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Contents:

Praise Worthy Prize

International Journal of Earthquake Engineering and Hazard Mitigation (IREHM)

Seismic Hazard Assessment: a Challenge for Science and Geoethics

Nils-Axel Mörner

Abstract – *When science itself cannot solve a problem, it is necessary to combine available data with philosophy and geoethics. Storage of high-level nuclear waste calls for an absolute isolation of the waste from the biosphere of at least 100,000 years. To make meaningful seismic hazard assessments over such an immense time period is very hard, if at all possible. Seismology only covers a century. Paleoseismology in Sweden covers 13,000 years (with some additional records from around 30,000 BP). In this situation, we must restrict ourselves from making too optimistic assessments. It is here where geoethics, philosophy and common sense become vital for a balanced evaluation. As some sort of seismic hazard assessment, one may multiply the recorded paleoseismic hazard over the past 13,000 yr by ten. The absence of a clear scientific methodology of assessing the true seismic hazard over this long time-period must not be used to present careless statements. We must also evaluate who says what, and in what interest. The principles of geoethics call for a strict application of scientific facts, observational evidence and physical laws.* **Copyright © 2016 Praise Worthy Prize S.r.l. - All rights reserved.**

Keywords: *Seismic Hazard Assessment, Paleoseismics, Storage of Nuclear Waste, 100,000 Yrs Time Scale, Principles of Geoethics, Fennoscandia*

I. Introduction

This paper was presented at the SENIX conference in Stockholm in June, 2016 [1] and addresses the problems of making meaningful seismic hazard assessments over such enormous time units as 100,000 years, which is requited in the case of nuclear waste storage in the bedrock [2]. The Independent Committee on Geoethics (ICG) was launched in 2015 [3].

The principles of geoethics were stated as [4]: (1) Keep to science always being ready for new findings and concepts, (2) Always anchor your ideas in observational facts from nature and firm experiments, (3) Beware of advocacy and lobbying by or on behalf of special interest groups, and (4) Never let your opinion be influenced by money, promotion, or easy publication.

II. Seismic Hazard Assessment

Seismic hazard analysis based on instrumental records is a common methodology to assess theoretical danger for damage and destruction of various human buildings and constructions. The assessment of future seismicity is, of course, a function of the seismic activity observed by instruments in the past, which varies from decades up to a century at best. When we extend our aspiration to make seismic hazard assessment over time-scare of millennia or even hundreds of thousands of years, we have run-out of ability to do so on the basis of our short-term seismic instrumental records, and we need to consult our paleoseismic and/or archaeoseismic data bases (Fig. 1).

"When the time units for our predictions increase to hundreds of thousands of years, we have extended our abilities *in absurdum*" [6]. In the case of proposed deposition of high-level nuclear waste in the bedrock, a long-term seismic hazard assessment is needed for a period of, at least, 100,000 years.

This paper analyzes how to cope with this question, which partly is beyond our scientific ability today.

We have to do the best of the situation posted on us. Much worse would be to give up, and leave to field free for meaningless speculations and subjective wishes.

III. Fennoscandia

Today, Sweden and Finland have a low to moderately low seismicity as recorded by seismometers. At the time of deglaciation, some 10,000 years ago, the situation was totally different and the area was a high-seismic area [7]. This will reoccur during the next 100,000 years.

After the last Ice Age, land has gone up by 800 m in the center of uplift and by 450 m in the Stockholm area (Fig. 2). The cone-shaped uplift implies vertical as well as horizontal radial and tangential extension [7].
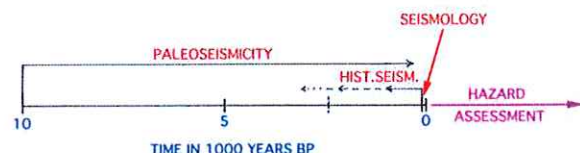

