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and industrial research

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SEISMOTECTONIC RISK MODELLING FOR NUCLEAR WASTE DISPOSAL IN THE SWEDISH BEDROCK

by

F. Ringdal, H. Gjøystdal and E.S. Husebye

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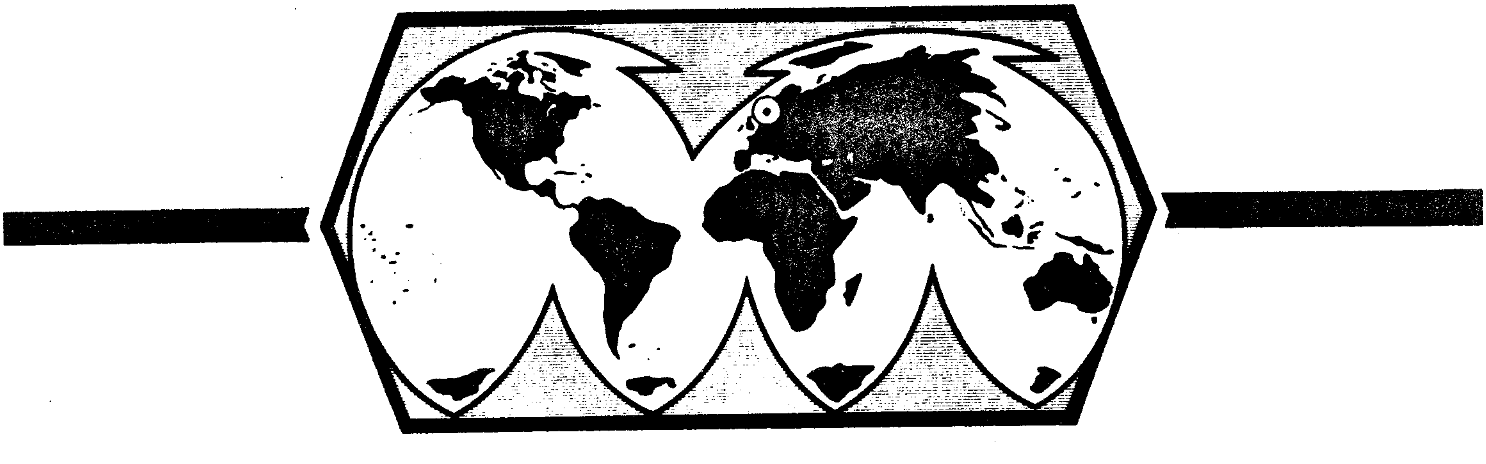

Abstract

The problem studied in this report concerns geotectonic risk factors for nuclear waste canisters stored underground in the Swedish bedrock, and embedded in tunnels filled with a clay-like material. The tectonic events causing potential damage can be classed as (i) earthquakes and (ii) creep motion. The numerous existing faults observed in Sweden are in general the results of past orogenic cycles, dating several hundred million years back in time. Only a few faults have shown surface movements after the most recent glaciation (ending about 8000 years b.p.), and in most cases such neotectonic movements have occurred along already existing zones of weakness.

The most relevant tectonic forces presently acting on the Fennoscandian region are due to (i) glacial rebound, (ii) remnant stresses from past orogenic cycles and (iii) mid-oceanic ridge push forces. Existing data are too scarce to allow a reliable separation of these components. The uplift of Fennoscandia is very smooth, and this implies that the probability of differential movements (or faulting) in this connection is low. A statistical analysis of the lengths and orientations of major faults in Sweden has shown that the distribution of fault lengths is approximately lognormal with a mean of 10-15 km and a standard deviation corresponding to a factor of two. Moreover, the fault density and distribution is quite similar over all of the Swedish area. The present seismicity of Sweden and surrounding areas is low, but occasional earthquakes of magnitude around 6 have been observed in historic times. Estimated depths of observed earthquakes are mostly 10 km or more, thus the expected seismic effect at the planned depths of canister storage will be small. Surface faulting of Swedish earthquakes is at present seldom, if ever, observed. Normal faulting is generally to be expected for Swedish earthquakes, although no fault plane solutions have yet been found in this area. A model has been developed to compute the probability of a storage area being intersected by a known or unknown fault. The model is based upon lognormal distribution of fault lengths and a random orientation of the faults with all directions having equal probability of occurrence. The model is used in conjunction with the assumption that the rate of creation of new faults has remained constant over the past 1500 million years, and will remain so in the future. The probability of a new fault created during the next 10,000 years intersecting a given circular storage area of 1 km radius is then of the order $5 \cdot 10^{-6}$.

