiga uppgifter och det är därför oklart om de tre förkastningszonerna nära Forsmark har rört sig i post-glacial tid, och i så fall, hur ofta och hur mycket. Detta behöver utredas och författaren av denna granskningsrapport föreslår ett tvådelat tillvägagångssätt. För det första, bör man använda den nya 2 meters Digitala Elevations

Modellen (DEM) från Nya Nationella höjdmodellen (NNH) för att göra en detaljerad geomorfologisk karta över Forsmarksområdet vilket skulle uppdatera Lagerbäcks rapporter som endast använde flygfotogrammetri. För det andra, bör man uppdatera datan över batymetrin utanför kusten till dagens tekniska standard och säkerställa att det inte finns några nya anomalier (lineament) på havsbotten. Ämnet är relevant på grund av att stora skalv kan skapa sekundära förkastningsrörelser större än 5 cm inom ett område av fem kilometer runt slutförvaret, orsakat av jordskalv flera kilometer utanför den radien. SKB:s nuvarande analys tar inte hänsyn till sådana sekundära förkastningsrörelser.

Projektinformation

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Diarienummer ramavtal: SSM2012-4735
Diarienummer avrop: SSM2012-5698
Aktivitetsnummer: 3030012-4044

SSM perspective

Background

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

Objectives of the project

This assignment is part of the review regarding the long-term evolution of the rock surrounding the repository. The assignment focuses on the handling by SKB on the impact of earthquakes on repository structures. SKB's conceptual handling and analyses related to post-glacial earthquakes is reviewed, so is also the robustness of the analyses performed.

Summary by the author

The SKB method of predicting seismic hazards within the repository differs in two ways from the standard analyses. First, fault displacements within the repository are calculated from numerical rock mechanics models rather than by the Probabilistic Fault Displacement Hazard Analysis (PFDHA), which is recommended by IAEA (2010). Second, frequency estimates for such displacements are derived from long-term strain rates or from the seismicity rates within a 650 km-radius area, rather than being based on smaller seismic source zones defined by discrete seismotectonic provinces. These two nonstandard approaches result in some aspects of the seismic hazard being overlooked or underestimated.

During the glacial reference cycle (approximately the next 100,000 years), SKB admits that the earthquake seismotectonics will change from the interglacial (present) period, glacial period, and de-glacial period. However, for predicting the frequency of various earthquake magnitudes within the reference glacial cycle, SKB use only present seismicity rates, and do not adjust them for the lower rates predicted during the glacial and higher rates during the de-glacial periods.

SKB's analysis of future large earthquakes near Forsmark is based on a series of searches for postglacial faulting in northern Uppland (Lagerbäck et al 2003, 2004, 2005). They conclude there is no evidence for large postglacial earthquakes near the repository, nor associated with the Forsmark, Eckarfjärden, or Singö deformation zones. However, conflicting conclusions have been published by Mörner (2003 and later) for the same area. SKB has not resolved the conflict between those two sets of publications, so it is unclear if the three fault zones near Forsmark have moved in postglacial time, how many times or how much they have moved. This matter needs to be resolved, and the reviewer suggests a twofold approach. First, use the new 2 m Digital Elevational Models (DEMs) of the New National Elevation dataset (NNH) to make a detailed geomorphological map of the

Forsmark area that would update the Lagerbäck reports, which used only aerial photographs. Second, update the offshore bathymetry to current technological standards and confirm there are no young anomalies (lineaments) on the seafloor. The issue is relevant because large earthquakes can cause distributed fault displacements greater than 5 cm within the repository 5 km radius, caused by earthquakes kilometers outside of that radius. The current analysis does not account for such distributed faulting.

Project information

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Strål säkerhets myndigheten
Swedish Radiation Safety Authority

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Cover Figure from Lagerbäck and Sundh, 2008, p. 61

1. INTRODUCTION

1.1 Scope of This Review

The assessment of this Technical note covers the previous work performed by SKB on the topics of postglacial earthquakes and paleoseismicity, as relevant to the siting and design of the proposed high-level nuclear waste repository at the Forsmark site in Sweden (Fig. 1). According to the contract with SSM, the reviewer was tasked to ”*...review SKB’s treatment of natural earthquakes with emphasis on SKB’s handling of post-glacial earthquakes and mechanisms behind them. The assignment also includes, apart from review of SKB’s licence application material, the identification and review of relevant publications in the scientific literature about paleoseismology and post-glacial earthquakes which have not been referred to by SKB. This may provide a broader basis for evaluating of SKB’s conclusions regarding the significance of post-glacial earthquakes for the long-term safety of a repository at Forsmark and for comparing with the supplier’s own understanding of the issue*.”

In addition the review should cover the appropriateness of SKB’s proposed design: ”*The concepts of “respect distances” from deformation zones and “acceptance criteria” for deposition holes intercepted by long fractures shall be broadly covered in this assignment, since these concepts are essential elements in SKB’s strategy to minimize the influence of earthquakes on repository long-term safety*.”

The present assessment does not cover the following topics, which are normally part of a formal Seismic Hazard Assessment: 1- Seismic Source Characterization of defined areal source zones and active faults at and surrounding the site; 2- Ground Motions Prediction at the repository site, such as calculated in a standard Deterministic Seismic Hazard Analysis (DSHA) or Probabilistic Seismic Hazard Analaysis (PSHA). Please note that PSHA is the recommended method of seismic hazard assessment for nuclear power plants (NPP) according to IAEA (IAEA, 2010, p. 26-28). This requirement exists because NPPs must be designed so the plant can be safely shut down after a strong earthquake, to avoid a core meltdown. Because there is no such danger in a nuclear waste repository, it could be argued that a PSHA is not required, and indeed no PSHA appears to have been performed for the Forsmark site. However, the US high-level nuclear waste repository was subjected to the most intense level of PSHA (SSHAC Level 4).

The advantage of doing at least the first half of a PSHA (the Seismic Source Characterization [SSC] part, as opposed to the Ground Motion Prediction part) is that all the spatial and temporal aspects of seismic source zones are rigorously defined in the SSC. These parameters (as contained in the SSC logic tree) then will become the main input for Probabilistic Fault Displacement Hazard Analaysis (PFDHA), or alternatively, for a deterministic-style analysis of possible displacements as done by SKB for Forsmark.

1.2 Detailed Topics Covered in This Review

SSM requested that I address the following topics in detail in this review:

1-SKB’s treatment of natural seismic events in the SR-Site Safety assessment and supporting reports.
2-The large-scale mechanical evolution of the area, earthquakes, state of stress and stress models used by SKB.
3-SKB’s handling of earthquakes during future glacial and post-glacial periods.
4-Mechanisms for post-glacial faulting and distributions in time and frequency.
5-SKB’s handling of earthquakes focus on the impact of large earthquakes on the near-field rock and the engineered barriers.
6-Examine if repeated smaller earthquakes could have any consequences that may have been overlooked by SKB.
7-Identification and review of relevant publications in the scientific literature about paleoseismology and especially post-glacial earthquakes which have not been used by SKB.

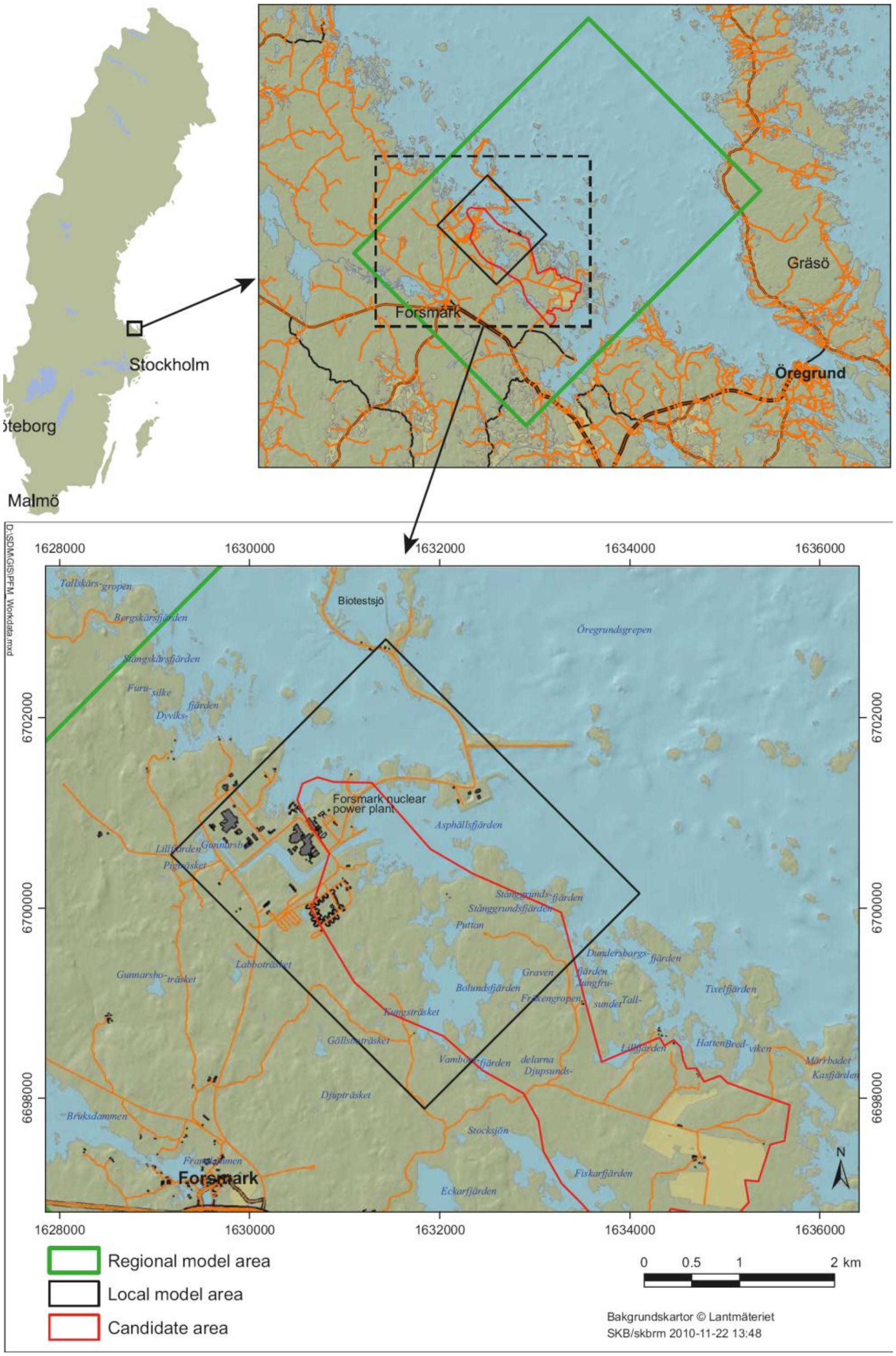

Fig. 1. Location of the Candidate Area for the proposed Forsmark repository. Source: SKB TR-11-01, page 106.

1.3 Guidance from SSM on Review Topics

According to SSM, "in the Main Review Phase all the external experts should consider the following items:
1-Completeness of the safety assessment
2-Scientific soundness and quality of the SR-Site
3-Adequacy of relevant models, data and safety functions
4-Handling of uncertainties
5-Safety significance Quality in terms of transparency and traceability of information in SR-Site and in the associated references
6-Feasibility of manufacturing, construction, testing, implementation and operation of repository and engineered barrier components (if relevant for the specific assignment)"

1.4 Reports Reviewed; SKB Reports and Others

The reviewed "mandatory reports" by SKB required in the work assignment are, in particular the main safety assessment, SR-Site report SKB TR-11-01, "relevant sections." In addition the following reports were reviewed:
SKB TR-08-11, Updated 2011-10, Effects of large earthquakes on a KBS-3 repository, Sections 1, 3.1, 4.8, 4.9, 6.1, 6.6, 7.3, 8.4 and 8.5
SKB TR-10-48, Geosphere process report for the safety assessment SR-Site, Sections 4.1.1-4.1.3, 4.3.7
SKB TR-09-15, Stress evolution and fault stability during the Weichselian glacial cycle, Section 9, 10 and 11
SKB R-06-67, Earthquake activity in Sweden, Section 4.4

SKB Reports- Relevant Readings (recommended):
SKB R-04-17, Respect distances, Section 3.5

2. MAIN REVIEW FINDINGS

In this Section the reviewer presents the main review findings, discussed under the topic headings suggested by SSM.

2.1-SKB's treatment of natural seismic events in the SR-Site Safety assessment and supporting reports

In general, SKB's treatment of natural seismic events was informal, compared to the normal level of effort and formalism found in other seismic hazard assessments for a high-level nuclear waste repositories. As an example, the seismic hazard study of the Yucca Mountain high-level nuclear waste repository in the USA was a SSHAC Level 4 PSHA, the highest and most rigorous level of PSHA. In the Seismic Source Characterization phase of that study, much effort was devoted to defining the locations of area source zones and active fault source zones, plus their maximum earthquake magnitude, and their magnitude-frequency relationships. SKB did not attempt to define such areal seismic source zones in the standard way. That is, they did not define source zones based on the spatial pattern of historic seismicity and bounded by major geological structures or by tectonic province boundaries, as in normally done. Seismic zones thus drawn constitute objectively-defined seismotectonic provinces, within which it is reasonable to assume that seismic activity will be spatially uniform. Instead, SKB analyzed the historic seismicity only in circles with radii of 650 km and 100 km around Forsmark.

A cursory examination of the earthquake epicenter map (Fig. 2) shows that the 650 km-radius circle (an arbitrary and non-standard radius in seismic hazard assessments) was evidently

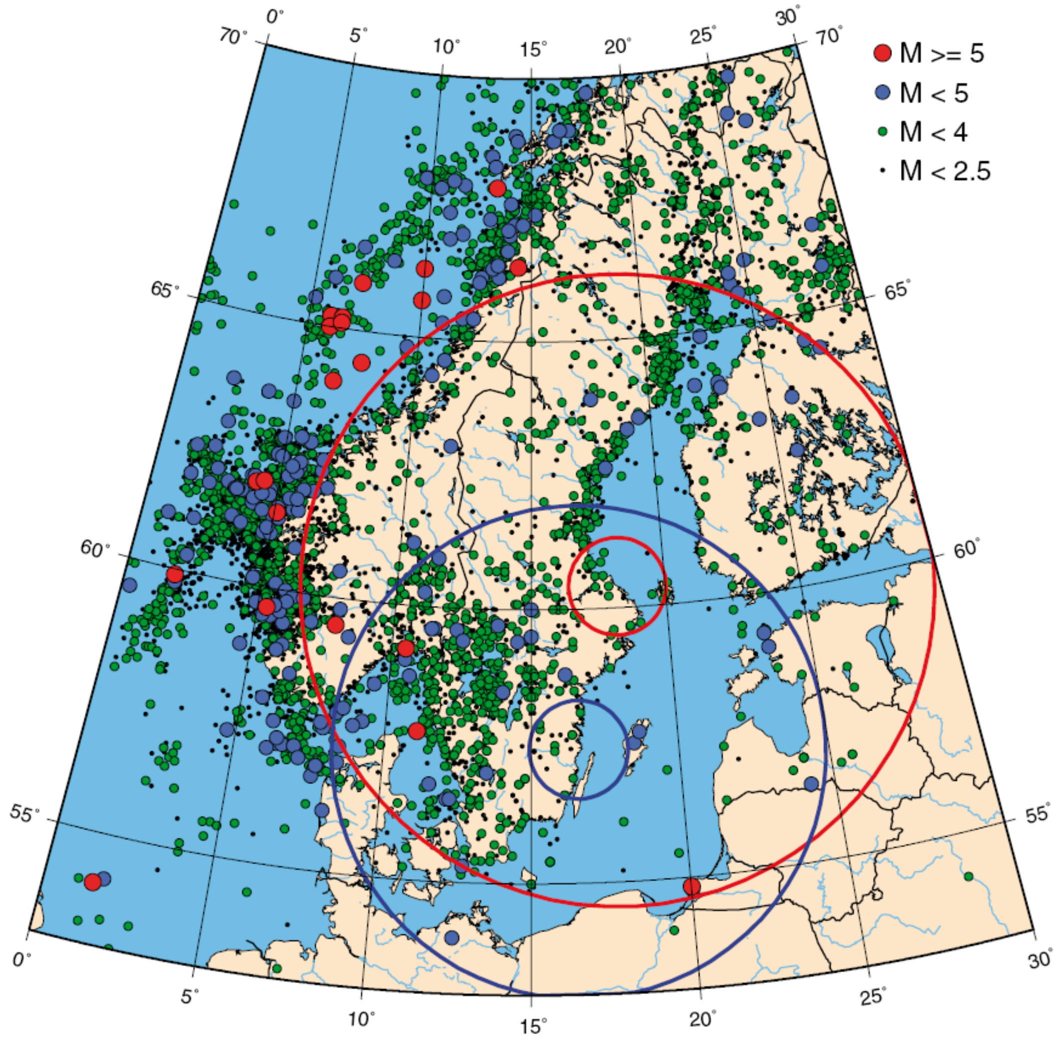

Fig. 2. Known earthquakes in the Nordic region from 1375 to 2005. The large red circle has a 650 km radius from Forsmark and the large blue circle has a 500 km radius from Simpevarp. Small circles have radius 100 km.

drawn to be as large as possible without extending into the active belt of earthquakes on the west coast of Norway and offshore. However, at that size it includes areas of Poland and the Baltic countries that have a completely different geology and tectonic setting than at Forsmark. The 650 km radius also includes the seismically active area SW Sweden and SE Norway, including the Oslo Graben and the Tornquist Zone, which are also dissimilar seismotectonic areas than at Forsmark. Fig. 3 shows the seismic source zonation of Scandinavia from the SHARE Project (www.share-eu.org). In that map you can see an example of a standard approach to seismic source zoning. The Oslo Graben, the Tornquist Zone, the active Höga Kusten area of Sweden's Bothnian coast, are all characterized as separate seismic source zones. It is a map like this that should form the basis for predicting how close to Forsmark earthquakes might occur in specified time frames, rather than the prediction made by Bodvarsson et al., (2006, Section 4.5, SKB Report R-06-67) based on the 650 km-radius circle.