Fig. 1. Means of recording seismic events over past and present time (from [5]). For meaningful seismic hazard assessments, the instrumental seismic records must be combined with paleoseismic analyses. Meaningful long-term predictions must be based on paleoseismic data of high quality and completeness
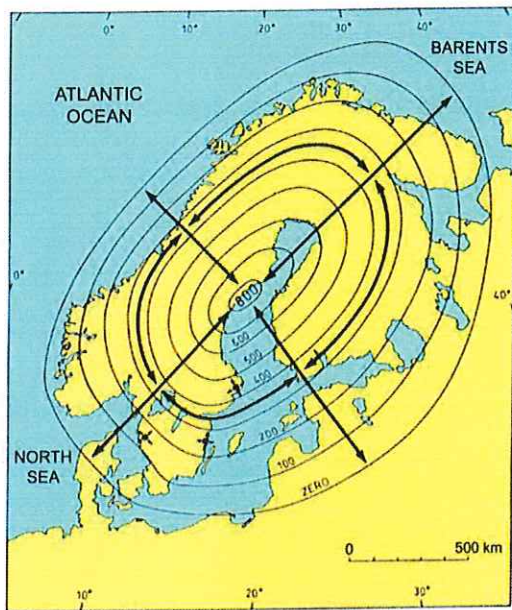
Fig. 2. Postglacial isostatic uplift of the Fennoscandian Shield (from [7]): a cone of 800 m uplift with related horizontal extension in the radial and tangential directions. The strain rates were 2 orders of magnitude larger than at present [7]

The rates were, at least, 10 times faster than maximum seafloor spreading rates. Hence it is not surprising that a high seismicity – in magnitude as well as in frequency – was initiated [8]. The first Paleoseismic Catalogue of Sweden included 52 paleoseismic events [8] and the second catalogue 62 events [2].

The magnitude distribution of the postglacial events (59 of them) are: 7 of M >8, 12 of M 8-7, 34 of M 7-6 and 6 of M 6-5 [2]. Half of the events occurred at the time of maximum uplift. Still, 13 events occurred during the last 5000 years with events reaching magnitudes of about 7 [9]. This is our paleoseismic database in Sweden, and this must be the base upon which we assess the long-term seismic hazard. In Finland, paleoseismic studies are very limited, however [10].

IV. Estimating Paleoseismic Magnitudes

The main means of estimating the magnitude of paleo-seismic events are [2] and [8]:
- Length and height of fault scarps
- Spatial distribution of liquefaction
- Height of tsunami waves
- Spatial distribution of bedrock deformation
- Spatial deformation of magnetic grains

Seismic events hardly leave any traces in nature at magnitudes below 5 to 5.5. Therefore, we can set the lower limit of paleoseismic events at about M 5.5 [2].

IV.1. Length and heights of fault scarps

There are international standards for converting the length and height of fault scarps into magnitudes [11].

In northern Sweden, it is easy to trace faults over long distances. It is much harder however, to interpret the height as it may represent multiple events.

In southern Sweden with thick sediment cover, dense vegetation and intense agriculture, it is necessary to investigate records, like bedrock fracturing, liquefaction, tsunamis, area of magnetic grain rotation [8]. When these records occurred in one and the same year, it provides evidence of severe paleoseismic events.

The Lapland faults are sometimes very impressive [12]-[13]. The trans-Svealand east-west fault passing Stockholm was reactivated in deglacial time (in full agreement with the theory of [14]). In total 7 separate events have been recorded within 102 varve years [5].

This gives evidence of a very high frequency of high-magnitude events along this fault.

IV.2. Spatial Distribution of Liquefaction

Several of the paleoseismic events are tied to one single varve [8] and [15].

This allows the recording of the spatial distribution of one and the same liquefaction event. Because there is a fairly strict relation between the spatial distribution of liquefaction and the magnitude or intensity of earthquakes [16], this provide good means of assessing paleoseismic magnitudes.

This is illustrated in Fig. 3 for the two events closely dated by varves [8]. This suggests a magnitude of M ~9 for the 10,430 BP event, and of M 7.5-8.2 for the 9663 BP event, in good agreement with additional material [5], [8] and [16]. The characteristics of various liquefaction structures have much to add for the estimate of causational magnitudes.

