NUCLEAR WASTE SITING IN VIEW OF GLACIAL BEDROCK INSTABLITY AND GEODYNAMICS

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Summary

In the case of nuclear waste siting, we have to consider stability and safity over time periods of 10s to 100s of thousands of years. We can, of course, make no serious predictions of such time periods. In the case of the Fennoscandian glaciated cratonal area, we are able to demask some fundamental factors indicating the the present cwertainly not is the key either to the past or to the future. At the time of deglaciation, Sweden was a very high-seismic region; in amplitudes as well as in frequency. In fact, this is not at all surprising con sidering the rates of glacial isostatic uplifting amounting 40-50 cm per year in the north and 15 cm per year in the Stockholm area; i.e. some 1.5 to 0.5 mm per day and about 10 times as high as present sea floor spreading raates). Thanks to the varve chronology, many of the paleoseismic event have been dated as to a single varve-year (in one case even to the season of a varve). In the Stockholm region, we have been able to date an extremely large paleo-seismic event to the autumn of varve year 10,430 BP. This event caused liquefactions and varve disturbancies over an area of about 60 x 320 km, which exceeds the liquefaction distribution of the famous Alaska 1964 event. The recording of five successive events (~10,490, 10,469, 10,447, 10,430, ~10,410 BP) is indicative of an unusually high frequency, too. In total, we have some 20 events recorded. At the First Future Ice Age, this seismicity will be repeated, invalidating any long-term safity or stablilty concept when it concerns nuclear waste siting scenarios.

In this situation, we must keep the control of the waste produced and store it in a dry bedrock repository under constant control and accessable for reparation, application of future processes to rander the waste harmless and even relocation. The DRD (Dry Rock Deposit) method concurs with these requirements and is hence recommended.

Deglaglacial geodynamics

In the last decades, we have come to realize that the geodynamics of the Fennoscandian craton include several novel elements referring to the amount and rates of glacial isostatic uplift (Mörner, 1979), the occurrence of seismo-neotectonic structures and paleoseismic events of quite other amplitudes and frequencies than we know today (Mörner, 1978, 1985, 1995, 1996, 1999a, 1999b; Mörner & Tröften, 1993; Tröften & Mörner, 1997; Mörner *et al.*, 2000).

Two decades ago, Mörner (1979, 1990) was able to present a totally new picture of the glacial isostatic land uplift both of total amount (800 m in the centre of uplift) and the rate of absolute uplift (amounting up to several decimetres per year). The mere rates of vertical uplift are about 10 times as high as the horizontal rates in our high-seismic areas today. Therefore, it should not be surprising – rather fully expected – that we find that the deglaciation period, with peak-rates of glacial isostasy (in the order of ~15-45 cm per year or ~0.5-1.5 mm per day), is linked to a very high paleoseismic activity. The glacial isostatic vertical uplift and tilting caused a corresponding extension also in the radial and tangential horizontal directions (Mörner, 1991). Faults and fractures seem to record the interaction of these forces (Mörner, 1989, 1991). The high deglacial paleoseismic activity may also be analysed as direct function of the rate of uplift and its parabolic decay with time (Mörner, 1996, Fig. 2).

Today, Fennoscandia is characterized by a low to moderately low seismic activity. At the time of deglaciation, the situation was quite different, however. The region was then characterized by both large and frequent earthquakes. In Sweden, we have the possibility of utilizing the varve chronology for the dating of paleoseismic events. This means that we can achieve an annual resolution despite ages in the order of 10,000 years. This technique has successfully been applied to some regions in Sweden.

In the Stockholm region, we have been able to date an extremely large paleoseismic event to the autumn of varve year 10,430 BP (Mörner, 1996). This event caused liquefaction and varve disturbances over an area of about 60x320 km (i.e. larger than the 1964 earthquake in Alaska), which seems to indicate that we are dealing with a magnitude above M 8. A second example of a varve dated high-amplitude paleoseismic event is presented in this paper, an event which occurred in the varve 9663 BP (Mörner *et al.*, 1999, 2000; Mörner, 1999a). A third example comes from the Umeå area, where heavy liquefaction, a major rock avalange and varve deformations over an area of, at least, 60 km can be assigned to a single varve, viz. varve 9428 BP (Mörner, 1999b, unpubl.).