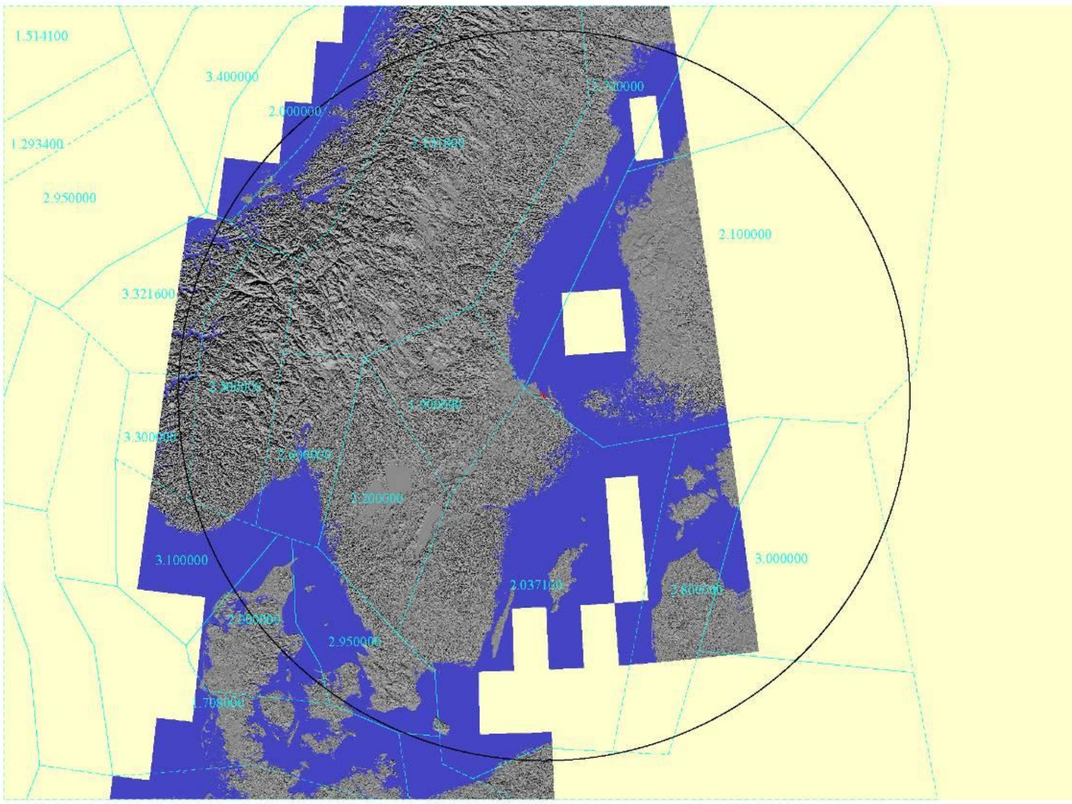

Fig. 3. The 650 km radius around Forsmark (black circle) compared to the areal seismic source zones defined by the SHARE Project (outlined by dashed blue lines; from www.efehr.org:8080/jetspeed/portal/hazard.psml). The blue numbers are the ”a” intercept value on the Gutenberg-Richter magnitude-frequency curve of historic seismicity within each source zone. Higher numbers indicate more active seismicity. Forsmark falls near the intersection of four source zones with different levels of seismic activity.

The SHARE seismic zone map (Fig. 3) was created after the Bodvarsson 2006 report was written, which explains why the authors did not cite it or use it in their analysis. However, this review was specifically tasked with identifying new data and approaches that were not used by SKB, and the SHARE seismic source zonation map appears to be an important example of that.

An interesting issue not addressed in the Bödvarsson report is why the linear band of earthquakes along the Höga Kusten seems to abruptly terminate northwest of Forsmark (see Fig. 2). The termination seems to be along a sharp line trending NW-SE that aligns with coastline at Forsmark, and may be controlled by NW-trending faults such as the Singo, Eckarfjarden, and Forsmark fault zones. Such a NW-SE line also constitutes the boundary between the seismic zones defined north and west of Forsmark by the SHARE Project (Fig. 3). To the north of the line is the Höga Kusten zone with high seismicity (a=2.7), and to the south of the line is a zone centered in Västmanland with much lower seismicity (a=1.9). A cluster of seismicity along the coast NW from Forsmark suggests that one or more of the three faults named above might be seismically active, and that the southernmost earthquakes in the Höga Kusten zone may in fact be along these same faults. If so, this has major implications for Forsmark, because seismicity spatially concentrated along faults near Forsmark implies higher hazard than assuming that Forsmark seismicity is spatially random at the same average rate as the entire 650 km circle.

To test the hypothesis above, one would use the best-available GPS data to try to detect differential movement across the three faults mentioned, as well look for associated microseismicity via a dense seismic network in the vicinity of the fault zones. However, the main point of such an exercise would be to see if the fault zones were associated with modern seismicity and thus should be considered ”active” by the usual international definitions. SKB makes the pessimistic assumption in their analysis that these three faults are potentially active, and can be expected to generate large earthquakes (up to M7.3 based on the 70 km length of the Forsmark zone). However, the rate at which these faults are allowed to generate earthquakes is limited to the average rate of the 650 km-radius area, not the rate derived from the faults themselves, or even from the seismic source zones that the faults traverse.

There is an additional advantage to examining the three faults with LiDAR DEMs to look for evidence of postglacial surface ruptures, because any displacements associated with such ruptures would give valuable information about the style of coseismic deformation very near Forsmark (i.e., sense of slip; displacement per event; primary versus distributed faulting; number of events post-glaciation= recurrence interval). This would be the geological ”reality check” on the size of earthquakes and distances to them, to be expected near Forsmark within various time periods (as predicted by Bödvarsson et al., 2006, based on overall seismicity distributed within the 650 km-radius circle). We know that faults displacing latest glacial deposits do exist within 50 km of Forsmark, because they have been photographed (see Fig. 4, Mörner 2003).

2.1.1 Large-scale mechanical evolution of the area

The reviewer admits not to be an expert in mechanical evolution of the crust, and therefore defer to Muir-Wood (1993), successive reports by SKB, and published papers about the seismotectonic setting. The recently-published literature concludes that the long-term seismotectonics of Sweden are controlled by ridge-push forces from west of Scandinavia that impose a weak (10^{-10} strain/yr) tectonic, east-west, compressive stress field in Sweden (Fig. 5a). Every 100,000 years an ice cap forms on Sweden and depresses the crust, which temporarily supresses the earthquakes that could have released the accumulating strain from the far-field tectonic stresses (Fig. 5b). When the ice cap rapidly melts at the end of each glacial cycle (in a little as 10,000 years), the Swedish crust rebounds vertically, as much as 800 m at the end of Weichselian. At this time much of the accumulated tectonic compressive strain accumulated during the glacial period can now be released in a cluster of large postglacial reverse-fault earthquakes (Fig. 5c). After that cluster of earthquakes, the seismicity declines down to a steady-state interglacial moment release rate controlled again by the far-field tectonic stresses (that is the present, interglacial situation).

Fig. 4. Photograph of a fault displacing glacial deposits near Mehedeby, 50 km northwest of Forsmark. (From Mörner, 2003, p. 225)

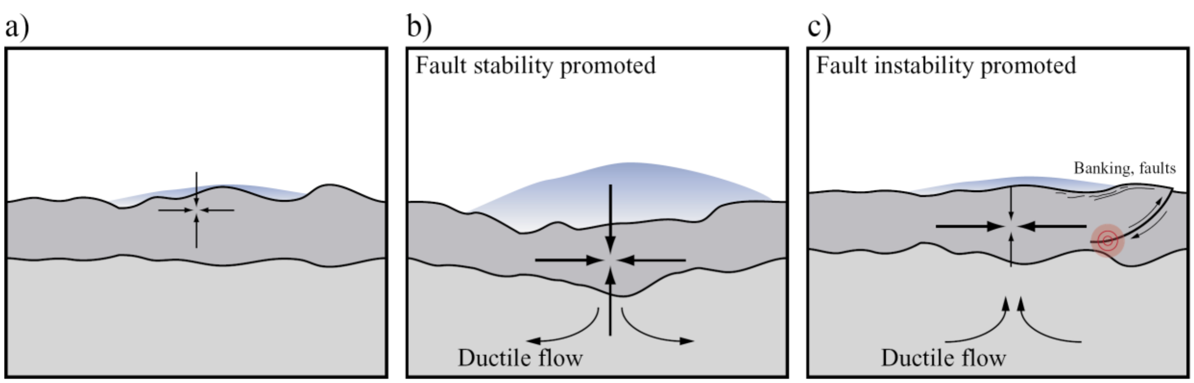

Fig. 5. Schematic cartoon illustrating how the stress field changes during the pre (a) syn (b) and c) post glacial times. During the growth of the glacier, horizontal tectonic stresses accumulate while differential compressibility promotes fault stability. Mantle material flows, relatively slowly, from beneath the glacier. When the glacier retreats, differential stresses promotes fault instability, in particular on gently dipping faults oriented perpendicular to σ1. Mantle material flows back, and the crust is slowly regaining its state of equilibrium. (From Munier and Fenton, 2004, p. 197)

2.1.2 Earthquakes

In this conceptual model described above, the rate of seismicity should vary between the interglacial period, the ice cap growth and maximum extent period, and the rapid deglaciation period (Fig. 6). We have historic/instrumental earthquake data over the full range of magnitudes only for the present (interglacial) period, and it is this data that SKB has used to predict the magnitudes, rates, and distances of earthquakes to Forsmark over the future 100,000 years to 1 million years (Bödvarsson et al., 2006, SKB R-06-67).

In my opinion SKB should have calculated future earthquake probabilities based on the above conceptual model, rather than on an assumed long-term tectonic strain rate of $10^{-10/}$yr over the small 5 km radius around Forsmark. Of the three magnitude-frequency curves that we need (interglacial, full glacial, and deglacial), we have only direct measurements from the current interglacial cycle. The other two magnitude-frequency distributions would have to be created by modifying the interglacial one in an appropriate way to honor the independent geological evidence and modeling outputs. For example, the seismic moment rate in the full-glacial should be less than in the interglacial, based on the analogy with imodern icecap areas such as Greenland and Antarctica. For the deglacial period, at a minimum the Mmax value should be increased, to honor the occurrence of M>6.5 surface-rupturing earthquakes during the deglacial in Lapland. Shifting the interglacial curve to the right would simultaneously increase Mmax and the ”a” value, without the need to change the ”b” value (about which we have no field data from the deglacial period).

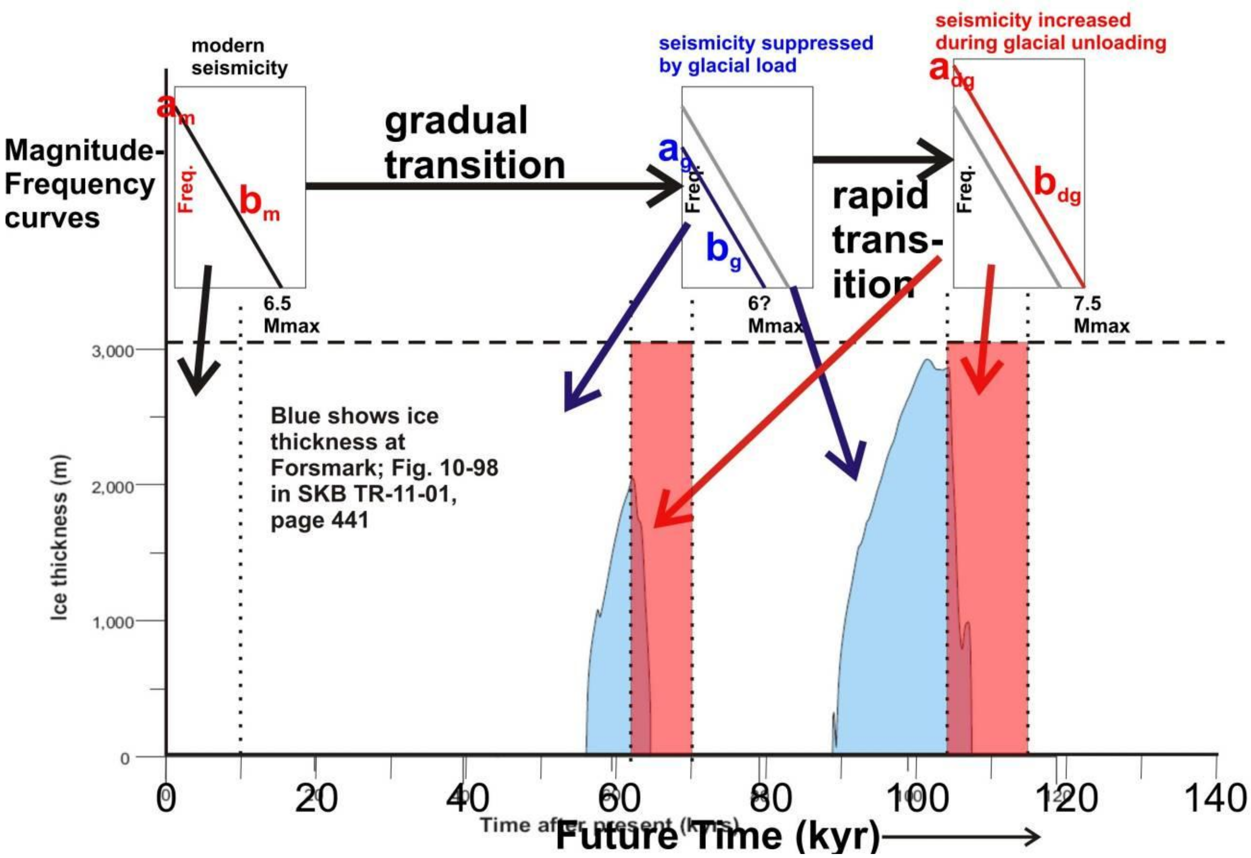

Fig. 6. Conceptual view of seismicity through the next 100,000-year glacial cycle. The lower half of the diagram shows the thickness of glacial ice at the Forsmark site (in blue) during the growth of the next ice cap. The red box marks the 10 kyr period of rapid deglaciation at the Forsmark site, when crustal rebound

leads to accelerated seismicity. The top half of the diagram shows hypothetical Gutenberg-Richter magnitude-frequency curves for the modern (interglacial) period, the full-glacial period, and the deglaciation period.

For the interglacial period, the relevant seismic source zones around Forsmark can be characterized by the modern ”a” and ”b” values from historic/instrumental seismicity (a_m and b_m in this diagram). During the full-glacial period seismicity should be suppressed, so the ”a” value should decrease to a lower value (a_g), shifting the curve to the lower left. Mmax may also decrease and ”b_m” may change to ”b_g”. In the deglaciation period Mmax should increase, as indicated by the large postglacial surface ruptures in Scandinavia. This increase in Mmax could be obtained by shifting the Gutenberg-Richter curve to the right, and thus increasing ”a” to ”a_{dg}” The ”b” value may remain constant or it may change, but we have no real data on this parameter for the deglacial period, because the only earthquakes detectable are those large enough to rupture the surface (e.g., M>6.5).

The two approaches may yield similar numbers of earthquakes over the full glacial reference cycle, since the long-term strain budget over this cycle has to be honored in either case (the strain-rate approach used by SKB (Bödvarsssson et al, 2006) and the seismological approach recommended herein). But the seismological approach will honor the observed and modeled increase in seismicity during the deglacial part of the cycle.

2.1.3 State of stress and stress models

This topic was covered in the two SKB reports: Muir-Wood, 1993, (SKB TR-93-13); and (SKB TR-09-15). The review comments concerning the state of stress can be found in prior sections.

2.2-SKB’s handling of large earthquakes during future glacial and post-glacial periods

2.2.1 Mechanisms for post-glacial faulting

The general topic of large earthquakes was covered in SKB reports by Muir-Wood, 1993, (SKB TR-93-13), and their effects on the repository were addressed by Lund, 2005, (SKB TR-05-04); Lund, 2006, (SKB R-06-95); Lund et al., 2009, (SKB TR-09-15).

The liklihood of ”fault reactivation” at the Forsmark site was assessed via modeling in the reports by Lund listed above. However, Lund et al., 2009 only predict that certain faults become ”unstable” at times in the reference glacial cycle, due to static stress changes. They do not predict that those faults will slip and release earthquakes: ”*This study cannot conclusively determine whether or not endglacial faulting will occur (or rather, should have occurred) in Forsmark or Oskarshamn*” (p. 97). Nor do they include tectonic stresses in their analysis, but remark: *” In this study we have not included tectonic strain accumulation /Johnston 1987/... If the ice sheet suppresses strain release in earthquakes, the strain accumulation due to the plate motion will suffice to cause very large earthquakes. This line of reasoning should be further pursued...”.*

They conclude (p. 91): *”When we discuss instability at 500 m depth we do not imply that these potentially unstable fault conditions will cause earthquakes. Earthquakes generally nucleate below 2 km depth (there are notable exceptions, see /Bödvarsson et al. 2006/) so it is unlikely that unstable faults at 500 m depth would evolve into earthquakes. The instability analysis is nevertheless valuable as it shows which fault orientations at 500 m may be more vulnerable to* *slip, given other external factors such as high pore pressures during a glaciation or secondary motion due to nearby earthquakes*." [underlining added]. However, it does not predict either the strengths or temporal probability of secondary motions due to nearby earthquakes. Those parameters would normally be predicted during a PSHA, but a PSHA has not been performed for the Forsmark site.