The venting of coarse gavel implies very strong forces and magnitudes of about 8 or more [5] and [8]. This is, for example, documented at the 10,388 BP event and the 6100 BP event. At the Hudiksvall 9663 BP event, 5 phases of liquefaction were recorded in two sites, 35 km apart (Fig. 4).
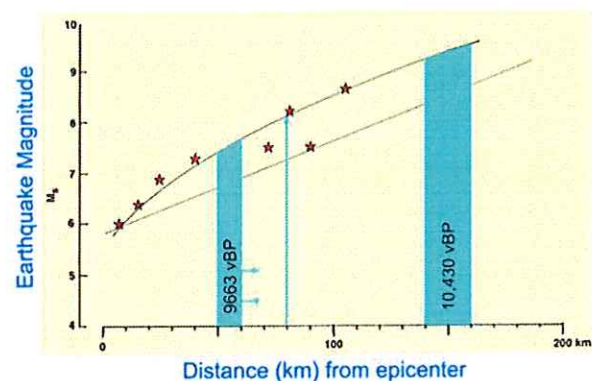

Fig. 3. Relations between observed magnitudes (vertical Ms scale) and related distribution of liquefaction (horizontal km-scale). Into this diagram are plotted the observed liquefactions of the big Stockholm event in the autumn of varve-year 10,430 BP and of the Hudiksvall event of varve 9663 BP. The relations suggest magnitudes of about M 9 and M 7.5–8.2, respectively [5], [8]
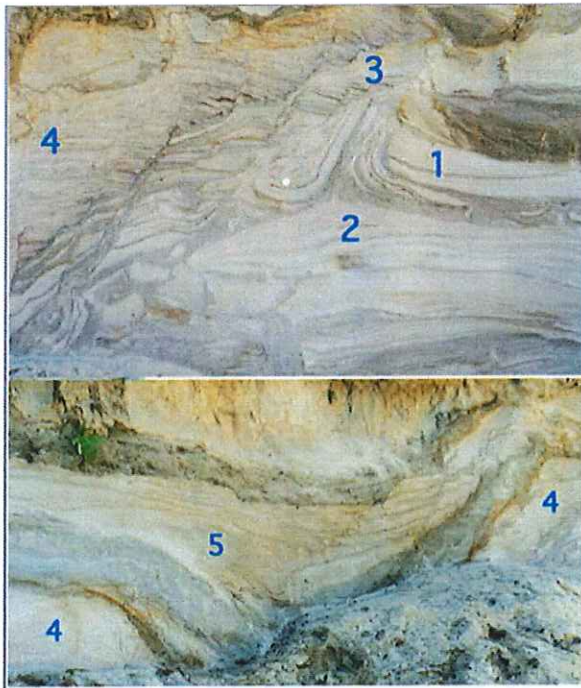
Fig. 4. Sequence of 5 phases of liquefaction of the 9663 BP event at site West Mura [8], interpreted as recording the main event and a number of afterchocks

It was interpreted [8] in terms of a main seismic shock and after shocks. This has strong bearing on the evaluation of magnitude, as the main shock often is about one magnitude stronger than the aftershocks.

IV.3. Height of Tsunami Waves

The Swedish database includes the recording of 17 tsunami events [8], [17] and [18]. In some cases the tsunami height is very well defined, and may hence be used for the estimation of corresponding magnitudes.

There is a relation between seismic magnitude and maximum tsunami height [19].

There are eight major tsunami events in the last 12 years that generated high-amplitude tsunamis. They are: (1) Indian Ocean, 2004, of M 9.1, (2) Java, 2006, of M 7.7, (3) Benkula, 2007, of M 8.5, (4) Peru, 2007, of M 8.0, (5) Samoa, 2009, of M 8.1, (6) Mentawai, 2010, of M 7.7, (7) Chile, 2010, of M 8.8, and (8) Tihoku-oki, 2011, of M 9.0 [19]. Six of those form a straight-line tsunami-height/magnitude relation (Fig. 5). With this relation set so well by modern data, we can introduce our Swedish tsunami height values and obtain interesting conversions into corresponding magnitudes. This is done in Fig. 5 for three of the events.