The high frequency of paleoseismic events is revealed by the multiple events identified in the Stockholm area reoccurring about every 20 varve; ~10,490, 10,469, 10,447, 10,430, ~10,410 BP (Mörner, 1989, 1995; Mörner *et al.*, 1989; Mörner & Tröften, 1993; Tröften & Mörner, 1997; Tröften, 1997). This is illustrated in Fig. 2.

Sweden is full of faults and fractures that must be of postglacial age (Mörner, 1978, 1985, 1989, 1993a, 1995, 1996, 1999b; Mörner *et al.*, 1989, 2000; Mörner & Tröften, 1993; Tröften & Mörner, 1997; Tröften, 1997). The Pärve and Lansjärv faults in northern Sweden represent large-scale fault systems (Lundqvist & Lagerbäck, 1976; Lagerbäck, 1990). Sjöberg (1994) has documented the occurrence of "bedrock caves" over almost the entire Sweden and interpreted them in terms of seismotectonics. It is still unclear whether methane dehydration venting could be involved in this often "explosive" fracturing (Mörner, 1993b; Sjöberg, 1994). The largest, and most impressive, cave system is the Boda cave at Iggesund south of Hudiksvall. A special project has been devoted to the study of the characteristics and origin of the Boda cave system. The work has been in progress since late 1997. It is now defined as the "9663 BP Iggesund event" (Mörner *et al.*, 2000).

Fig. 1 gives the geographic location of the main paleoseismic events recorded up to now with further details in Table 1. The 10,430 BP event and the Pärve and Lansjärv events must all have been well above M8. Our records come from the whole of Sweden and no region can be claimed to have been "aseismic" in the deglaciation period.

Material and methods

It is true that the varved clay beds in Sweden offer a chronology with an annually resolution (maybe, even seasonal). It should be remembered that the chronology as such is always subjected to revi-

TABLE 1. Some large paleoseismic events in Sweden (age in years BP).
The column 1 numbers refer to the geographic locations given in Fig. 1.

no	age	magnitude	name/location
1	~12,500	>6	Ronneby
2	~12,000	6–7	Äspö (subglacial)
3	11,700	>7	Kinnarumma
15	<11,500	6–7	Hallandsåsen-1
4	aut. 10,430	>>8	Mariefred-1 = Stockholm-4
5	~10,490	6–7	Stockholm-1
5	10,469	6–7	Stockholm-2
5	10,447	6–7	Stockholm-3
4–5	10,430	>>8	Stockholm-4
5	~10,410	6–7	Stockholm-5
6–4	~10,400	6–7	Billingen
7	~10,000	6–7?	Gillberga (to be confirmed)
8	9,663	~8	Iggesund
9	9,439	6–7?	Sundsvall (uncertain)
10	9,428	~7	Umeå (Röbäck)
11	9,239	6–7?	Zero varve
12	~9,150	>8	Lansjärv
13	~9,000	>8	Pärve
14	~8,500	7?	Sturuman (to be confirmed)
15	~8,000	?	Hallandsåsen-2
4	~3,500	6–7	Mariefred-2
15	<2,500	6–7	Hallandsåsen-3a
15	~1,000	6–7	Hallandsåsen-3b