2.2.2 Earthquake distributions in time and frequency

In SKB report TR-11-01, p. 466, it is reported that: "*There have been few attempts to estimate the earthquake frequency for time periods relevant to SR-Site* [that is, 100,000 to 1 million years].. *To our knowledge, these are restricted to the ones listed in Table 10‑14.*"

Table 1 (the same as *Table 10‑14 in SKB TR-11-01). Estimated yearly frequency of earthquakes ≥ M5 within a 5 km radius area.These frequencies are then divided (f) amongst the 30 local deformation zones susceptible to reactivation (see Table 10-15 and /Fälth et al. 2010/), out of the 36 deformation zones intersecting the area (Figure 10‑128).*

Reference	Earthquake frequency (M≥ 5/year) for the 5 km radius area around Forsmark	f
/Böðvarsson et al. 2006/	$2.4 \cdot 10^{-6}$	$7.8 \cdot 10^{-8}$
/La Pointe et al. 2000, 2002/	$8.7 \cdot 10^{-7}$	$2.9 \cdot 10^{-8}$
/Hora and Jensen 2005/[1]	$2.5 \cdot 10^{-6}$	$8.3 \cdot 10^{-8}$
/Fenton et al. 2006/	$2.0 \cdot 10^{-6}$	$6.8 \cdot 10^{-8}$

[1]The frequency estimates of /Hora and Jensen 2005/ in Table 10‑14 concern earthquakes of magnitude M6 or larger. The references therein were not readily scalable to ≥ M5 but, as the slope of the logarithmic G-R relationship is close to unity /Scholz 2002/, we increased the frequencies in Table 10‑14 by a factor 10 to incorporate earthquakes of magnitude M5 or larger as an approximation.
[2]In /Fenton et al. 2006/ frequency estimates ≥ M4.9 were provided and we choose to use the original values rather than rescaling to M5. This will slightly overestimate the frequency.

SKB report TR-11-01 goes on to explain how these earthquake frequencies for the 5 km-radius area were derived by dividing the frequencies of earthquakes of a given magnitude in the 650 km-radius circle, by the proportional area of a 5 km-radius circle.*"The frequencies shown in Table 10‑14 were, for comparative reasons, normalised by averaging the original frequencies predicted by each estimate over the area covered by each assessment* [a 650 km radius circle] *and here rescaled to an area corresponding to a circle with 5 km radius. It is emphasised that estimates of anticipated earthquakes at Forsmark, based on frequencies in Table 10‑14, are associated with some yet unresolved uncertainties and fundamental assumptions*.[underlining added by this reviewer]

...B. The reason for the locations of all of the unequivocally identified post-glacial faults being restricted to the Lapland region is unclear. [underlining added by this reviewer]. *It is cautiously assumed that the estimated frequencies of large earthquakes are applicable to Forsmark. However, whether strain energy release at Forsmark will indeed be dominated by seismic or aseismic slip is an open issue. The lack of markers for large earthquakes at Forsmark is taken as an indication that faults following the retreat of Weichsel either slipped aseismically, with small magnitudes, or not at all.* .[underlining added by this reviewer].

Paragraph B above indicates several uncertainties about the "estimated frequencies of large earthquakes" that underlies the earthquake model in TR-11-01. At present the number of M6 and M7 earthquakes to occur in the Forsmark area in the next 100,000 to 1,000,000 years is predicted from the rate of M5 earthquakes, which itself is estimated from the frequency of M5 earthquakes in historic time in the 650 km radius around Forsmark.

An alternative way to estimate the frequency of M6 and M7 earthquakes in the Forsmark area is to identify evidence of postglacial faulting, either *primary evidence* such as fault scarps (surface ruptures) or *secondary evidence* such as liquefaction, landslides, and tsunamis (after the classification of McCalpin and Nelson, 2009, p. 11-12). This has been done in many parts of Sweden in numerous published papers by Nils-Axel Mörner over the past 4 decades (see Reference List). In particular, Mörner (2012b) contends that the seismic moment rate during the deglacial period will be 100 to 1000 times greater than the present seismic moment rate (see Fig. 6). As a result, he strongly criticizes SKB for estimating the frequency of future earthquakes based on the present (interglacial) rate of seismicity.

Because Mörner's 2012 publication postdates all the SKB reports that reviewed here, his alternative theory has not been formally rebutted in an SKB report (to the reviewer's knowledge). The evidence supporting Mörner's "neotectonic claims" is described in the next section.

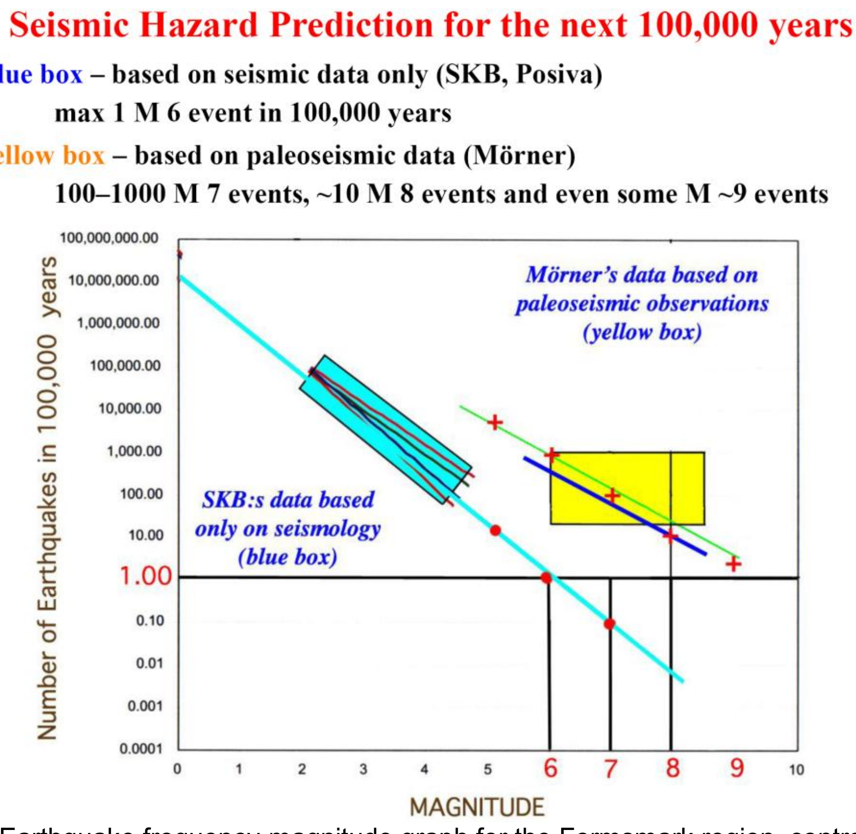

Fig. 6. Earthquake frequency-magnitude graph for the Formsmark region, contrasting the number of earthquakes of various magnitudes in the next 100,000 years predicted by SKB (light blue line and rectangle) versus Mörner (yellow rectangle and dark blue line). Mörner's number of earthquakes represents those predicted in the entire country of Sweden, whereas SKB's number of earthquakes represents only those for the Forsmark region. Source: Mörner, unpublished PDF of his presentation at the 2012 INQUA-IGCP-567 meeting in Morelia, Mexico. A four-page condensation of his talk was published in the proceedings volume (Mörner, 2012b), but due to space limitations this figure was omitted.

2.2.3 The Completeness of SKB's Record of Postglacial Faulting, and the Issue of Additional "Neotectonic Claims" Published by Others

Three SKB Reports describe a search for evidence of postglacial faulting around Forsmark (Lagerbäck, R. and Sundh, M., 2003, SKB P-03-76; Lagerbäck et al., 2004, SKB P-04-123; Lagerbäck et al, 2005, SKB R-05-51). The first two reports do not make any mention of Mörner's neotectonic claims in Sweden, because none at the time were near Forsmark. However, in 2003 Mörner published a 320-page book summarizing all his evidence for postglacial earthquakes in Sweden. His paper #6 in that volume is titled "The North Uppland region; Gillberga Gryt and Mehedeby" and describes evidence for five strong postglacial earthquakes in the Forsmark region (Fig. 7, site 10) . The towns of Gillberga and Mehedeby lie 45 km west of Forsmark, and 50 km northwest of Forsmark, respectively. In this paper Morner describes deformation of latest glacial deposits, including faulting (see Fig. 4), liquefaction, "shaken beds", and "strongly deformed bedrock."

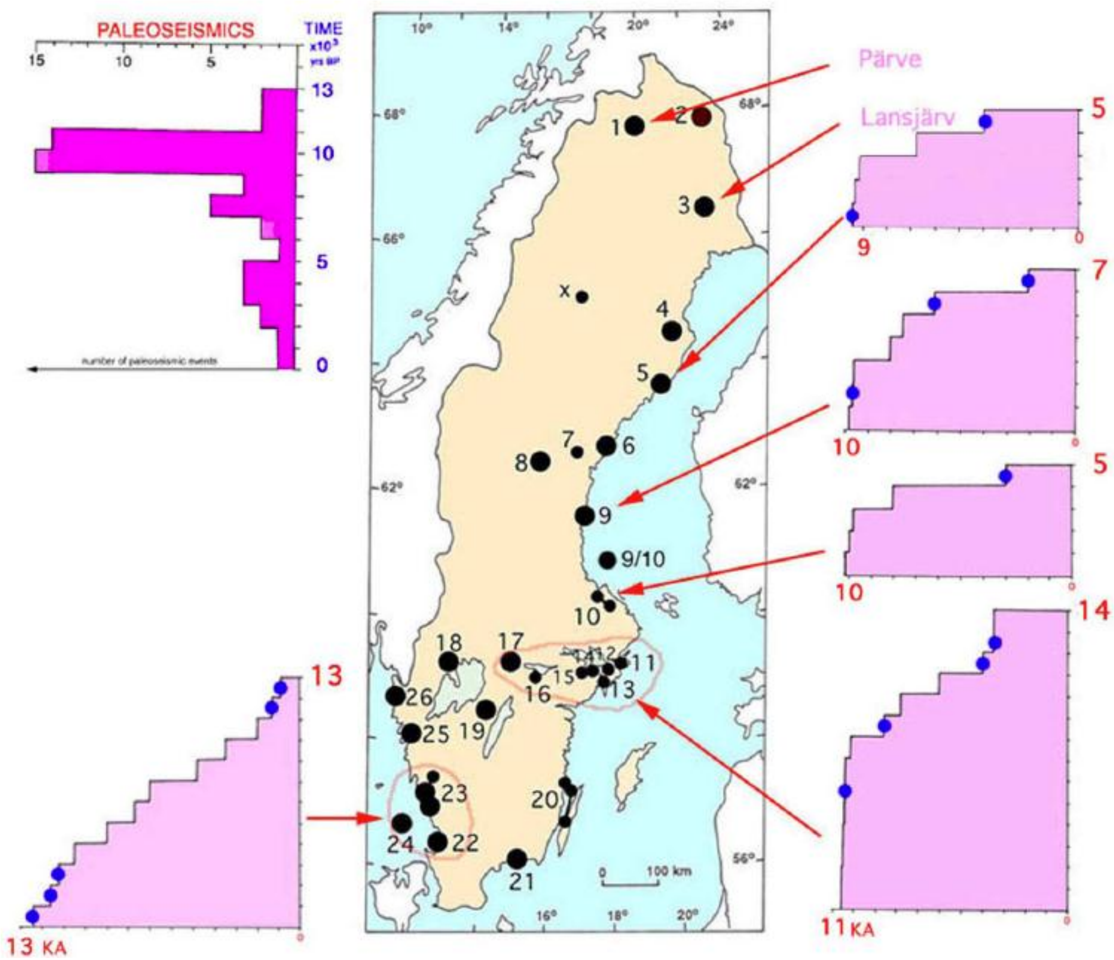

Fig. 7. Map of paleoseismic sites in Sweden, from Mörner (2003, p. 16)

Thus we have to question whether the catalog of postglacial faulting used by SKB in the Forsmark area, and in Sweden in general, is complete. The first SKB report to formally assess the validity of claims of neotectonic deformation in Scandinavia was that of Muir-Wood (1993). His analysis was restricted to the 17 cases known in the early 1990s, and he proposed the following 5-category grading system: (A) almost certainly neotectonics, (B) probably neotectonics, (C) possibly neotectonics, (D) probably not neotectonics and (E) very unlikely to be neotectonics. Only two of the 17 cases were classified as A, and one of those was "probably superficial" (i.e., sackung).

Subsequent to 1993 Mörner has published many neotectonic claims, and proposes the occurrence of 56 large paleoearthquakes in Sweden during the postglacial and Holocene periods. The evidence for most of his claims are "seismites", that is, structures of soft-sediment deformation and liquefaction observed in late-glacial unconsolidated sediments. Other claims are based on the interpretation of sand beds overlying erosive surfaces as tsunami deposits, and of fractured bedrock being broken by severe earthquake shaking.

Mörner's neotectonic claims, especially those made in his 2003 book and later, have never been formally assessed. This includes his claims near Forsmark. The SKB reports by Lagerbäck do not discuss his claims in any detail, even though they occur in the same area as his SKB studies. The SKB report on Respect Distances (Munier et al., 2004) contains a large Appendix entitled "Review of postglacial faulting" by Munier and Fenton. In that appendix they state: " *Although investigations in southern Sweden have yet to describe a convincing example of postglacial faulting, recent investigations by Mörner and his co-workers /Mörner and Tröften, 1993; Tröften and Mörner, 1997; Mörner et al. 2000/ have described widespread, contemporaneous soft-sediment deformation in varved sequences <u>that appear to have been triggered by strong seismic shaking during the late- or post-glacial period</u>*." [underlining added]. But despite this admission by SKB that the features near Forsmark may indicate postglacial faulting near the repository, the matter has not been further investigated.

2.2.4 Critical Neotectonic Claims Relevant to Forsmark

The most critical group of claims refers to paleoearthquakes in northern Uppland quite near the Forsmark site, attributed to reactivated movement on the Singo Fault. Three paleoearthquakes are interpreted at 10,430 vBP, ~8000 vBP, and ~2900 cBP (for the latter, see Appendix 4, based on Mörner, 2009).

NORTHERN UPPLAND EVENTS:
The figure from Mörner, 2012b, shows only the two other on-land faults, not the Singö fault offshore, so implies the "event" was on an on-land fault.

"We have discussed the 7 events in the Hudiksvall area, and we are now down in northern Uppland where 5 evens are recorded; occurring ~10,150 vBP, ~10,000 vBP, 9813 vBP, ~8000 cBP and ~2900 cBP. There is a clear linkage to the old tectonic fracture zones... The 2900 cBP event is a tsunami event traced in off-shore setting, in the coastal zone and in basins 10-20 m up (Mörner, 2008a, 2008b)." (all from Mörner, 2003, p. 55).

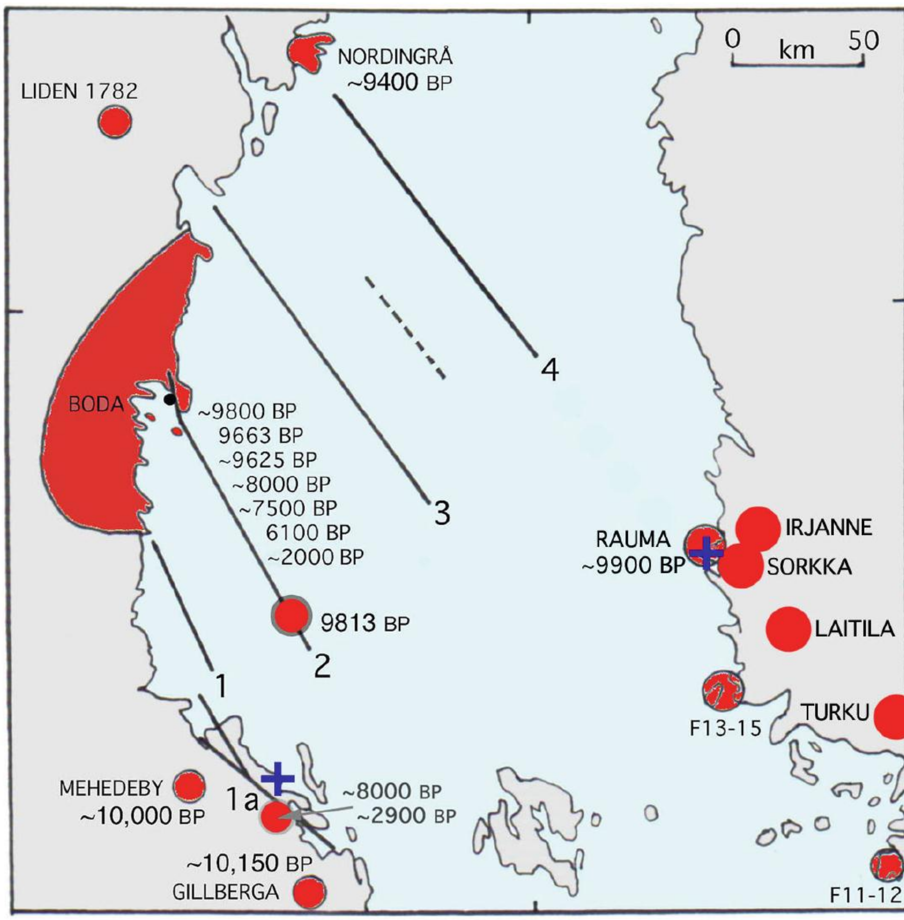

Fig. 8. Map of late Holocene paleoearthquake localities from Morner, 2012a, his Fig. 4. His caption reads: " *The Bothnian Sea region with all the paleoseismic events recorded in Sweden (areas b-c in Fig. 3; Mörner, 2003, 2009) and Finland (Kuivamäki et al., 1998; Koltainen & Hutri, 2004; Mörner, 2010). Blue crosses mark the location of the proposed repositories of high-level nuclear waste at Forsmark (Sweden) and Olkiluoto (Finland)."*

TYPES OF EVIDENCE FOR LARGE EARTHQUAKES NEAR FORSMARK:

1-Faulting

Faults in Bedrock:
Fault scarps in bedrock are a commonly-used indicator of postglacial faulting in formerly glaciated regions. Munier and Fenton, 2004, refer to the difficulty in determining whether the scarp pre-dates or post-dates deglaciation: *"A common argument for recency of faulting has been the 'fresh' nature of bedrock scarps /Lukashov, 1995; Mörner, 2003/. Without accompanying evidence, such as offset of late and postglacial deposits and landforms, such claims must also be called into question. A number of mechanisms, including glacial plucking and endglacial freeze-thaw action can also produce scarps that appear to be 'fresh'.*" The standard practice is to compare the scarp's characteristics to a set of field-based criteria that are indicative of pre-glacial versus post-glacial age (see Munier and Fenton, 2004).