According to the Fig. 5 relation, the magnitudes of the three events would be: M 8.8 for the 10,430 BP event, M 8.5 for the 9663 BP event and M 8.1 for the 2900 BP event. In Fig. 6, the entire Swedish database (17 events) is plotted with respect to age, height and magnitude level.

It indicates, beyond doubts that we are dealing with quite strong events with 11 events above M 7.1.
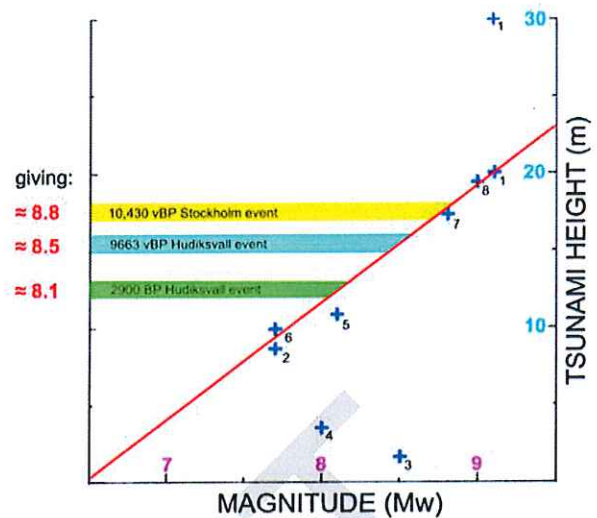
Fig. 5. Relation between tsunami heights and earthquake magnitudes for eight high-amplitude events in the last 12 years [19]. The tsunami heights of the 10,430 BP, 9663 BP and 2900 BP events [8] and [18] are introduced (color bands) and the corresponding magnitudes read
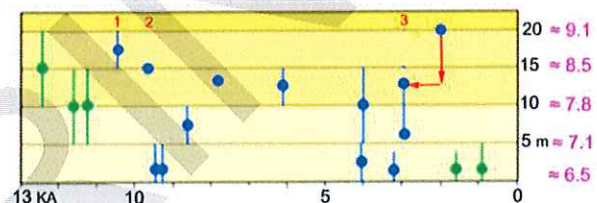
Fig. 6. The Swedish paleoseismic database [2] includes 17 tsunami events [18]; 5 in the Kattegatt (green) and 12 in the Baltic (blue). Purple figures to the right give magnitude conversions According to Fig. 5

IV.4. Spatial Distribution of Bedrock Deformation

In association with the 10,430 BP event, we record a lateral fault of 6-8 m at 1.0 km from the main fault, and fractured and displaced bedrock 100 km away from the fault. This must imply a very high magnitude event [10] in full agreement with the Figs. 3 and 5 graphs.

The 9663 BP event is associated with 2-4 m motions 12 km from the epicenter, and some 100 sites of bedrock deformation over an area of 40 km [8] and [10]. This, too, calls for a high magnitude event (just as do the records of Figs. 3 and 5 indicate).

These records violate some of the basic conditions claimed for long-term safety [10], viz. the model of so-called "respect distance" claiming a maximum bedrock deformation of 10 cm at 1 km from the epicenter.