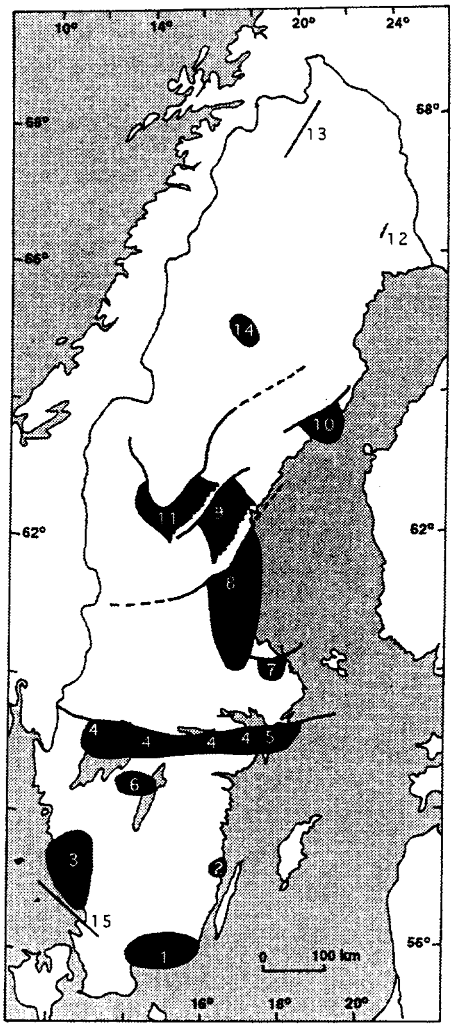

Fig. 1. Distribution of major paleoseismic events in Sweden (1-15,cf. Table 1). Dark zones mark the areal distribution of recorded paleoseismic effects. Boardering heavy lines give the corresponding ice marginal position. At the time of deglaciation, the whole of Sweden was "high-seismic", in amplitude as well as in frequency.

sions. This may affect the year assigned to an event. It does not affect the sedimentological identification of an event to a specific varve. And just here, is the strength of the method. The various signs of a paleosesmic event can be identified as to one specific varve, and this varve can – on varve chronological grounds – be correlated over a wide area. By this all signs of an event can be shown to belong to the same year (= varve). The 10,430 BP, 9663 BP and 9428 BP events have, up to now, been studied in details. It seems significant that corresponding varves, by previous varve chronologists (De Geer, 1940; Strömberg, 1989; Bergström, 1968), had been noted as peculiar varves cutting over several individual drainage basins.

By being able to assign liquefaction structures to single paleoseismic events, their areal distribution can be recorded. In the 10,430 BP case they cover an area of 320 km, and in the 9663 BP case an area of, at least, 80 km. We believe that this is of great significance as it adds a new independent measure of the intensity of the event as illustrated in Fig. 3.

Our studies of liquefaction structures and related deformational structures began in 1995 when we found some excellent road and railroad cuttings west of Stockholm where the structures and their relation to the varves and one specific varve could be studied in section after section over a length of 6 km (Mörner, 1996). Shortly after, we found an additional 8 km road section south of Stockholm where the same type of studies were performed (Tröften, 1997). In 1997, we found our first liquefaction structures of the 9663 BP event. The liquefaction structures of the 9428 BP event were found as late as in 1999.

With this material in our hands, we invited a large international excursion through Sweden, from Umeå in the North och Hallandsåsen in the South (Mörner, 1999b). By this group of highly qualified specialists from abroad we were able to analyse and discuss our observations and interpretations. Liquefaction structures of the 9428 BP, 9663 BP, 10,430 BP, Kinnarumma and Hallandsåsen-1 events (Table 1) were examined and approved.

Conclusions and implications

The paleoseismic conditions disclosed and their practical implication for the handling of long-term repositories of high-level nuclear waste are summarixed in the following five points.

(1) Sweden (Fennoscandia) was a high-seismic area at the time of deglaciation. This must be due to the exceptionally high rates of uplift.

(2) This "super-seismicity" will re-occur at future Ice Ages. As a matter of fact, it is a characteristic of glaciation/deglaciation deformations.

(3) This impies that long-term "safity" scenarios become illusive and unfounded. The Fennoscandian bedrock cannot offer any "safe" repository for periods entering into and passind future Ice Ages.

(4) An alternative method of deposition must be used. We believe that the DRD (Dry Rock Deposit) method is the answer (Mörner *et al.*, 1999).

(5) The DRD method refers to an artificially drained bedrock repository, where the waste is placed under constant controll and where it remains accessable for the good (the application of future methods of randering the waste harmless) and for the bad (the need of reparations).