Lagerbäck et al. (2005, p. 21) examined what they called "escarpments" in bedrock in the Forsmark area. They concluded: " *The most prominent of the fresh-looking escarpments and crevasses noted in connection with the aerial photo interpretation were field-checked. However, all these tentative candidates for young fault movement turned out to be more or less strongly glacially abraded, i.e. not late- or postglacial in age."* They imply (but do not state) that the face of the scarp was glacially abraded, which is a citerion for pre-glacial formation of the scarp. In contrast, none of Mörner's publications mention fresh bedrock fault scarps in the Forsmark area. Overall, it does not seem that bedrock fault scarps are common in the Forsmark area, although this needs to be checked with the LiDAR DEM.

Faults in Quaternary Deposits:
Fig. 4 shows a fault exposed in a gravel pit in Mehedeby, 50 km from Forsmark, which displaces glacial deposits (from Mörner, 2003). Lagerbäck et al. (2005) were aware of at least one fault exposure in a gravel pit observed previously, but it is not clear that is was the same exposure as photographed by Mörner. They state: " *The gravel pit with the fault described by /Persson, 1985/ was visited but found to have been restored and no longer in operation. However, in another gravel pit, situated ca 1 km to the south along the Börstil esker, a more or less vertical fault was encountered. The origin of the fault is uncertain but settling of the sediments is probably the most likely interpretation, though a glaciotectonic origin cannot be ruled out as glacial till was found covering the glaciofluvial deposits.*"
Due to the uncertainty about the interpretation of this fault, a directed effort should be made to see if the fault is associated with a lineament on the LiDAR DEM that has the same strike as the fault in the exposure (see Recommendations, Appendix 3, Section 4.3.5).

2-Liquefaction

Lagerbäck and Sundh (2003; SKB P-03-76), Lagerbäck et al. (2004; SKB P-04-123), and Lagerbäck et al. (2005; SKB R-05-51) examined the area of northern Uppland for evidence of postglacial faulting and sediment deformation caused by strong earthquake ground shaking. They excavated numerous trenches and examined many man-made exposures, and observed numerous deformations in late glacial deposits that they called ”water-escape structures.” These deformation features are strikingly similar to features described by other researchers as liquefaction features (see Fig. 9).

Lagerbäck and Sundh (2004) concluded: *”...no significant features related to liquefaction were noticed in any of the trenches.”* Yet a few sentences later they state: ” *Minor faults and water-escape structures were also found in the more fine-grained sediments covering the glaciofluvial deposits. The water escape structures, mainly in the shape of sand filled pipes or more diffuse seepage features, were generally of small magnitude. Most of them originated in the glaciofluvial sandy deposits but reached to and finished at varying depths of the covering sediments, sometimes in the shape of a thin sand layer. It appears that dewatering has occurred repeatedly during the deposition of sediments.”* From these descriptions, it is unlcear to the reviewer how they distinguish between ”water escape” features and ”liquefaction” features, since most liquefaction is expressed as water and sand ”escape.” The features he describes are very similar to those described by Obermeier (2009, p. 532) in the New Madrid Seismic Zone of the USA, which are widely held to be of seismic origin (see Fig. 9). Likewise, his ”water escape structures” are similar to those attributed by Mörner (2003, 2008) to postglacial earthquake shaking in Sweden.

Lagerbäck’s choice of terminology for the Forsmark studies is curious, because he had earlier (1988; SKB TR-88-25; p. 24-27) described seismites at sites near the postglacial fault scarps of northern Sweden. There he inferred that the seismites formed by liquefaction during the same earthquakes that created the scarps. Yet because he could find no postglacial scarps in northern Uppland, he apparently interpreted similar deformation features there as nonseismic. Lagerbäck admitted that the origin of the observed features in Uppland was ambiguous, and that a seismic origin could not be ruled out, but his preferred interpretation was that the features were formed by some types of unspecified nonseismic mechanisms.

The reviewer found Lagerbäck’s interpretation to be rather arbitrary, because it did not attempt to use any criteria in a formal way to distinguish between seismic and non-seismic deformation features. For example, there is a large published literature decribing glacio-tectonic deformation including liquefaction, as listed in the on-line Bibliography of Glaciotectonic References hosted by James Abers of Kansas State University, USA (www.geospectra.net/glatec_biblio/glatec_biblio.htm). Likewise, there is a large published literature on seismic-induced deformation of unconsolidated sediments as observed to have formed in historic earthquakes, and an even larger literature on ”seismites” (for example, the excellent review of Wheeler, 2002, on small soft-sediment deformation features and what causes them). Lagerbäck does not refer to any of these bodies of literature in his three reports.

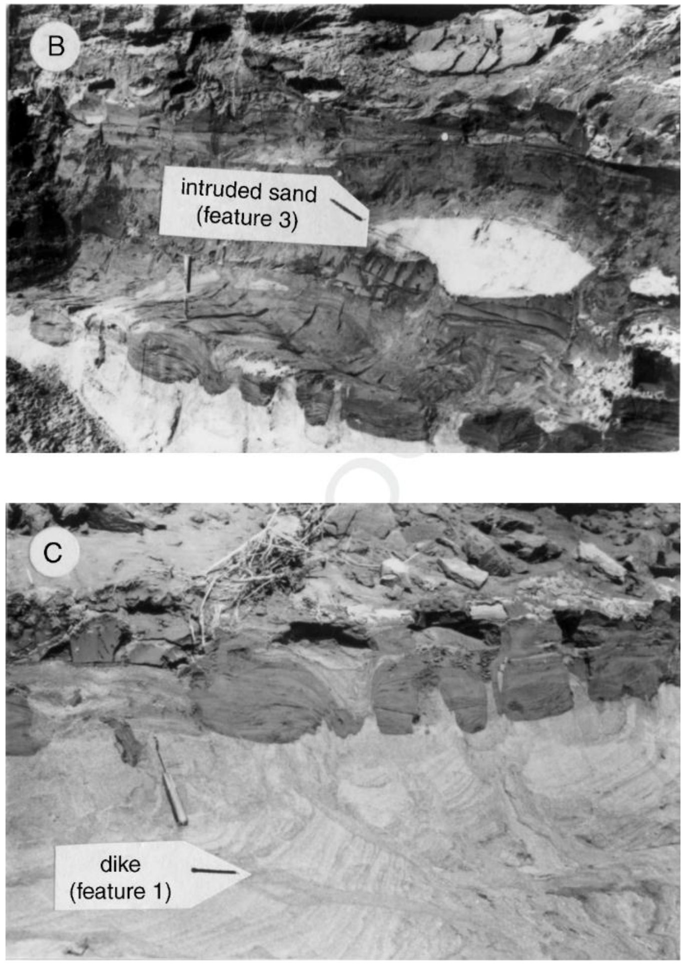

Figure 5-3. Minor faults and water escape structures occur rather frequently in the thick, sandy glaciofluvial deposits at Östansjö (E8). Scale in cm and dm.

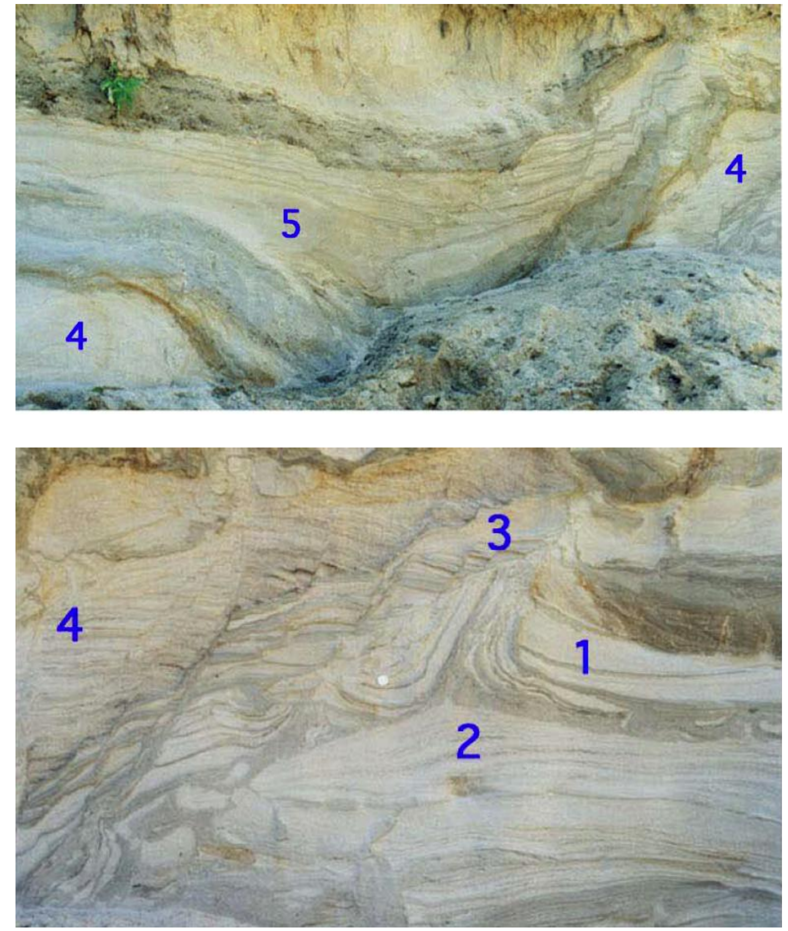

Fig. 9. Comparison of liquefaction features in the New Madrid Seismic Zone, USA (at left; from Obermeier, 2009), with ”water escape features” observed in trenches near Forsmark (center, from Lagerbäck et al., 2004). At right are liquefaction features observed by Mörner (2008) in the Västra Myra gravel pit between Hudiksvall and Uppsala, The numbers 1-5 indicate five interpreted episodes of liquefaction.

3-”shaken beds”

Exposures near Forsmark show deformation features in cohesive clays. Lagerbäck et al., (2005, p. 21) describe these as follows: ”*Strongly contorted and folded sequences of glacial clay were encountered at several localities, but the deformations were interpreted as a result of sliding. At a few localities, sandy-gravelly beds with a tendency to graded bedding were found to intercalate clay sequences. Sliding of clayey deposits as well as coarse sediment intercalating clay sequences later proved to be common phenomena along the gentle slopes of the eskers in the investigation area.” [see Fig. 10].*

Fig. 10. Photograph of strongly contorted and folded clay at Marka (E6), about 25 km south of Forsmark. From Lagerbäck et al., 2004, Figure 5-8. The original caption describes this exposure as ”*Abruptly cut folds in glacial silt at Marka (E6) indicate substantional erosion of a formerly thicker sequence.”*

Lagerbäck et al. (2004, p. 19) continue: ” Evidence of sliding or folding was met within almost all of the trenches. Slabs of clayey and silty deposits have detached along planar failures parallell to the bedding and then slided down“slopes” to cover previously deposited sediments. The slided deposits vary from plates of more or less undisturbed sediments... to strongly folded sequences... or a chaotic mixture of all kinds of sediments without any primary sedimentary structures preserved... In some of the sections there is evidence of at least three episodes of sliding separated by erosional events or by periods of undisturbed sedimentation...

They conclude that the slides were caused by dewatering of the underlying permeable sediments: *”It appears that the slided deposits were easily mobilized when they originally rested on sandy glaciofluvial deposits. The occurrence of dewatering features follows the same pattern and most likely there is a causal relationship between sliding and* *dewatering of underlying sediments. Where resting on glacial till, the fine-grained sediments remained undeformed despite sloping ground. Due to a low porosity and tight packing, glacial till cannot produce an excess of water to initiate and facilitate sliding by lubrication."* However, Lagerbäck et al. do not offer a preferred explanation for the dewatering itseld. They state (p. 42): " *Seismically induced compaction – or purely gravitational settling – of the glaciofluvial deposits may have resulted in a sudden increase in pore-water pressure and expulsion of water, but puncturing of an artesian aquifer in the clay-draped deposit during or after land-upheaval is perhaps an alternative."* In other words, they do not rule out a seismic origin for the water-escape process.

4-"strongly deformed bedrock"

According to Mörner (1985, p. 141), it was De Geer who first suggested that "deglaciation was associated with intense seismic activity that fractured the bedrock." Mörner (2003, p. 225-227) accordingly places much reliance on two areas of "blown-up" bedrock at Gillberga and Mehedeby as indicators of violent seismic shaking. In contrast, Lagerbäck et al. (2005) conclude the opposite: " *Intensely disrupted bedrock, forming masses of angular blocks with interstitial cavities, so-called "boulder caves", occur sporadically in Sweden. Not least among speleologists it is widely believed that these features have a postglacial seismotectonic origin, but credible evidence for this is generally missing. The concept of a "neotectonic" origin of the features is so generally cherished that it is sometimes proclaimed an official truth... Bodagrottorna, located near Iggesund in the province of Hälsingland, is the most impressive of the Swedish boulder caves... According to /Mörner, 2003/ the bedrock fracturing at Boda reflects a major palaeoseismic event in 9,663 BP according to the applied clay-varve chronology, i.e. well after local deglaciation. The deformation of the bedrock is attributed to the interaction of "shaking, rise and fall of the ground at the passing of seismic waves and methane venting" (Mörner, op cit). However, this imaginative process of massive bedrock disruption is hardly demonstrated elsewhere."*

This reviewer visited the Boda Cave site in 2008 and made the following observations. The granite at Boda cave was cut by two prominent vertical joint sets striking perpendicular to each other. Some joint bounded blocks appeared to have been plucked out of the outcrop by ice and redeposited a few meters away. The area of shattered rocks is the summit of a hill, where subglacial drainage was less likely to be present. Instead, a hill in the subglacial surface would be a site where cold-based conditions would be more likely. Cold-based conditions, in turn, increase the probability of plucking. My overall impression was that this boulder field was like several I had seen in Alaska and was not unusual in glaciated terrain. I also wondered why, if this bedrock outcrop had been "blown up" by strong seismic shaking of regional extent, why all the other bedrock outcrops nearby had not also been blown up. My observations during this brief visit do not constitute any type of rigorous, criteria-based test of the seismic hypothesis, but my overall impression was that seismic shaking would not be required to explain the pattern of blocks and intervening void spaces.

5-Anomalous sand deposits overlying an unconformity

Lagerbäck (2004, p. 26) state: *"The upper parts of the sediment sequences appear to be stongly eroded before the sites were raised above the sea. Typical postglacial clay was not met with at any of the sites whereas evenly spread sand or gravel, with a clear*

erosional unconformity to underlying deposits, occurred in the ground surface at most of them. It is reasonable to assume that this sand and gravel correspond to the sandy or gravelly layer separating the postglacial clay from the glacial clay at the coring sites. A distinct, sandy layer between glacial clay and overlying postglacial clay is known to be a characteristic element of the sediment stratigraphy in the region /e.g. Hedenström and Risberg, 2003/...
An erosional unconformity accompanied by a laterally persistant layer of coarse-grained sediments, occurring not only in positions that were exposed to the waves of the ancient sea but also in sheltered positions in the terrain, <u>indicates that potent currents rather than wavewashing were responsible for erosion and deposition</u>. [underlining added].
Strongly shell-bearing sand at one of the coring sites indicates that deposition and preceding erosion took place in rather shallow water during a late stage of the Holocene. A similar conclusion is drawn by Hedenström and Risberg /2003/ who suggest that the flat topography of northern Uppland, in combination with strong currents, has resulted in erosion and transport of fine grained particles towards the deeper parts of the Baltic basin. Together with sliding, this erosion has resulted in an extensive redistribution of sediments and in a substantial levelling of the terrain."

Mörner (2009, p. 182-183) uses a similar set of evidence as proof for a ”major tsunami event.” He states: *”In several lakes in northern Uppland (the Forsmark region), we recorded a major tsunami event (Mörner 2008). A coring and dating programme was conducted in 2004 (N.-A. Mörner, unpublished work). A tsunami bed was recorded in offshore sediments, in shore-zone sediments, and in lake and bog sediments at elevations up to 20 m (or at least 6 m) above the corresponding sea level. A tsunami with a run-up of 20 m implies a significant event...*

We followed the tsunami bed from offshore basins (15 to 35 cm sand and gravel in graded bedding), via lagoonal basins (with 70 cm sandy beds at the clay/gyttja interface) up into lake basins above the corresponding shore (40–50 cm sandy-gravelly beds erosively deposited between the marine clay and lacustrine gyttja). Six C14 dates provide a close age for the offshore and lagoonal sites and a strong erosive effect in the lake basins at least up to a level 5 m above the corresponding shore... The data record a vertical spread of the tsunami beds from 220 m to þ 6 m. The lake and bog coring suggests that the tsunami may have had a run-up of 20 m. This is not yet supported by dates, which suggest only a 6 m run-up...

The Singö Fault zone crosses the area. This zone seems to have been reactivated during the deglacial phase some 10,000 years ago (Mörner 2003, 2004). Therefore, it seems likely that even this 2900 BP event represents a reactivation of this zone. We have recently investigated the tsunami signals in the lake and bog records. Judging from the tsunami run-up, we seem to be dealing with an intensity XII (20 m) or XI (6 m) event with respect to the INQUA intensity scale”.

From the publications cited above it is unclear if Lagerbäck and Mörner are describing the same sand bed and interpreting it differently, or if they are describing sand deposits at two different stratigraphic levels. Without knowing this, it is impossible to evauate the validity of their conflicting interpretations of large postglacial earthquakes in the Forsmark area.