IV.5. Spatial Deformation of Magnetic Grains

The minute magnetic grains are affected by seismic ground shaking both in the form of deformation and in the form of a second moment of free alignment with respect to the pole [20]. At the 10,430 BP event, such *"seismomagnetization"* has been documented over an area of 300,000 square km (Fig. 7, from [8]).
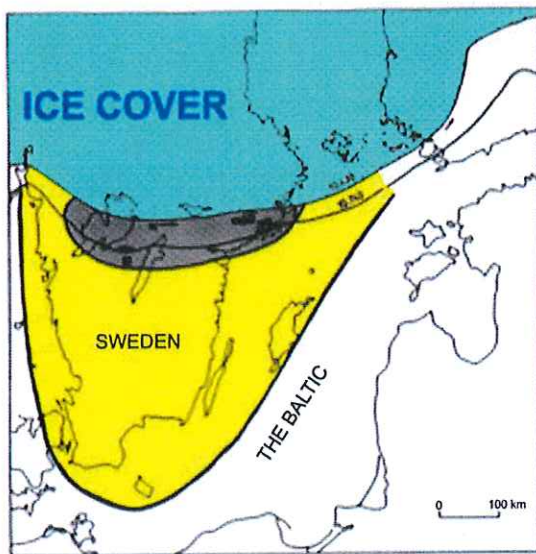
Fig. 7. Ice cover (blue), liquefaction (dark) and magnetic grain rotation (yellow) at the mega-earthquake occurring in the autumn of 10,430 BP

At present we have no means of converting this into magnitude. It seems evident, however, that the magnitude must have been exceptionally high (which is just what Figs. 3 and 5, and bedrock fracturing indicate).

IV.6. Summing Up and Utilization

The Swedish database of paleoseismic event was above subjected to five different and independent means of estimating magnitudes. This can be seen as some sort of validation of the magnitudes assigned [2] and [8].

The result seems straightforward: the magnitudes assigned are well supported in Figs. 3-7 (at least all those checked).

This implies that the quality of the paleoseismic database for Sweden [2] justifies its us also for long-term hazard assessment. We need to cover at least 100,000 years. The easiest way of estimating an assessment is simply to multiply the available database of the last 13,000 years by 10 so that it would cover some 130,000 years [2]. This way of simple long-term seismic hazard assessment gives: 70 of M >8, 120 of M 8-7, 340 of M 7-6 and 60 of M 6-5. This is illustrated in Fig. 8, and it is stressed that each doubling implies a step down in quality, and that somewhere the validity may even break down. Certainly, however, this methodology is superior to the utilization of short seismic records, which must be discarded as meaningless and misleading.

For a better analysis, we have to go down to regional scales in relation to the proposed nuclear waste repositories at Forsmark in Sweden and at Olkiluoto in Finland (cf. discussions in [2] and [10]). IAEA recommends an areal distribution with "a radial extent of typically 300 km" [21].

Fig. 9 illustrated the Swedish paleoseismic database with a circle of 250 km radius around the Forsmark nuclear site in green.
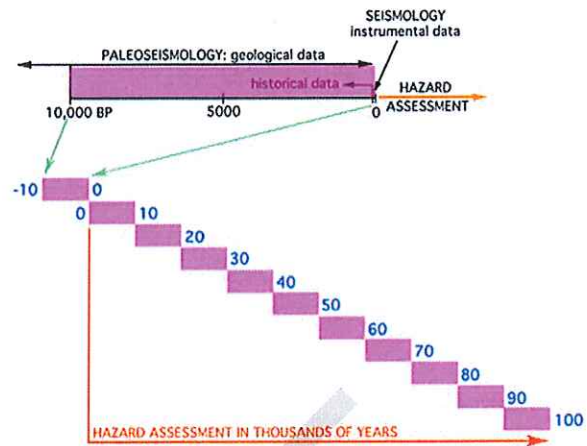
Fig. 8. The transformation of our paleoseismic database (covering 10,000-13,000 years) into the future (nest 100 000 years) by repeating the time frame of the original database 10 times. However good the base data are, each time doubling implies a deterioration of the quality of hazard assessment. Somewhere, the validity may even break down. (from [2]). Still, this is the best we can do over this immense time unit
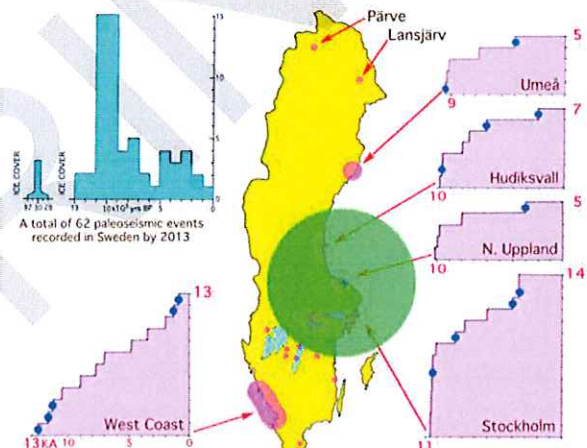
Fig. 9. The Swedish paleoseismic database [2] expressed as time histogram [blue] and areal distribution of events with recurrence diagrams for 5 separate areas (purple). Green circle mark the area around Forsmark at a radius of 250 km.