In Fig. 4 we compare the long-term safity of the KBS and DRD methods with respect to an arbitrary safity scale (0 to 5). At the First Future Ice Age all safity estimates break down (with removal for a DRD and damage for a KBS repository).

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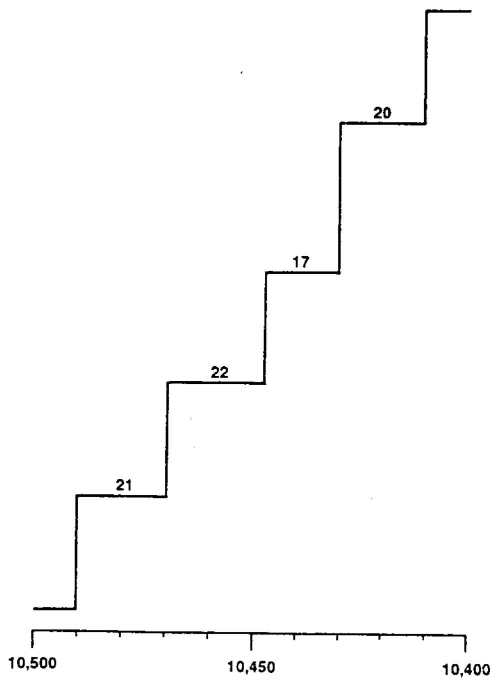

Fig. 2. Cumulative seismic events from the Stockholm area with figurs on each step giving time in varve years

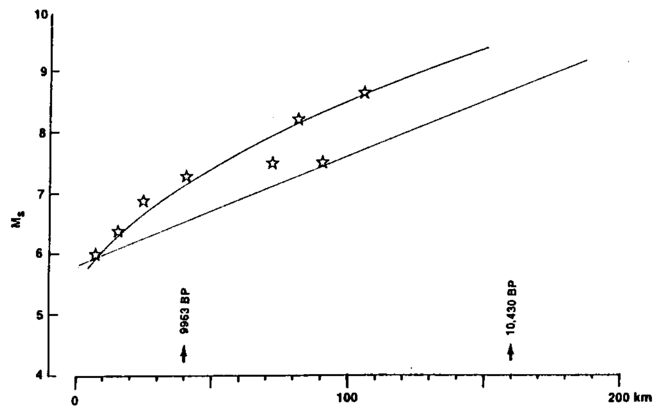

Fig. 3. Relations between instrumental magnitude (Ms) and areal distribution of liquefactions(stars) and the half distance areal occurrence of liquefactions at the 9663 and 10,430 BP events.

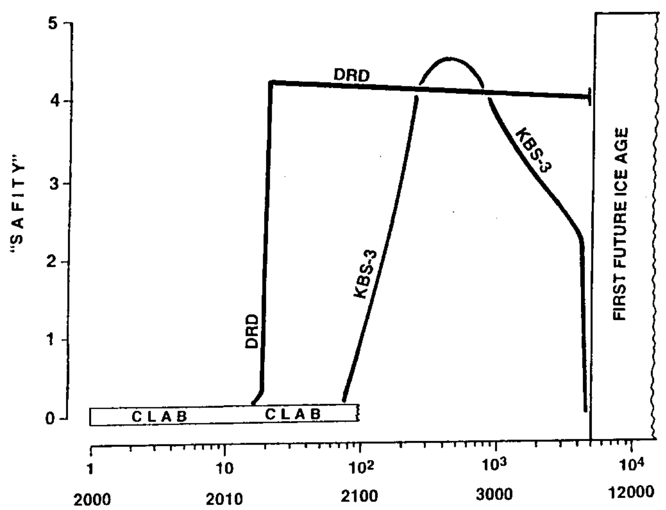

Fig. 4. Compatisions between the DRD and KBS-3 methods with respect to long-term safity on an arbitrary scale from 0 to 5. At the First Future Ice Age all safity estimates break down. Whilst a DRD repository can be moved, a KBS-3 repository is left for destruction.