6-Associated seismicity

Lagerbäck et al. (2005) place much emphasis on the absence of historic seismicity in the Forsmark region, compared to that observed near the major postglacial fault scarps of Lapland. Concerning the latter, Lagerbäck and Sundh (2008) note that most of the northern fault scarps are associated with concentrations of active historical seismicity. ”*A tentative relationship between the current seismicity and the major faults in northern Sweden was indicated by Lagerbäck (1977, 1979) and, by means of more accurate data, Arvidsson (1996) showed that about 50% of the recent earthquakes in the region appeared to be associated with these faults*.” Lagerbäck et al. (2005) thus interpret the lack of historic seismicity near Formark as indicating that no postglacial faulting could have occurred there.

However, Munier and Fenton (2004, p. 172) point out that nor every large postglacial fault in Lapland is associated with elevated historic macroseismicity, using the example of the Lansjärv fault. ”*Though Wahlström /Wahlström et al. 1987, 1989/ could not demonstrate any significant spatial correlation between contemporary seismicity and postglacial faults, a recent study by /Arvidsson, 1996/, using improved locations of microearthquakes at the Lansjärv PGF, showed that the microseismic activity in the Lansjärv region is correlated to the Lansjärv fault. This has later been further elaborated /Arvidsson, 2001/ using Mohr- Coulomb calculations that implies that micro-earthquake locations that deviates from the fault surface is the result of the state of stress on the fault.”*

Munier and Fenton (2004) continue (p. 194) to propose that ”*association with contemporary seismicity cannot be used as a criterion for recognizing postglacial faulting...”* because ”*Areas with recognized postglacial faults, however, are almost always in areas where there is insufficient seismograph coverage to accurately locate microseismic activity.* Because no microseismicity studies have been made at Forsmark, it is not possible to say whether there are alignments of microseismicity that might correlate with postglacial faults near Forsmark. The only way that this matter could be conclusively settled is to monitor microearthquakes near Forsmark.

7-Summary

Table 2 summarizes the conflicting interpretations of Lagerbäck and Mörner. Mörner's assertions of seismic origin are emphatic but often lack unambiguous supporting evidence. In contrast, Lagerbäck's interpretations are couched in more cautious terms and often seismic origins are mentioned as possible, or at least not ruled out by any definitive evidence.

Table 2. Summary comparison of Lagerbäck's interpretation of Quaternary deformation near Forsmark, with that of Mörner.

Type of Evidence	Lagerbäck's Interpretation	Mörner's Interpretation
faulting	nonseismic; ” *The origin of the fault is uncertain but settling of the sediments is probably the most likely interpretation...”*	Was seismic
liquefaction	Was caused by ”*Seismically induced compaction – or purely gravitational settling – ...resulted in a sudden*	Was seismic

	increase in pore-water pressure and expulsion of water... puncturing of an artesian aquifer in the clay-draped deposit during or after land-upheaval is perhaps an alternative."	
"shaken beds"	Caused by sliding, which in turn was caused by water escape from underlying sands	Caused by seismic liquefaction
"strongly deformed bedrock"	Interpreted as glacial	Relied on heavily to interpret violent earthquake shaking at Gillberga and Mehedeby, but causative fault was not positively identified (inferred to be Singo fault zone)
Anomalous sand deposits overlying an unconformity	Interpreted as a late glacial transgression prior to crustal rebound	Interpreted as a major tsunami event at 2900 yrBP
Associated seismicity	Interpreted as evidence that no postglacial faulting has occurred	Not mentioned

Conclusions: because SKB reports do not conclusively disprove Mörner's neotectonic claims in any formal way, the seismic hazard analysis for Forsmark should assume that Mörner's assertion of three large-magnitude paleoearthquakes near Forsmark is correct. The causative fault for these three earthquakes is not known, so they should be assumed to have occurred on any of the three local deformation zones (Forsmark, Eckarfjärden, or Singö). In addition, the ages of these events (2900 yr BP, about 10,000 yr BP, and 10,150 to 10,162 yr BP), if correct, show that they are not all associated with rapid deglacial uplift. Thus, the 2900 yr BP event must be assigned to the magnitude-frequency curve of the interglacial time period.

There is an alternative to accepting Mörner's interpretation as the basis recalculating earthquake return times for the prediction of failed canisters at Forsmark in the next 100000 yr to 1000000 yr. That is, to perform a targeted field study of the critical field evidence used in support of the conflicting interpretations of Lagerbäck (no evidence of postglacial faulting) versus Mörner (three large postglacial earthquakes) for the Forsmark area. This review summarizes what that evidence is and where it is, but being a desk study only, obviously cannot determine which interpretation is correct.

2.3- Will repeated smaller earthquakes have any consequences that may have been overlooked by SKB?

The answer to this question really lies outside my area of expertise. I accept the reasoning and conclusions of SKB that earthquakes smaller than M5 will probably not induce shear displacement on fractures above the millimeter or sub-millimeter level.

2.4-Identification and review of relevant publications in the scientific literature about paleoseismology and especially post-glacial earthquakes which have not been used by SKB.
(This may provide a basis for comparison and assessment of SKB's conclusions regarding the significance of earthquakes for repository long-term safety).

2.4.1 References Not Mentioned in SKB Reports; Recognizing Postglacial Fault Scarps in Forested Regions

Since about the year 2000 there have been many instances where previously-undiscovered postglacial fault scarps have been identified in forested regions. These areas had been examined previously with stereoscopic aerial photographs, but the fault scarps could not be detected on those. For example, in the Puget Sound, Washington area, USA, five new Holocene faults have been discovered. Publications are listed chronologically below:

Harding, D.J., and Berghoff, G.S., 2000, Fault scarp detection beneath dense vegetation cover: Airborne lidar mapping of the Seattle fault zone, Bainbridge Island, Washington State: Proceedings of the American Society of Photogrammetry and Remote Sensing Annual Conference, Washington, D.C., May, 2000, 9 p., http://duff.geology.washington.edu/data/raster/lidar/harding.pdf (March 2003).

Johnson, S.Y., Dadisman, S.V., Mosher, D.C., Blakely, R.J., and Childs, J.R., 2001b, Active tectonics of the Devils Mountain fault and related structures, northern Puget Lowland and eastern Strait of Juan de Fuca region, Pacific Northwest: U.S. Geological Survey Professional Paper 1643, 45 p., 2 plates.

Sherrod, B.L., Haeussler, P.J., Wells, R., Troost, K., and Haugerud, R., 2001, Surface rupture in the Seattle fault zone near Bellevue, Washington [abs.]: Seismological Research Letters, v. 72, p. 253.

Sherrod, B.L., 2002, Late Quaternary surface rupture along the Seattle fault zone near Bellevue, Washington: Eos (Transactions, American Geophysical Union), v. 83, n. 47, Fall Meeting Supplement, Abstract S21C-12.

Harding, D.J., Johnson, S.Y., and Haugerud, R.A., 2002, Folding and rupture of an uplifted Holocene marine platform in the Seattle fault zone, Washington, revealed by airborne laser swath mapping: Geological Society of America, Abstracts with Programs, v. 34, no. 5, p. A-107.

Haugerud, R.A., 2002, Lidar evidence for Holocene surface rupture on the Little River fault near Port Angeles, Washington [abstract]: Seismological Research Letters, v. 73, p. 248.

Nelson, A.R., Johnson, S.Y., Wells, R.E., Pezzopane, S.K., Kelsey, H.M., Sherrod, B.L., Bradley, L., Koehler, R.D., III, Bucknam, R.C., Haugerud, R., and Laprade, W.T., 2002, Field and laboratory data from an earthquake history study of the Toe Jam Hill fault, Bainbridge Island, Washington: U.S. Geological Survey Open-File Report 02-0060, http://pubs.usgs.gov/of/2002/ofr-02-0060/ (March 2003).

Nelson, A.R., Johnson, S.Y., Kelsey, H.M., Wells, R.E., Sherrod , B.L., Pezzopane, S.K., Bradley, A., Koehler, R.D., III, and Bucknam, R.C., 2003, Late Holocene earthquakes on the Toe Jam Hill fault, Seattle fault zone, Bainbridge Island, Washington: Geological Society of America Bulletin, v. 115, p. 1388–1403, doi:10.1130 /B25262.1.

Haugerud, R.A., Harding, D.J., Johnson, S.Y., Harless, J.L., Weaver, C.S., and Sherrod, B.L., 2003, High-Resolution Lidar Topography of the Puget Lowland, Washington —A Bonanza for Earth Science: GSA Today, June 2003 Issue, p. 4-10.

Sherrod, B.L., Brocher, T.M., Weaver, C.S., Bucknam, R.C., Blakely, R.J., Kelsey, H.M., Nelson, A.R., and Haugerud, R., 2004, Holocene fault scarps near Tacoma, Washington, USA: Geology, v. 32, p. 9–12, doi:10.1130 /G19914.1.

Muller, J.R. and Harding, D.J., 2007, Using LIDAR Surface Deformation Mapping to Constrain Earthquake Magnitudes on the Seattle Fault in Washington State, USA: Urban Remote Sensing Joint Event, 11-13 April 2007, Paris, p. 1-7.

Sherrod, B.L., Blakely, R.J., Weaver, C.S., Kelsey, H.M., Barnett, E., Liberty, L.M., Meagher, K.L., and Pape, K., 2008, Finding concealed active faults: Extending the southern Whidbey Island fault across the Puget Lowland, Washington: Journal of Geophysical Research, v. 113, B05313, doi:10.1029/2007JB005060.

Witter, R.C., Givler, R.W., and Carson, R.J., 2008, Two post-glacial earthquakes on the Saddle Mountain West fault, southeastern Olympic Peninsula, Washington: Seismological Society of America Bulletin, v. 98, p. 2894–2917, doi:10.1785/0120080127.

Blakely, R.J., Sherrod, B.L., Hughes, J.F., Anderson, M.,Wells, R.E. and Weaver,C.S., 2009, Saddle Mountain fault deformation zone, Olympic Peninsula, Washington: Western boundary of the Seattle uplift: Geosphere, v. 5, no. 2, p. 105-125.

USGS, 2013, Lidar discovers active faults: http://geomaps.wr.usgs.gov/pacnw/resfzplr1.html

The LiDAR DEMs show so much additional topographic detail relevant to geological mapping (both glacial landforms and postglacial faulting) that USGS has begun revising its earlier mapping. For example, Tabor et al. (2011) state ” *The greater resolution and accuracy of the lidar DEM compared to topography constructed from air photo stereo models have much improved the interpretation of geology in this heavily vegetated landscape, especially the distribution and relative age of some surficial deposits.”*
Tabor, R.W., Haugerud, R.A., Haeussler, P.J., and Clark, K.P, 2011, Lidar-revised geologic map of the Wildcat Lake 7.5′ Quadrangle, Kitsap and Mason Counties, Washington: U.S. Geological Survey Scientific Investigations Map 3187, scale 1:24,000, 12 p., http://pubs.usgs.gov/sim/3187/.

Other forested areas of the USA where new Holocene faults have been discovered using LiDAR include the following:

Sierra Nevada Mountains, California and Nevada:

Hunter, L.E., Howle, J.F., Rose, R.S. and Bawden, G.W., 2011, LiDAR-Assisted Identification of an Active Fault near Truckee, California: Bulletin of the Seosmological Society of America, v. 101, no. 3, p. 1162-1181.

Howle, J.F., Bawden, G.W., Schweickert, R.A., Finkel, R.C., Hunter, L.E., Rose, R.S. and von Twisten, B., 2012, Airborne LiDAR analysis and geochronology of faulted glacial moraines in the Tahoe-Sierra frontal fault zone reveal substantial seismic hazards in the Lake Tahoe region, California-Nevada USA: Geological Society of America Bulletin, 2012, doi: 10.1130/B30598.1.

Rocky Mountains, USA:

Thackray, G.D., Rodgers, D.W. and Streutker, D., 2013, Holocene scarp on the Sawtooth fault, central Idaho, USA, documented through lidar topographic analysis: Geology, April 16, 2013, doi: 10.1130/G34095.1.

LiDAR was first flown in northern Europe in 2007 to look for unknown active faults in forested areas; see:

Cunningham, D., Grebby, S., Tansey, K., Gosar, A., and Kastelic, V., 2007, Application of airborne LiDAR to mapping seismogenic faults in forested mountainous terrain, southeastern Alps, Slovenia, Geophysical Research Letters, V. 33, Issue 20, DOI: 10.1029/2006GL027014.

The ”LiDAR Revolution” is now widely accepted in neotectonics and paleoseismology, e.g. Meigs, 2013:

Meigs, A., 2013, Active tectonics and the LiDAR revolution: Lithosphere, v. 5, no. 2, p. 226-229, doi: 10.1130/RF.L004.1.

Thus, the state-of-the-art in identifying and mapping late Pleistocene and Holocene faults, in both forested and unforested regions, has changed within the past 5 years from stereo aerial photography to LiDAR DEMs. I do not know any researcher or top-line consultant who now uses aerial photographs to map active fault traces, particularly in forested areas. They all now use LiDAR DEMs. The relevance of this situation to Forsmark is that SKB’s reports on postglacial faulting were all completed before 2005 and thus none of them used LiDAR DEMs. However, 75% of Sweden is now covered by 2m LiDAR DEMs including the Forsmark area, making it possible to check on the earlier mapping of Lagerback et al. , just to make sure than no postglacial faults (such as small-displacement strike-slip faults, which are difficult to identify) have been overlooked near the repository.

2.4.2 References Not Mentioned in SKB Reports; Probabilistic Fault Displacement Hazard Assessment (PFDHA)

NOTE: IAEA (2010, p. 31-32) recommends that for calculating the future displacement on faults in and near a nuclear facility, including ”distributed faulting”, that the PFDHA method should be used (see references below). That method has not yet been used at Forsmark.

Youngs, R. R., W. J. Arabasz, R. E. Anderson, A. R. Ramelli, J. P. Ake, D. B. Slemmons, J. P. McCalpin, D. I. Doser, C. J. Fridrich, F. H. Swan III, A. M. Rogers, J. C. Yount, L. W. Anderson, K. D. Smith, R. L. Bruhn, L. K. Knuepfer, R. B. Smith, C. M. dePolo, K.W.O’Leary, K. J. Coppersmith, S. K. Pezzopane, D. P. Schwartz, J. W. Whitney, S. S. Olig, and G. R. Toro (2003). A methodology for probabilistic fault displacement hazard analysis (PFDHA), Earthq. Spectra 19, 191–219.

Chen, R.; Petersen, M. D, 2011, Probabilistic fault displacement hazards for the southern San Andreas fault using scenarios and empirical slips: Earthquake Spectra, v. 27, p. 293 – 313.

Petersen, M.D., Dawson, T.E., Chen, R., Cao, T., Wills, C.J., Schwartz, D.P. and Frankel, A.D., 2011, Fault Displacement Hazard for Strike-Slip Faults: Bulletin of the Seismological Society of America, v. 101, p. 805-825. plus electronic supplements at: http://seismosoc.org/publications/BSSA_html/bssa_101-2/2010035-esupp/

Moss, R.E.S. and Ross, Z.E., 2011 Probabilistic Fault Displacement Hazard Analysis for Reverse Faults Bulletin of the Seismological Society of America, August 2011, v. 101, p. 1542-1553, doi:10.1785/0120100248

PSHA is now used in many seismic hazard assessments:
1-Nuclear projects, for example IAEA,
2- Utility projects, for example Chen and Peterson, 2011:
Chen, R.; Petersen, M. D, 2011, Probabilistic fault displacement hazards for the southern San Andreas fault using scenarios and empirical slips: Earthquake Spectra, v. 27, p. 293 – 313.
2- Petroleum development projects (Angell et al., 2003).
Angell, M.M., Hamson, K., Swan, F.H., Youngs, R. And Abramson, H., 2003, Probabilistic Fault Displacement Hazard Assessment For Flowlines and Export Pipelines, Mad Dog and Atlantis Field Developments, Deepwater Gulf of Mexico: Offshore Technology Conference, 5 May-8 May 2003, Houston, Texas, ISBN 978-1-55563-250-2.

The deterministic approach used by SKB to predict fault displacements at Forsmark using 3DEC is very different from PFDHA. PFDHA, like PSHA for ground motion, was designed by seismologists and is grounded in seismology (where the earthquake displacements originate) rather than in engineering, which is more concerned with the effects of earthquakes on the built environment. Given its seismology-centric origin, PFDHA first determines the locations and dimensions of primary seismic sources (active faults), and secondly determines their seismic source characteristics (maximum magnitude and magnitude-frequency relationships, i.e., the Gutenberg-Richter curve). Once these have been established, PFDHA relies on the statistics of how displacement in historic surface ruptures varies along the strike of the primary (seismogenic) fault, and how secondary (distributed) displacements occur away from the primary rupture with less displacement.

2.5-Respect Distances

"*The respect distance is the perpendicular distance from a deformation zone that defines the volume within which deposition of canisters is prohibited, due to anticipitated, future seismic effects on canister integrity"* (Definition from Munier and Hokmark, 2004, SKB R-04-17)*.*

How Respect Distances Control the Final Repository Layout (from SKB TR-11-01, p. 473)
The text excerpt below summarizes how respect distances were defined and applied to the repository design (see Fig. 11):
"...deformation zones [that intersect the repository] *were divided into two categories: zones 3–5 km* [long] *able to host minor earthquakes (≤ M5.5), and zones exceeding 5 km in trace length which are able to host large earthquakes (> M5.5). If both respect distances and rejection criteria ... are applied, the canisters will avoid the impact of earthquakes even occurring on zones intersecting portions of the repository volume. For this to be valid, however, the following need to be ensured...*

1. No canister is placed within the damage zone of a deformation zone (fault). The damage zone of a fault is the volume of rock within which the zone may grow... This is ensured by repository design... and using the site descriptive models... The boundaries of the deformation zones will be delineated with further detail and less uncertainty during underground mapping and modelling.