In total, this includes 29 events in Sweden and 6 events on the Finnish coast with the following magnitude distribution; 4 of M >8, 5 of M 8-7, 19 of M 7-6 and 7 of M 6-5. A 10 fold increase of this database would give 40 M >8, 50 M 8-7, 190 M 7-6 and 70 M 6-5 events in the area surrounding both Forsmark and Olkiluoto, and may stand as an improved preliminary seismic hazard assessment.

V. Different Views and Claims

The repositories for high-level nuclear waste under construction at Olkiluoto in Finland and in planning at Forsmark in Sweden are located in an area, which over the last 10,000 years must be classified as a high-seismic area (Fig. 10).
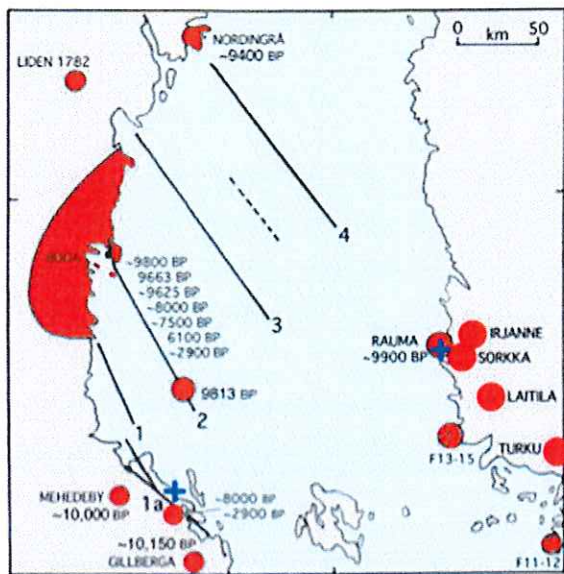
Fig. 10. Paleoseismic records (red marks with dates) and the location of the Forsmark site in Sweden and the Olkiluoto site in Finland (blue plus signs). This was a high-seismic area in deglacial time

According to the nuclear agencies, the waste must remain safely stored for "at least 100,000 years" [21] in Sweden, and "for 1 million years" [22] in Finland.

According to the preliminary seismic hazard assessment just given no such long-term safety seems possible to be given, however.

V.1. Very Weird Claims

Serious "safety analyses" or estimated of possible long-term seismic hazard must be based on facts as illustrated in Fig. 1.

Seismology, limited to the last century, has little to offer, and may rather be misguiding [2]. Below, I will review a few claims because they illustrate how long-term nuclear hazard should not be performed, at the same time as it gives examples of how organizations may operate in view of their own interests just because there are unclear conditions (at least for those outside the paleoseismic community) of how to handle the long-term safety aspect. In 1983, the Swedish nuclear agency analyzed the seismicity over 25 years (1951-1976) and claimed that this seismicity would remain the same for the next 100,000 to 1 million years [23].

An updated version in 2000, proudly stated that the maximum seismic magnitude event in the next 100,000 years would be 1 M 6 event [24]. This value is still used [21] as the base for the claim of a guaranteed long-term safety for a repository over 100,000 years.

This is of course not a serious risk analysis, just a part in their project drive. In comparison with the documented paleoseismic events and their magnitudes (above), I see it as an insult to geology and geophysics.

The Swedish Nuclear Regulation Agency (SSM) said they lack own expertise in paleoseismology, and hence employed an international expert (Jim McCalpin).