2. No canister is intersected by any fracture that is mechanically connected (i.e. splay) to any deformation zone. The risk for this to occur is lessened by the use of 100 m respect distances... to the boundary of the deformation zone, defined to include the damage zone... There is an uncertainty, however, as to whether this respect distance is sufficient to include all splays. The splays are smaller than the deterministically modelled zones and ought to consist of fractures or *small deformation zones with radii in the order of about 100–500 m. Hence most of them will be detected and characterised by underground investigations... It is, however, important, during underground investigations, to ensure that such splays do not intersect any deposition hole.*

3. Deposition hole rejection criteria are applied to the rock volumes beyond the 100 m respect distance which depend on:
a. the size of the nearest deformation zone (i.e. the maximum size of anticipated earthquake, should it occur),
b. the distance to the deformation zone,
c. the orientation of the fracture intersecting the deposition hole,
d. the size of the fracture intersecting the deposition hole."

SKB also mentions that: " *... it may be possible to reduce the respect distance of 100 m to some deformation zones based on an a site-specific detailed and individual assessment of the actual extent of the damage zone including splays combined with revised criteria for what fractures should be avoided in deposition holes.*" (TR-11-01, p. 828).

The respect distance concept was evidently conceived without reference to the issue of distributed faulting, as understood in PFDHA. Certainly, use of the 100 m respect distances from faults > 3 km long will reduce the possibility of canister rupture, as opposed to not having a respect distance. However, it is not clear to this reviewer that honoring the 100 m respect distances will prevent some unanticipated shear displacements beyond the respect distance, due to induced distributed faulting.

SKB mentions that (TR-11-01, p. 147; see Fig. 11) " *Within the target volume there are only four deformation zones that are large enough to potentially require a respect distance: the three steeply dipping zones ZFMENE060A, ZFMENE062 and ZFMNW0123, and the gently dipping zone ZFMA2... Furthermore, large fractures are not allowed to intersect deposition holes in accordance with the Extended Full Perimeter Intersection Criterion (EFPC).* "

2.5.1 Coseismic Fracturing and Faulting

SKB Report TR-11-01, vol. 2, states: "*An integrated evaluation of the response of the buffer and canister to rock shear has led to the criterion that the shear movement should not exceed 5 cm (safety function R3b), and that the shear velocity should be less than 1 m/s (safety function R3c)."*

In order to compute the number of canister failures, SKB further assumes the following (SKB TR-11-01, p. 549): *"The issues relating to canister failure due to shear load are as follows.*
• *The occurrence of earthquakes of a sufficient magnitude to cause secondary shear movements in fractures intersecting deposition holes.*
• *The extent of detrimental secondary shear movements given sufficiently large earthquakes.*
• *The impact of secondary shear movements on the buffer/canister system*.

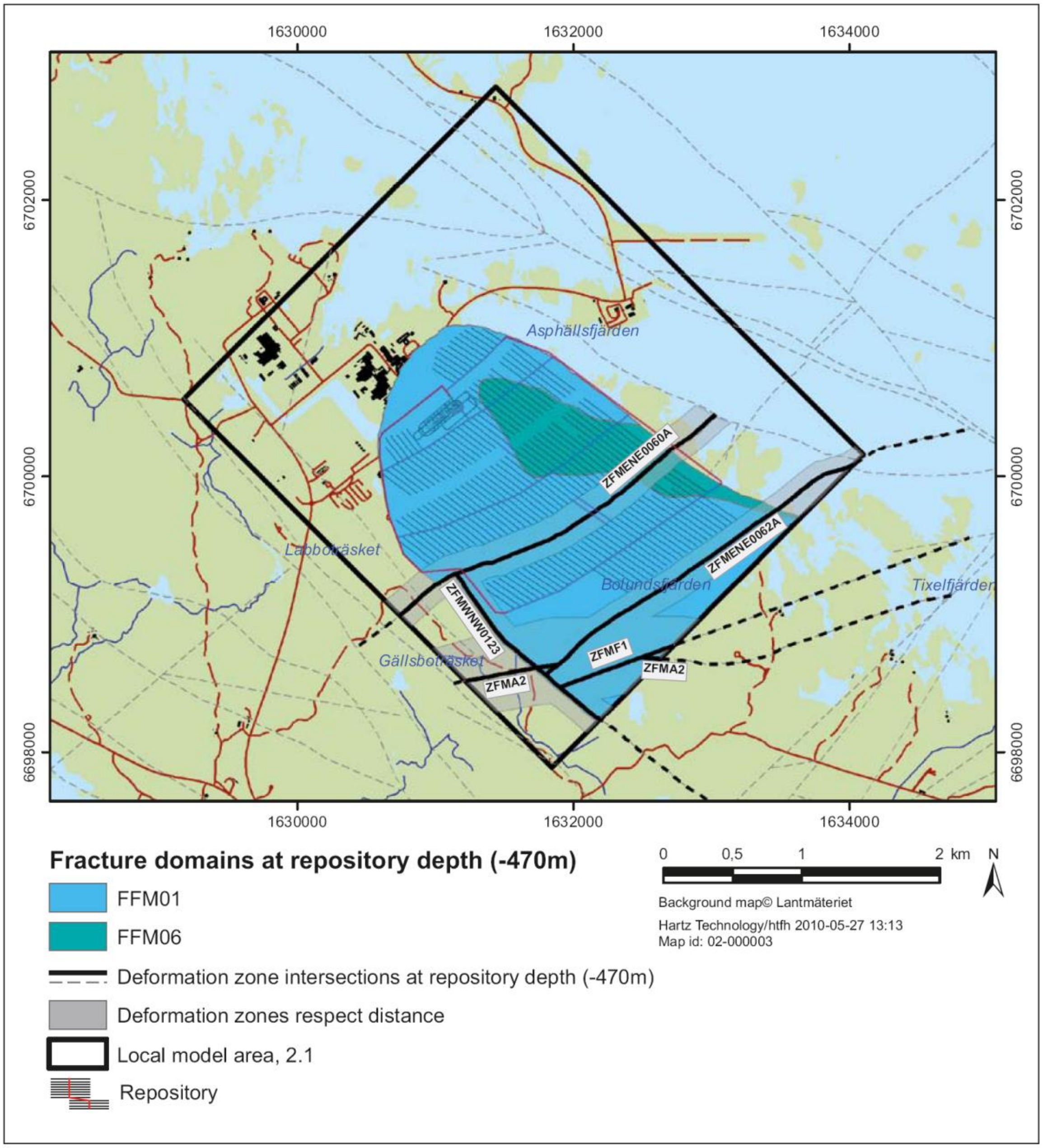

Fig. 11. Reference design layout for the repository at Forsmark, showing respect distances and the deformation zones requiring the respect distances. Fig. 5-6 from SKB TR-11-01.

Note that the first two factors are the temporal frequency of earthquakes and the spatial extent of secondary shear movements. Both of these factors are explicitly addressed by the PFDHA process, which was not used at Forsmark. Instead their earthquake frequencies were assumed to be at the same rate as in the 650 km-radius area, and their spatial extent was claculated by rock mechanics modeling. Their final conclusions about canister failure are thus: ” *During a glacial cycle, it is estimated that between 8.3·10–4 and 5.7·10–3 canisters may fail. For the 1,000,000-year time frame, we assume at maximum two seismic events and estimate, using the most pessimistic way* *of accounting for the combined effects of both, that between 8.1·10–3 and 6.9·10–2 canisters may be sheared 50 mm or more. As the numbers of failed canisters are substantially less than one, they can be interpreted as the probabilities of a canister failure occurring over the cited time frames.(*SKB TR-11-01, p. 536).

Criticisms of the Respect Distance Approach:
There are two general ciriticisms that can be made of the respect distance approach. The first is that it assumes that future shear displacements caused by earthquakes can only occur on preexisting fractures. The second is that there is empirical evidence that larger displacements than SKB predicts have occured off the primary (coseismic) fault traces.

As to first criticism, Lagerbäck (1988, p. 1) observed in Lapland that: ”*Often the bedrock shows signs of older tectonic influence, and it seems that the* [postglacial] *faults largely have been released along existing zones of weakness in the bedrock. However, striking exceptions, with fracturing through unaltered rock, have been found in several places.”* In addition, Lagerbäck and Witschard (1983) state that crystalline bedrock had been broken (faulted) in northern Sweden along ”new” fault planes that had no evidence of prior movement. These observations indicate that new fractures in intact rock may form during earthquakes, and thus displacement is not limited to preexisting, mappable fractures, as assumed by SKB.

The second criticism is based on the occurrence of secondary ”distributed” faulting that has formed meters to kilometers away from the main fault trace in historic earthquakes worldwide. The outlines of this process and its relevance to Forsmark are described in the next section. In Sweden, Mörner (unpublished PDF presentation, 2011) contends that: ”*At the 10,430 BP event in the Stockholm region, a 6-8 m lateral fault was formed 1 km from the primary fault.”* This value, if correct, is much greater than the displacement predicted 1 km from a source fault using the rock mechanics approach.

THE QUESTION OF DISTRIBUTED FAULTING
In all the SKB reports reviewed the only type of faulting discussed was primary seismogenic faulting. But many field studies after surface-rupturing earthquakes in the past few decades have described simultaneous displacement on faults various distances away from the primary fault rupture. These faults are called ”distributed faults” in the terminology of PFDHA (Youngs et al., 2003). IAEA (2010, p. 31-32) recommends that for calculating the future displacement on faults in and near a nuclear facility, including ”distributed faulting”, that the PFDHA method should be used (see references in Section 2.4.2). That method has not yet been used at Forsmark, but it has relevance.

Definitions from Youngs et al., 2003:
Principal faulting is slip along the main plane (or planes) of crustal weakness responsible for the release of seismic energy during the earthquake. Where the principal fault rupture extends to the surface, it may be represented by displacement along a single narrow trace or over a zone that may range from a few to many meters wide. The faults of concern are those that may produce earthquakes (i.e., are directly related to the primary source of energy release). Principal faulting is the type of fault displacement hazard that has typically been evaluated in the past.

Distributed faulting is defined as displacement that occurs on other faults, shears, or fractures in the vicinity of the principal rupture in response to the principal faulting. It is expected that distributed faulting will be discontinuous in nature and occurs over a zone that may extend outward several tens of meters to many kilometers from the principal rupture. A fault that can produce principal rupture may also undergo distributed faulting in response to principal rupture on other faults.

Fig. 12 shows the amount of displacement on distributed faults during five normal-faulting earthquakes in the Basin and Range Province of the USA (Stepp et al., 2001).

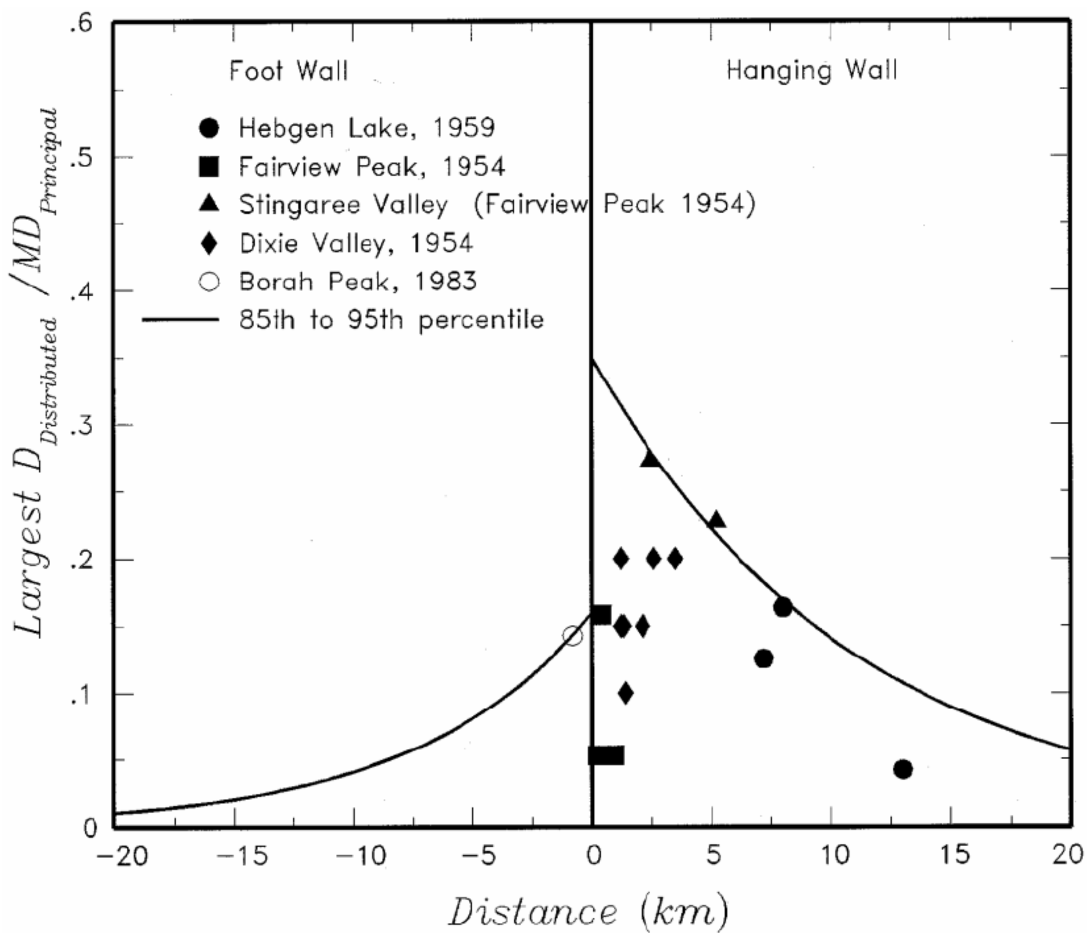

Fig. 12. Data for larger displacements on distributed ruptures divided by the maximum displacement on the principal rupture, for a set of five normal fault surface-ruptures in the USA. The curves represent a high percentile (e.g., 85th to 95th) of the distribution for $D_{distributed}/MD_{principal}$. The data were compiled by C. dePolo for the Yucca Mountain PSHA (Stepp et al., 2001).

Petersen et al. (2011), in their study of distributed faulting during strike-slip earthquakes, distinguish two types of distributed faulting. ”Connected faults” merge with the primary fault trace at the surface, whereas ”triggered faults” do not. They further remark that: ”*Principal faults in this analysis are more mature faults, while distributed faults may be at* *earlier stages of development. Triggered faults are assumed to occur on mature strands that are related to principal faulting. Therefore, the physics governing the deformation of triggered ruptures would, most likely, be more similar to that operating on principal faults."* Finally, Moss and Ross, 2011, performed a PFDHA analysis for reverse faults, but unfortunately only analyzed principal faulting, not distributed faulting.

Petersen et al. (2011) analyzed the patterns of primary and distributed faulting in eight historic strike-slip earthquakes (5 in California and 3 elsewhere), ranging from M6.5 to M7.6. The off-fault displacement data developed for their analysis were primarily based on perpendicular distances from the mapped fault trace to the nearest rupture but also include a few secondary ruptures off the ends of the faults. They demonstrate that distributed faulting extended as far as 12 km away from the primary fault (Figs. 13 and 14). They mention that: "*35-cm displacements can be triggered on faults more than 10 km away from the principal fault."* (p. 809). They summarize as follows: "*Displacements off the principal fault (distributed faults) decay slightly at distances out to several kilometers... Furthermore, displacements also correlate with magnitude. Figure 14 shows that rupture displacements for the large magnitude events cause the largest displacements, while smaller magnitude events cause displacements that are generally lower. However, these correlations are weak, and in earlier versions of this analysis, we did not account for any decay with distance."*

We can compare the maximum shear displacements predicted for fractures 2 km from the M6.1 earthquake (from figure 14), with the observed displacements of distributed faults 2 km away from an M6.5 earthquake (Fig. 15). At a source-to-site distance of 2 km the rock mechanics approach predicts a maximum shear displacement of 0.0022 m, or 0.22 cm. In contrast, observed distributed faulting 2 km from the primary fault in M6.5 historic earthquakes has a mean displacement of 2.7 cm (12 times the rock mechanics value) and a maximum displacement of around 15 cm (68 times larger than the rock mechanics value) (see Fig. 15).

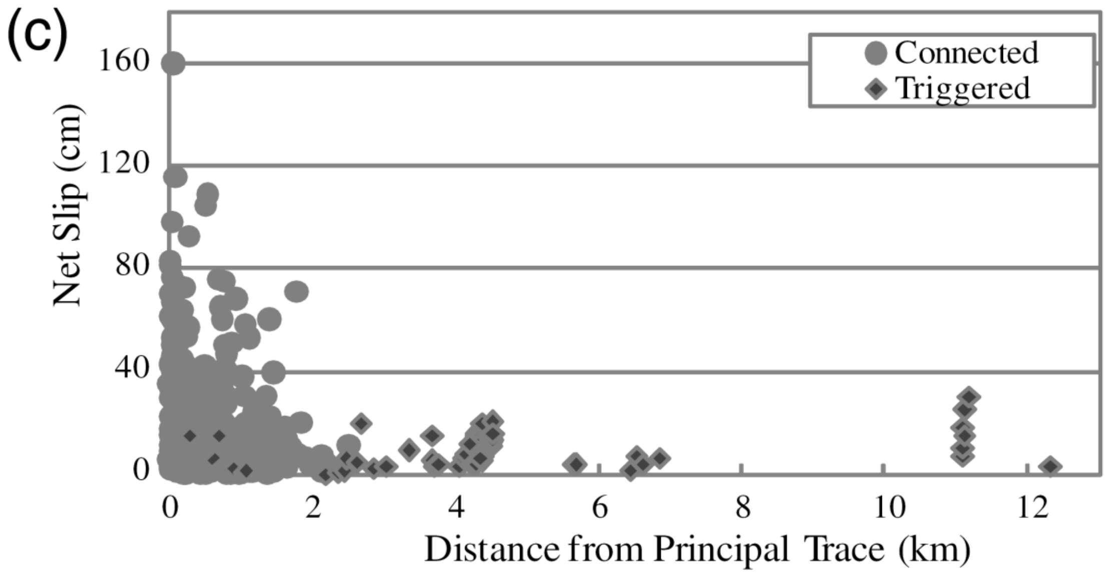

Fig. 13. Net slip on distributed faults during strike-slip surface ruptures, as a function of distance from the primary fault. Triggered faulting dominates beyond about 2 km from the primary fault. From Petersen et al., 2011, Fig. 2.