He had serious criticism to the handling of the question by the authorities, and insisted that the true risk must be assessed [25]. SSM did nothing about it, however, hence giving over the risk analysis to the producers themselves. The Swedish Council for Nuclear Waste (Kärnavfalls-rådet) has no expertise of their own, but their geologist (Karin Högdahl) addressed the risk [26] stating that "there are no stronger earthquakes in the area" (which is wrong), that "the risk area was scaled down to 10 km radius" (which is against the recommendation by IAEA), and that there was "a risk of 2 above magnitude 5 earthquakes in 1 million years".

In my opinion, this is simply bad science, and has nothing to do with risk analysis.

V.2. Back to Real Risk Analyses

It cannot be a serious risk analysis unless all available data are evaluated and incorporated in the efforts.

There are two main databases: the seismological one covering the last 100 years and the paleoseismological one covering the last 30,000 years (Fig. 11).
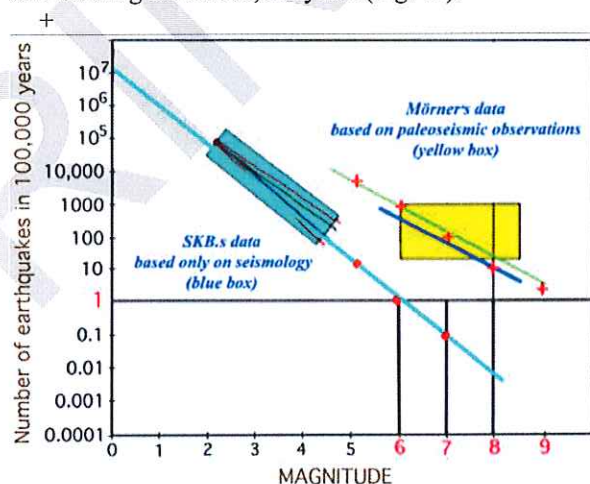
Fig. 11. The seismological database (blue) used by the nuclear agencies to predict seismicity in 100,000 years, and the paleoseismological database (yellow) used by the author. The difference is enormous in terms of frequency and magnitude of future earthquakes.

The two databases are compared in Fig. 11. It is, of course, directly meaningless to try to predict the seismicity of next 100,000 years based on seismology, which only cover the last 100 years. Much better is the use of paleoseismic data. It is true that each doubling of the record implies a step down in quality (Fig. 8). Still, it is the only way of obtaining meaningful results. Scaling to the near-field area (Fig. 9) is essential, however.

Figs. 12 illustrate the various ways of approaching a long-term seismic hazard assessment.

Only, the paleo-seismic database can provide meaningful estimates of the long-term seismic hazard.

Instead of using the entire database of Sweden, it is better to use events occurring within a 250 km radius from the sites of nuclear waste repositories.
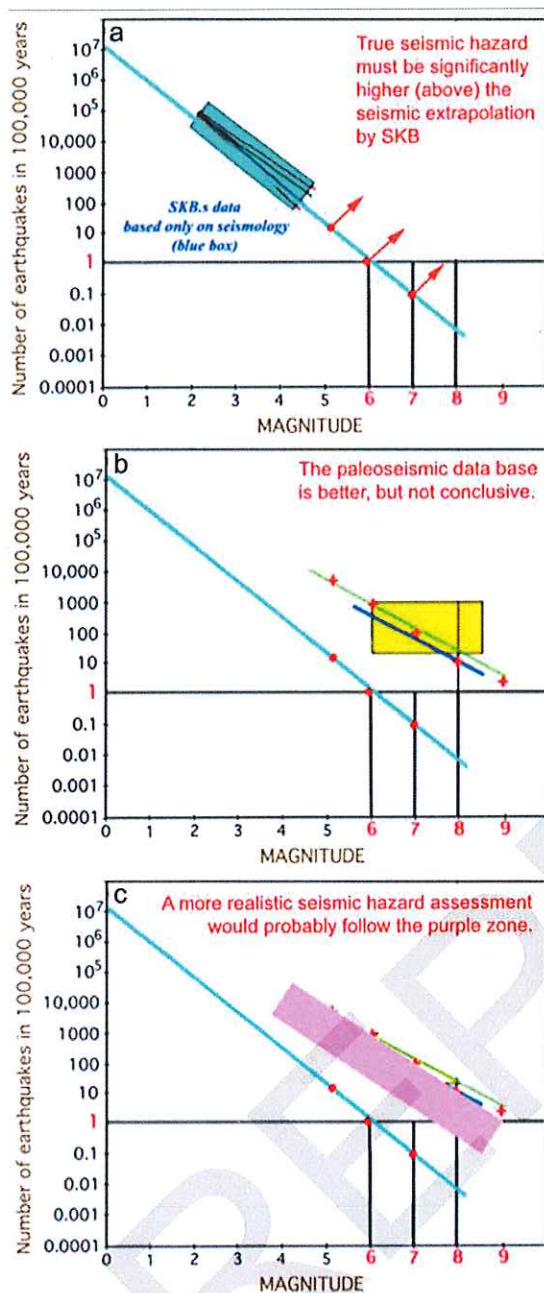
Figs. 12. Long-term seismic hazard assessments. (a) Seismology is useless for long-term assessments. The only good is that we know that the true values must be far beyond the blue line. (b) Paleoseismology provides an excellent database. Its conversion into long-term assessment is complicated, however. (c) A more realistic long-term seismic hazard assessment probably would be as marked with the wide purple zone. It includes the database referring to the 250-radius field, which suggests 40 M >8, 50 M 8-7, 190 M 7-6 and 70 M 6-5 events over a time period of 100,000 years

This database includes 35 events, and their 10 fold duplication gives 40 M >8, 50 M 8-7, 190 M 7-6 and 70 M 6-5 events over a time period of 100,000 years.

I hereby propose this as the best long-term seismic hazard assessment of the nuclear waste repositories in Sweden and Finland. It provides a totally different picture than those claims (above) used as basic input-

values for the safety analyses in Sweden [21] and Finland [22]. This implies that both safety analyses are, in fact, invalidated.

VI. Conclusion

Long-term seismic hazard assessment for time periods as long as 100,000 years is very hard and complicated. We must exercise both skill and wisdom. Short-term records from seismology cannot be used. Only a well-established paleoseismic database can provide estimates and meaningful seismic hazard assessments.

In this paper we have tested the magnitude estimates with respect to liquefactions (Figs. 3-4) and tsunami heights (Figs. 5-6). The magnitudes were validated.

The paleoseismic events within a 250 km radius from the nuclear waste repositories at Forsmark and Olkiluoto amounts to 35 events: 4 of M >8, 5 of M 8-7, 19 of M 7-6 and 7 of M 6-5. Over the 10 times longer period of 100,000 years, this database might be increased by 10, too, which would give 40 of M >8, 50 of M 8-7, 190 of M 7-6 and 70 of M 6-5 as possible long-term seismic hazard assessment. At present, this seems to be the best assessment we can do. The long-term safety analyses for the repositories in Sweden and Finland are based on seismological extrapolations (Fig. 11), here shown to be completely without true geodynamic meaning. It seems evident that the analyses must be repeated on the basis of existing paleoseismic data.

Personally, I find it hard to imagine [2] that – in view of the high seismicity – the repository types proposed will pass such an updated safety analysis.

If the closed KBS-3 type method would fail to meet the criteria of long-term safety, maybe the accessible and controllable DRD-methodology would do [27].

Section V.1 includes examples of the handling of the long-term seismic risk, not only by the waste handling agencies, but also the Swedish Nuclear Regulation Agency and the Swedish Council for Nuclear Waste [26], which surely upsets scientific and geoethical rules.

Acknowledgements

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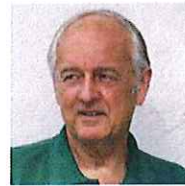
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