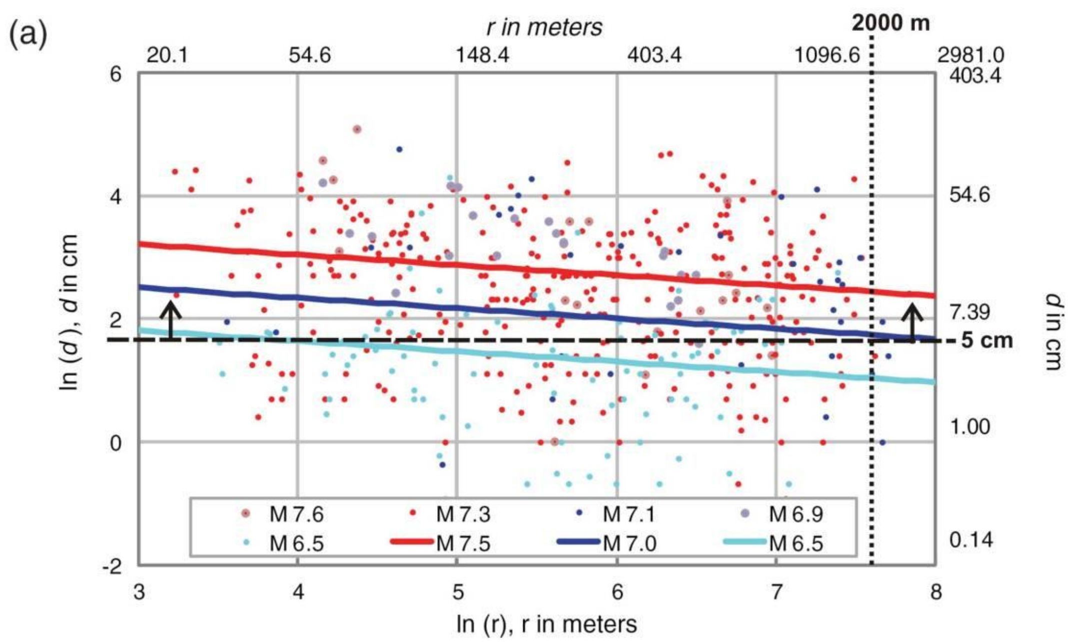

Fig. 14. Displacement on distributed fault traces during strike-slip surface ruptures, as a function of distance from the primary fault. The 5 cm displacement criterion of SKB has been added to the graph. The least-squares regression lines are shown for M6.5 (light blue), M7 (dark blue), and M7.5 (red). These lines indicate mean displacements >5 cm for M7 and M7.5 earthquakes up to a distance of 3 km from the primary fault. For M6.5 the regression line falls below 5 cm displacement at a distance of ca. 55 m from the primary fault. However, note that many individual displacement measurements from M6.5 ruptures (light blue points) are larger than 5 cm as far as 1.5 km away from the primary fault. From Petersen et al., 2011, Fig. 7.

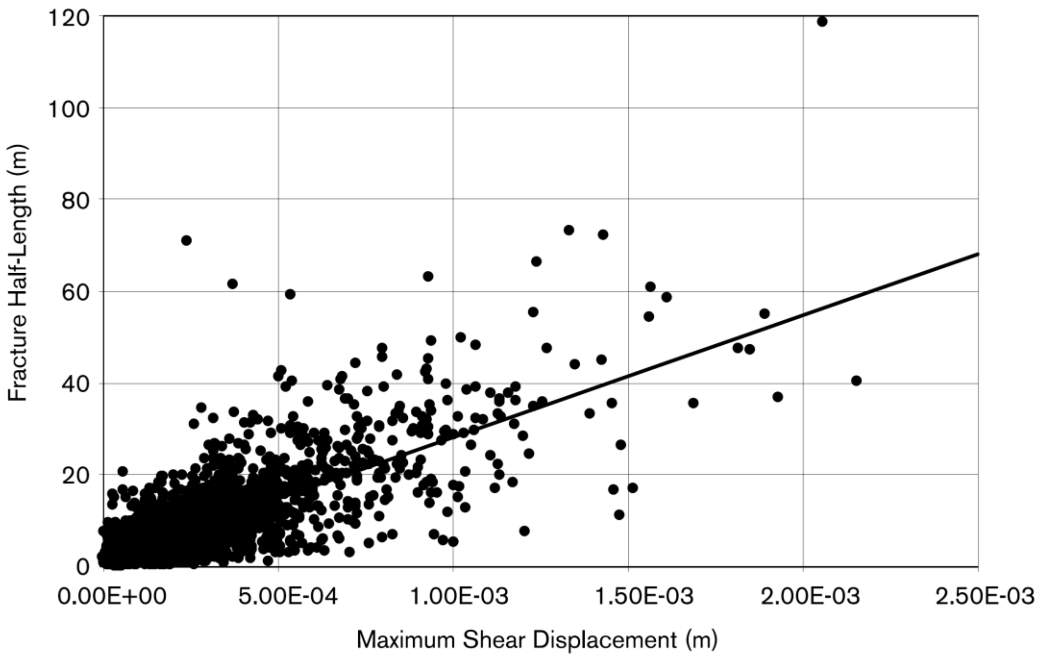

Fig. 15. Induced shear displacements in population of target fractures within box-shaped rock volume at 2 km distance from a fault generating a M6.1 strike-slip earthquake /from La Pointe et al. 1997/.

One could argue that the cause of this large discrepancy is the different magnitudes of earthquakes (M6.1 versus M6.5). However, Munier and Hökmark (2004, p. 32) concluded that the static effects of earthquakes on ”target fractures” will be independent of earthquake magnitude on the primary source fault. So if the discrepancy is not attributable to magnitude, what is causing it?

My personal opinion is that the rock mechanics approach to calculating displacement on target fractures is just too simplistic compared to the real complexity of what happens during a large earthquake rupturing through a heterogenous, previously faulted crust. Throughout the description of the rock mechanics process there are references to numerous smplifications and assumptions made. Munier and Hökmark (2004, p. 6) state that: ”Many of the simplifications and assumptions used in modelling are conservative.” Yet, if the assumptions are overwhelmingly conservative, why do the models predict displacements so much smaller than those observed in actual earthquakes?

As previously mentioned, distributed faulting in historic earthquakes has been measured with decimeter displacements more than 10 km from the primary source fault. What this means for Forsmark is that distributed faulting could occur within the repository's 5 km radius from primary faults outside of the 5 km radius. For example, if M7 earthquakes on local faults induce distributed faulting with >5 cm displacement 10 km away from the primary fault, then any primary fault less than 15 km from the center of the repository could cause >5 cm displacements within the 5 km radius. Fig. 16. shows this situation graphically. Faults capable of generating only M6 or M6.5 earthquakes would have to be closer to the repository before they could induce >5 cm displacements within the 5 km radius. Conversely, faults capable of generating M7.5 or larger earthquakes could lie farther than 15 km from the repository center and still be capable of inducing >5 cm displacements within the 5 km radius, according to papers published on PFDHA.

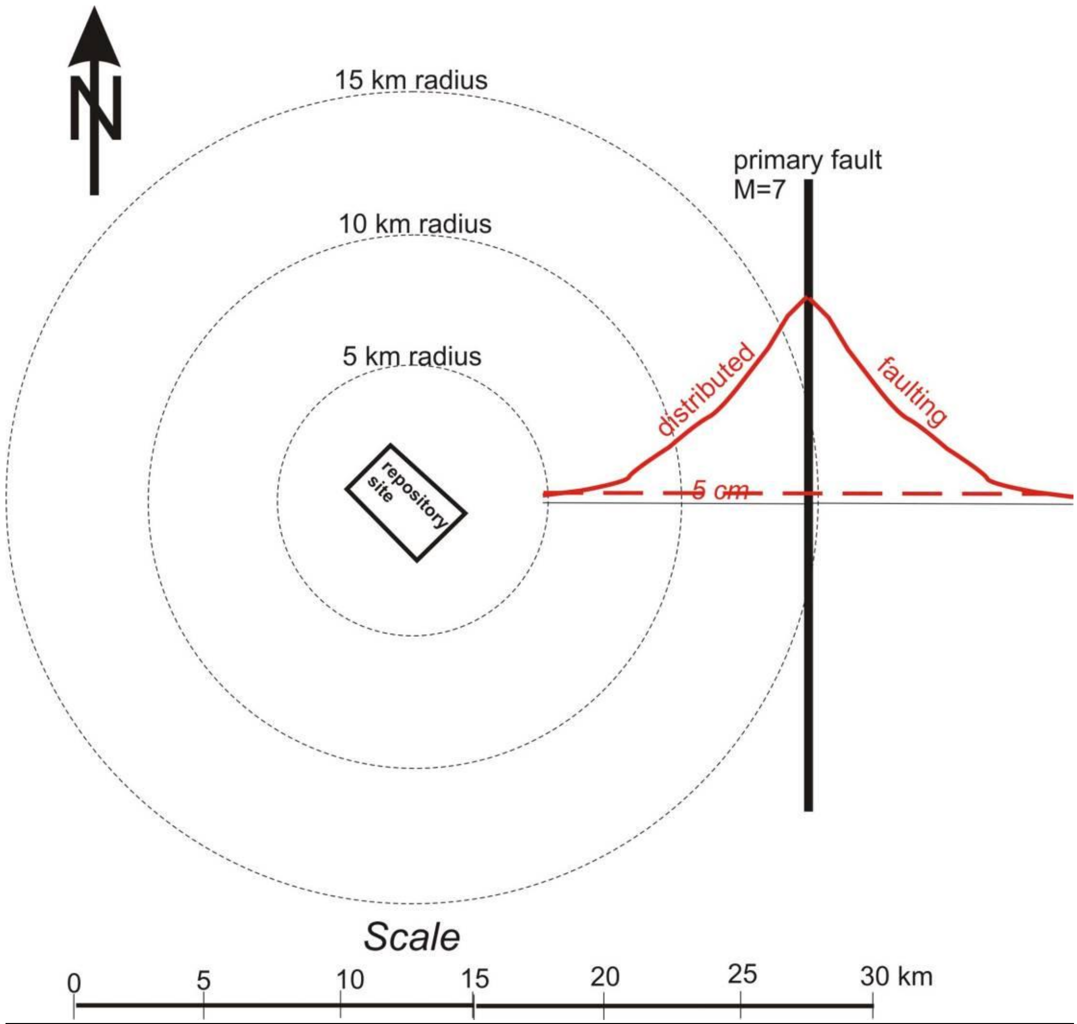

Fig. 16. Schematic diagram showing the effects of distributed faulting on the Forsmark repository due to a nearby M7 earthquake. The example shows a primary fault (thick black line) capable of producing M7 earthquakes, and its associated envelope curve of distributed displacements, including up to 5 cm displacement 10 km away from the fault (red line; schematic, but based generally on data from Youngs et al., 2003 and Petersen et al, 2011). Any fault that can generate an M7 earthquake and is closer than 15 km to the repository center (i.e., less than 10 km from the 5 km radius circle) could be accompanied by distributed faulting of >5 cm within the 5 km radius circle.

What this means for seismic assessment at Forsmark, is that it is not sufficient to calculate the frequency of M5 and larger earthquakes only within the area of the 5 km radius. There is an additional hazard arising from distributed faulting from M>5 earthquakes that occur outside of the 5 km radius. For example, the relevant frequency of M7 earthquakes to calculate for canister failures is the frequency of M7 events within the area of a 15 km radius around the repository, because any such events could induce >5 cm displacements within the 5 km radius (see Fig. 16). Note that the area of a 15 km-radius circle is 9 times larger than the area of a 5 km-radius circle. Thus, the frequency of M7 earthquakes that could affect the repository will be 9 times larger than the frequency previously calculated to occur just within the 5 km radius. Similar areas can be made for earthquakes larger and smaller than M7.

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4. APPENDICES

4.1 APPENDIX 1: DESCRIPTION OF THE ACHIEVED COVERAGE OF SKB REPORTS

The following mandatory SKB reports (or sections of reports) were reviewed:
1-The main safety assessment SR-Site report SKB TR-11-01, relevant sections
2-SKB TR-08-11, Updated 2011-10, Effects of large earthquakes on a KBS-3 repository, Section 1, 3.1, 4.8, 4.9, 6.1, 6.6, 7.3, 8.4 and 8.5
3-SKB TR-10-48, Geosphere process report for the safety assessment SR-Site, Section 4.1.1-4.1.3, 4.3.7
4-SKB TR-09-15, Stress evolution and fault stability during the Weichselian glacial cycle, Section 9, 10 and 11
5-SKB R-06-67, Earthquake activity in Sweden, Section 4.4
6-SKB R-04-17, Respect distances, Section 3.5

The following other reports were reviewed:
Lagerbäck R. and Sundh M., 2008, Early Holocene faulting and paleoseismicity in northern Sweden: Geological Survey of Sweden, publication C386.
All the papers by Morner listed in the Reference List, including:
Mörner, N-A. 2005. An investigation and catalogue of paleoseismology in Sweden. Tectonophysics 408, 265-307.

4.2 APPENDIX 2: LIST OF SUGGESTED ESSENTIAL QUESTIONS TO SKB REQUIRING CLARIFICATIONS, COMPLEMENTARY INFORMATION, COMPLEMENTARY DATA, ETC.

Q1: Has SKB performed a field study to resolve the differing interpretations (Lagerbäck versus Mörner) with respect to large postglacial earthquakes having occurred near Forsmark?

Q2: Has SKB performed any empirical ”reality checks” on its predicted shear displacements on target fractures, using real data from historic earthquakes? This can be found in the literature on PFDHA.

Q3: Has SKB attempted to map geomorphology and structures (lineaments) near the Forsmark site with the new LiDAR DEMs of the NNH?

Q4: Is the existing bathymetric data for offshore at Forsmark up to the technological standard used, for example, in the study of the Shoreline Fault in California, USA, for the Diablo Canyon NPP?

4.3 APPENDIX 3: RECOMMENDATIONS TO SSM FOR THE CONTINUATION OF THE REVIEW AFTER THE PRESENT ASSIGNMENT

4.3.1-Update the survey for late- and post-glacial faults of Lagerbäck et al (2005) with detailed geomorphological mapping based on LiDAR DEMs of the New National Elevation Model (NNH).

The search for late- and post-glacial faults performed in 2002-2004 in the Forsmark region was based on interpretation of stereoscopic aerial photographs. However, subsequent to the early 2000s, the state-of-the-art for geomorphological mapping in forested regions (including mapping of active faults) has shifted from aerial photographs to very detailed digital elevation models (DEMs) based on airborne laser swath mapping (ALSM, often abbreviated as LiDAR). The main advantage of LiDAR DEMs is not so much their resolution, as the fact that the bare-earth DEM accurately portrays the details of the ground surface beneath the forest canopy, something that is often obscured in aerial photographs.

This shift in preferred technique was acknowledged in Sweden in 2013, when Peterson and Smith (2013a) stated "*Landforms that are not visible in aerial photographs, due to forest cover or size, stand out clearly in the LiDAR DEM. This makes LiDAR images the ideal medium for mapping geomorphology…As NNH* [New National Elevation Model] *data becomes available the Geological Survey of Sweden (SGU) plans to map the geomorphology of Sweden, producing a digital nationwide database generated from one uniform dataset and using one conceptual model*." Fig. A3-1 shows the areas of LiDAR DEM coverage as of 2013; about 75% of Sweden has now been covered, including the Forsmark region.

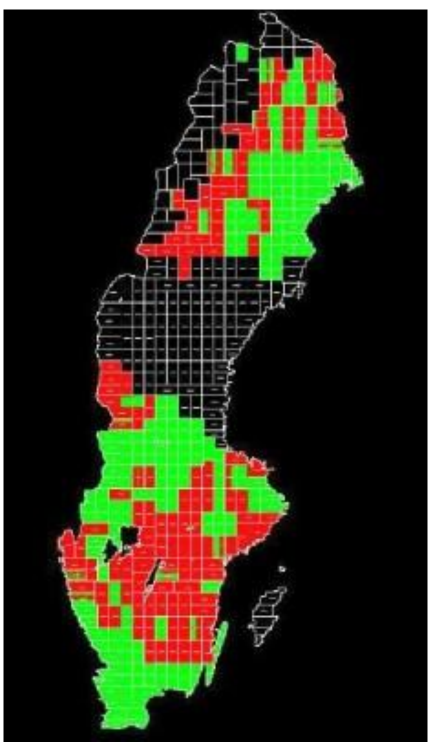

Fig. A3-1. Status map of LiDAR DEMs in the New National Elevation Model as of 2013.

The reason the reviewer is recommending that new geomorphological mapping be done in the Forsmark region, is because of a controversy about the occurrence of postglacial faulting near the site. Lagerbäck et al. (2005) could find no evidence of postglacial fault movement near the site. In contrast, Mörner (2013) stated "*underground repositories for high-level nuclear waste are under final assessment in Sweden and partly already under construction in Finland. In both cases, the seismic hazard assessments are quite badly performed by the responsible firms (SKB and Posiva)… [The SKB] study (Lagerbäck et al., 2005) includes extensive trenching (recording multiple deformational structures) but with a very weak interpretation."* In another publication Mörner (2012) states that there is evidence for 5 large postglacial earthquakes in the Forsmark region (Fig. 2a), probably associated with the Eckarfjärden or Forsmark Deformation Zones (DZ).

One way to settle this controversy is to make a detailed geomorphological map of the Forsmark area, showing all the types of glacial landforms identified by Peterson and Smith (2013b). These landforms should record any postglacial faulting movement as linear anomalies displacing the landform; for example, along the mapped traces of the Eckarfjärden or Formark Deformation Zones. Alternatively, if the detailed mapping of landforms from the LiDAR DEM does not reveal any such linear anomalies, even at the 2 m scale of the DEM, then that is powerful evidence that the aforementioned faults have not been active in postglacial time. The recommended geomorphological map must extend at least 50 km from Forsmark so that it includes: (1) the sites of Quaternary deformation described by Mörner and Gillberga and Mehedeby, including the fault shown in Fig. 4 of this report; and (2) the extent of the Eckarfjärden and Forsmark deformation zones on land, and the area where the Singö fault would come on-land north of Fordsmark.

According to Peterson and Smith (2013a), LiDAR mapping was already tried at Forsmark:
"For both sites, extensive Quaternary cover limited the identification of lineaments from topography. LIDAR mapping, which was used for identification of minor deformation zones down to a length scale of 100 m at the Laxemar site, was judged to be unsuitable for Forsmark for the same reason." These comments indicate that the interpreters of LiDAR were only looking for lineaments in areas of bedrock outcrops, not in areas of Quaternary deposits. But the proven utility of LiDAR for mapping postglacial faults in other countries has resulted from its ability to reveal fault scarps and other linear anomalies in Quaternary deposits (see references cited in Section 2.4.1). In this case, the LiDAR interpreter would be looking for either a fault scarp with vertical relief (indicating reverse faulting), or a lineament across which small-scale landforms had been shifted laterally (indicating strike-slip faulting). The latter would be more difficult to see, or to distinguish from erosional/depositional landforms, and would require a high-resolution DEM (2 m grid size or smaller). Recent fault mapping in the USA has used DEMs as with grid sizes as small as 0.5 m (see the EarthScope Northern California LiDAR Project at www.opentopo.org, which contains complete DEM coverage of the northern (forested) trace of the San Andreas fault with 0.5 m grid size).

4.3.2 **-Update bathymetric surveys of the Singö fault zone.**

The Forsmark site is located very close to the Gulf of Bothnia, so much of the 200 km radius around the site is submerged. The submerged area includes the Singö fault zone, about which Mörner (2009) states the following: "*This zone seems to have been reactivated during the deglacial phase some 10,000 years ago (Mörner 2003, 2004). Therefore, it seems likely that even this 2900 BP* [tsunami] *event represents a reactivation of this zone. We have recently investigated the tsunami signals in the lake and bog records. Judging from the tsunami run-up, we seem to be dealing with an intensity XII (20 m) or XI (6 m) event with respect to the INQUA intensity scale*."

If the Singö fault experienced displacement as young as 2900 yr BP, confirmatory evidence should be preserved along its submerged fault trace. This evidence could be identified on a detailed bathymetric survey of the fault zone, as is now commonly practiced for nuclear power plants (NPPs). For example, recent studies of the Diablo Canyon NPP in California, USA, have identified the closest potentially active fault (the Shoreline fault) to lie about 600 m offshore of the plant. This young-looking fault was discovered in 2010 by a detailed bathymetric survey in the form of a 2 m digital elevation model (see the detailed report by the NPP operator, Pacific Gas & Electric; http://www.pge.com/en/myhome/edusafety/systemworks/dcpp/shorelinereport/index.page). The chapter describing the collection and interpretation of the multibeam survey is given at: http://www.pge.com/includes/docs/pdfs/shared/edusafety/systemworks/dcpp/19_SFZ_Appendix_F_Multibeam_Data.pdf

Evidently bathymetric data already exist near Forsmark. Peterson and Smith (2013b, Table 2) describe this data as "High-precision bathymetry." They further state: "*For Forsmark, access to high-precision bathymetric data improved detection of lineaments in the seabed. However, even with these data, the interpreted lineaments are noticeably more sparse offshore than onshore.*" This statement suggests that the bathymetric DEM is not as detailed as the LiDAR DEM for onshore areas; that is, it has less than a 2 m grid size.

My recommendation is to obtain high-resolution bathymetry of the seafloor along the Singö fault zone that conforms to the technological state-of-the-art, and is roughly comparable to the 2 m LiDAR DEMs of onshore areas provided by the New National Elevation dataset. The specific purpose of acquiring and interpretaing this data is to confirm or disprove that postglacial faulting has occurred on faults currently submerged near Forsmark.

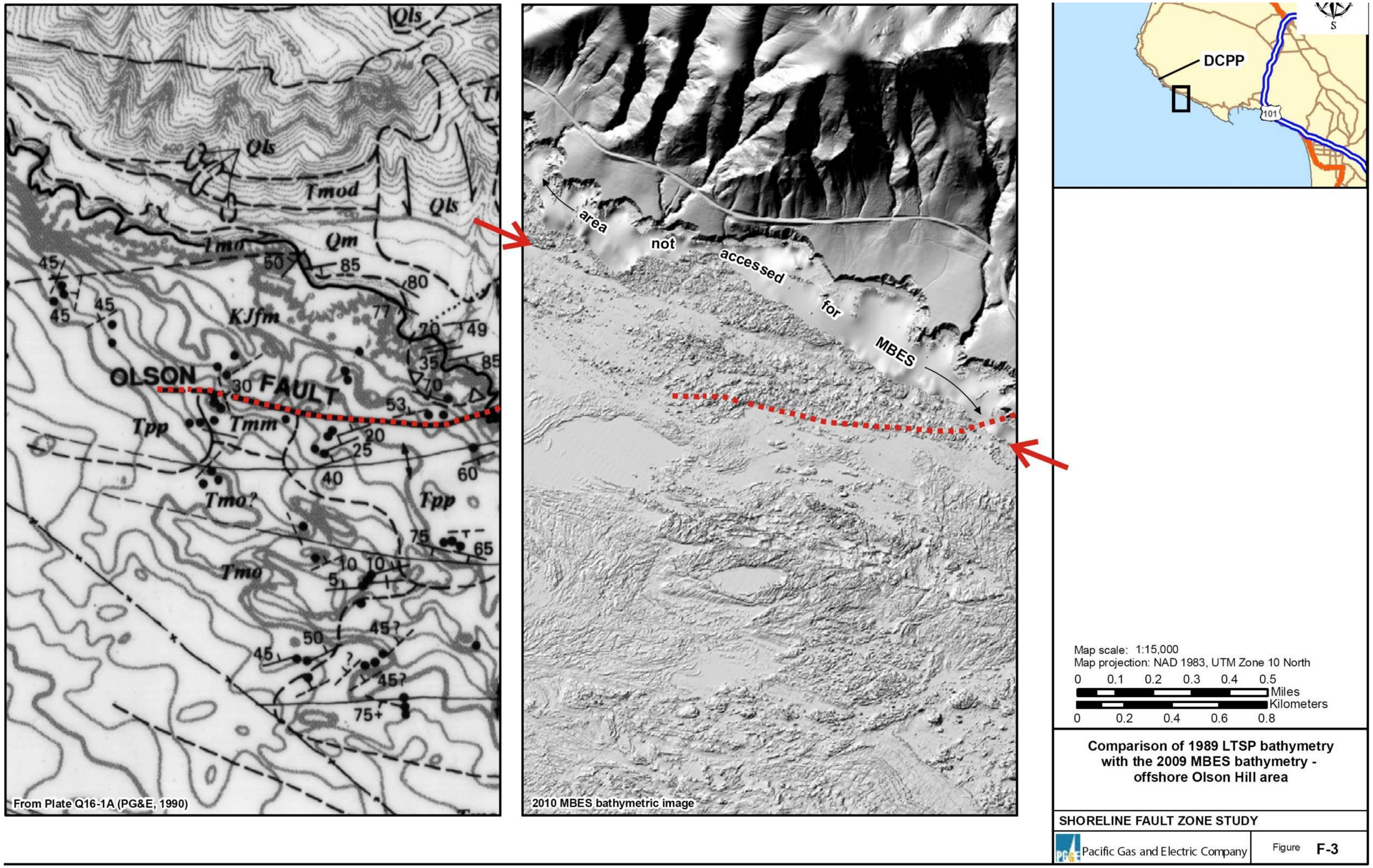

Fig. A3-2. Example showing how detailed bathymetric DEMs can reveal the presence of previously-unmapped faults on the seafloor. At left, the best available bathymetry contours and interpreted faults from the 1990 offshore study of the Diablo Canyon NPP, California, USA. At right, the 2 meter bathymetric DEM from 2009, which revealed for the first time the Shoreline Fault (between red arrows). Note that the Shoreline Fault could not be identified on the 1990 bathymetry data, although the Olson Fault could be. The linear trace of the Shoreline Fault clearly cross-cuts all older geologic structures on the seafloor. Source: PG&E, 2011.

4.3.3-Calculate earthquake frequency-magnitude relationships for each distinct part of the reference glacial cycle (interglacial, glacial, and deglacial time periods).

This task should be performed on the basis of distinct seismic source zones that include Forsmark and its surroundings out to a radius of at least 200 km. The seismic source zones should be based on seismotectonic provinces, rather than on simple radii from Forsmark.

4.3.4-Compare the shear displacements on target fractures predicted by the rock mechanics approach, to observed distributed fault displacements in historic earthquakes.

This task would provide a geological ”reality check” on SKB's predicted shear displacements on target fractures, by comparing them with observed off-fault displacements at the same distance from earthquakes of the same magnitude. The comparison will ask if the results from the rock-mechanics approach are compatible with those from the method of Probabilistic Fault Displacement Hazard Analysis (PFDHA), as described by Youngs et al. (2003) and Petersen et al. (2011). PFDHA is the recommended procedure cited by the International Atomic Energy Agency (IAEA) for use with nuclear power plants.

4.3.5-Make a detailed study of the two (?) fault exposures in gravel pits near Forsmark described by Mörner (2003) and Lagerbäck et al. (2005) (see Section 2.2.4)

These faults constitute the only positive evidence for faulting of glacial deposits near Forsmark, but the poor description of them in the above publications leaves many questions unanswered. First, are the two exposures described by Mörner and Lagerbäck the same exposure, or different exposures? If different exposures, are they the same fault? What is the strike of this fault and its observed displacement (vertical and horizontal)? Is the fault located in a previosly mapped bedrock shear zone? What are the ages of the displaced deposits on each fault, and based on that, is it likely that they are the same fault? What is the evidence that the fault(s) are tectonic or non-tectonic? Can the faults be traced laterally away from the gravel pit exposure as a scarp or lineament on the LiDAR DEM or aerial photographs, on a strike line that is the same as the strike measured in the exposures? Or conversely, do the faults appear to be restricted to a single landform such as an esker, and definitely cannot be traced laterally beyond the limits of the esker? These are just some of the basic questions that must be answered before we can assess whether postglacial faulting has occurred near Forsmark.

4.4 APPENDIX 4. Commentary on the proposed large late Holocene paleoearthquake at 2900 yr BP in northern Uppland (site 7 in the figure below); from Mörner (2009).

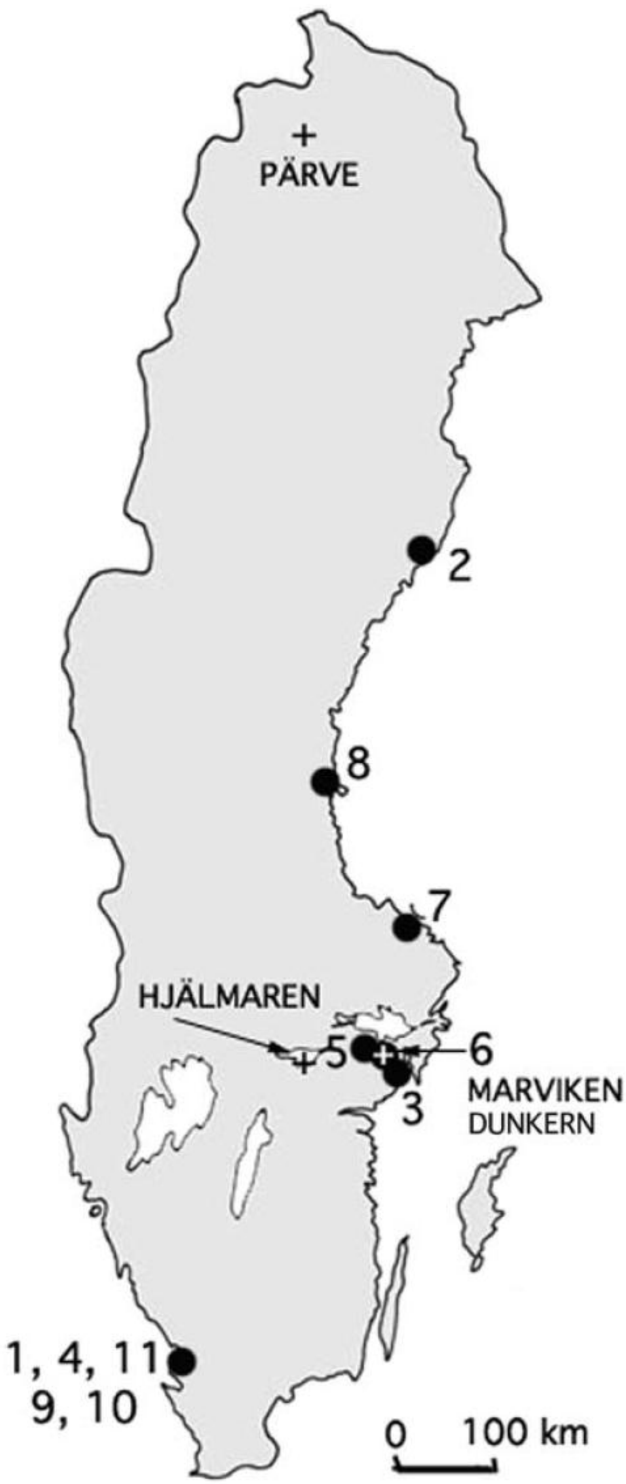

Fig. 2. Location of the 11 Late Holocene palaeoseismic events (Table 1) and some place names (+) discussed in the text.

No.	C14-YR BP	LOCATION	UTM X	UTM Y	FAULT	TALUS	LANDSLIDE	LIQUEFACTION	TSUNAMI	INTENSITY	MAGNITUDE
7	2900	North Uppland-Forsmark			(x)				x	(XI-XII)	(~7)

MÖRNER 2009 TEXT (Reicherter et al, GSL volume): "*In several lakes in northern Uppland (the Forsmark region), we recorded a major tsunami event (Mörner, 2008b). A coring and dating programme was conducted in 2004 (N.-A. Mörner, unpublished work). A tsunami bed was recorded in offshore sediments, in shore-zone sediments, and in lake and bog sediments at elevations up to 20 m (or at least 6 m) above the corresponding sea level. A tsunami with a run-up of 20 m implies a significant event...We followed the tsunami bed from offshore basins (15 to 35 cm sand and gravel in graded bedding), via lagoonal basins (with 70 cm sandy beds at the clay/gyttja interface) up into lake basins above the corresponding shore (40–50 cm sandy-gravelly beds erosively deposited between the marine clay and lacustrine gyttja). Six C14 dates provide a close age for the offshore and lagoonal sites and a strong erosive effect in the lake basins at least up to a level 5 m above the corresponding shore as illustrated in Figure 6. The data record a vertical spread of the tsunami beds from -20 m to +6 m. The lake and bog coring suggests that the tsunami may have had a run-up of 20 m. This is not yet supported by dates, which suggest only a 6 m run-up (Fig. 6)...*
The Singö Fault zone crosses the area. This zone seems to have been reactivated during the deglacial phase some 10 000 years ago (Mörner 2003 [Paleoseismicity of Sweden], *2004* [Tectonophysics]). *Therefore, it seems likely that even this 2900 BP event represents a reactivation of this zone. We have recently investigated the tsunami signals in the lake and bog records. Judging from the tsunami run-up, we seem to be dealing with an intensity XII (20 m) or XI (6 m) event with respect to the INQUA intensity scale*."

MÖRNER 2008b TEXT (Polish Geological Institute Special Paper 23): "*The 2900 cBP Event: A major tsunami event was recorded in several lake-basins in northern Uppland. A coring and dating programme was conducted in 2004 (Mörner, unpublished). A tsunami bed was recorded in lakes in off-shore position, shore-zone position and land position up to an elevation of 20 m above the corresponding sea level. A runup of 20 m implies a very significant tsunami. A full presentation is in preparation*."

MCCALPIN COMMENTS:
DATE: 2900 C14 yr BP; i.e., not related to deglacial rapid uplift; in today's seismotectonic setting.

LOCATION: the specific lake basins containing the evidence are not identified in Mörner's publications.

UTM COORDINATES: unknown

FAULT: Mörner does not identify the fault surface rupture associated with this tsunami. He infers that the source was the Singö fault zone.

TALUS: none

LANDSLIDE: none; Mörner does not mention seeing the slide planes described by Lagerbäck et al. (2005) in the same area.

LIQUEFACTION: Mörner (2003, p. 225) mentions "In pits and sections close to Mehedeby, we have observed liquefaction, shaken beds, and even up-faulted gravel. However, he does not estimate the age of the liquefaction event, so it is unclear whether it is contemporaneous with his other evidence (faulting and tsunami).

TSUNAMI: This interpretation of Mörner's is his main line of evidence for the occurrence of this earthquake. The sand beds that he cites as evidence of this tsunami (see paragraphs above) appear to be very similar to the evidence cited by Lagerbäck et al. (2005) for a late-Holocene marine incursion*: " An erosional unconformity accompanied by a laterally persistant layer of coarse-grained sediments, occurring not only in positions that were exposed to the waves of the ancient sea but also in sheltered positions in the terrain, indicates that potent currents rather than wavewashing were responsible for erosion and deposition. [underlining added]. Strongly shell-bearing sand at one of the coring sites indicates that deposition and preceding erosion took place in rather shallow water during a late stage of the Holocene."* Lagerbäck's description of currents is compatible with a tsunami origin, although he does not make that interpretation, nor could he cite Morner's papers on the subject, which were published four years later in 2009.

INTENSITY: based on the runup of the proposed tsunami, Mörner (2009) estimates an intensity of "XII (20 m) or XI (6 m) event with respect to the INQUA intensity scale."

MAGNITUDE: none cited by Mörner

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