1. INTRODUCTION

The problems associated with the disposal of radioactive wastes produced by nuclear power plants are often cited as one of the principal drawbacks to the operation and in particular to the expansion of energy generation by nuclear fission processes. The reason for this is two-fold: firstly, the generation of radioactive material in any form has become a highly emotional issue and thus is not always subjected to rational thinking, and secondly, in the past scant attention has been given to the problem of safe storage of wastes produced in nuclear power plants. Today, the situation is strikingly different; many countries are now planning to base their future energy supply on nuclear power and consequently the waste storage problem has come into focus during the last few years, both as an integral part of nuclear power plant operation and in connection with growing public environmental concern.

There are many facets of the problem of safe storage of nuclear wastes, and some of the issues being considered concern the requirements for temporary surface storage of wastes, the extent and necessity of reprocessing of wastes, and the choice of environment for final deposition. With respect to the latter consideration, several suggestions have been forwarded, e.g., extraterrestrial disposal via rockets, deep deposit in oceanic subduction zones of the lithosphere, sedimentary burial in the oldest parts of the oceans, storage in salt mines and finally depositing the wastes in the deep bedrock (e.g., at depths of around 5-600 m) in apparent geologically stable areas like the Baltic Shield. For a number of reasons disposal in not easily accessible areas like the oceans is currently out of question, so besides salt mines, bedrock storage is most actual. Indeed the topic of this report is restricted to considerations relevant to storage of nuclear wastes in deep bedrock in Sweden. Therefore, the main problem addressed in the following will be the question of the stability of the Swedish bedrock, or more specifically, the probability of extensive damage to nuclear waste canisters buried in tunnels at depths of 5-600 m in carefully selected areas in Sweden.

In Section 2 of this report the general problem of nuclear waste handling is discussed. The general tectonic setting of Sweden and Fennoscandia is reviewed in Section 3, with particular attention to the stability of the geotectonic formations. Section 4 is devoted to an assessment of the seismicity of Fennoscandia and the expected fault movements caused by earthquakes in this region. In Section 5 a probabilistic model of the tectonic fault pattern in Sweden is developed, and is used to estimate some of the risk factors resulting from geotectonic forces and relevant to the storage of canisters in bedrock. Section 6 presents the main conclusions of this study.

2. GENERAL PROBLEM FORMULATION

Although this report addresses specifically the risk of geotectonic breakage of nuclear waste canisters placed in the deep bedrock (depths of the order of 500 m) of Sweden, this problem is not independent of certain disposal strategy factors like canister concentration, number of storage areas, canister 'life' if not subjected to geotectonic forces and so on. In order to adopt the proper scenario for our risk studies, we will briefly comment on relevant factors of the above kind.

2.1 Initial Stage of Nuclear Waste Handling

Prior to disposal of nuclear waste, temporary retention in special storage tanks preferably close to the plant itself is generally recommended on economic, technical and not the least safety grounds (for references see Cohen, 1977; and de Marsity et al, 1977). Without indulging in details on some controversial viewpoints concerning the above factors, we will just remark that delayed burial is an efficient way of ensuring relatively low temperatures within the canisters themselves as illustrated in Fig. 2.1 and will thus minimize the risk of premature leakage of radioactive wastes due to canister material failures.

2.2 Canister Design and its Durability

Essential to the safe storage of nuclear wastes even in deep underground tunnels is that the canisters and associated types of radioactivity barriers should remain intact for a considerable length of time. The reason for this is simply that the half-life of a significant portion of the radioactive elements constituting the nuclear waste is much larger than the transport time due to ground water circulation between leaking canisters and the surface or biosphere. This transport time is highly dependent on the types of rocks in which the waste canisters are to be stored and in this respect rocks with low permeability are essential. In certain adverse circumstances with the repository bedrock having relatively high permeabilities, the transport time ranges from 6 to 600 years (as illustrated in Table 2.1) and consequently in such cases canister breakage just after deposition can have potentially severe effects. On the other hand, if the canisters and associated barriers like clay embeddings have a 'life span' as an effective retainer of the radioactivity of the order of 10^4 years, then the transport time of radioactive elements

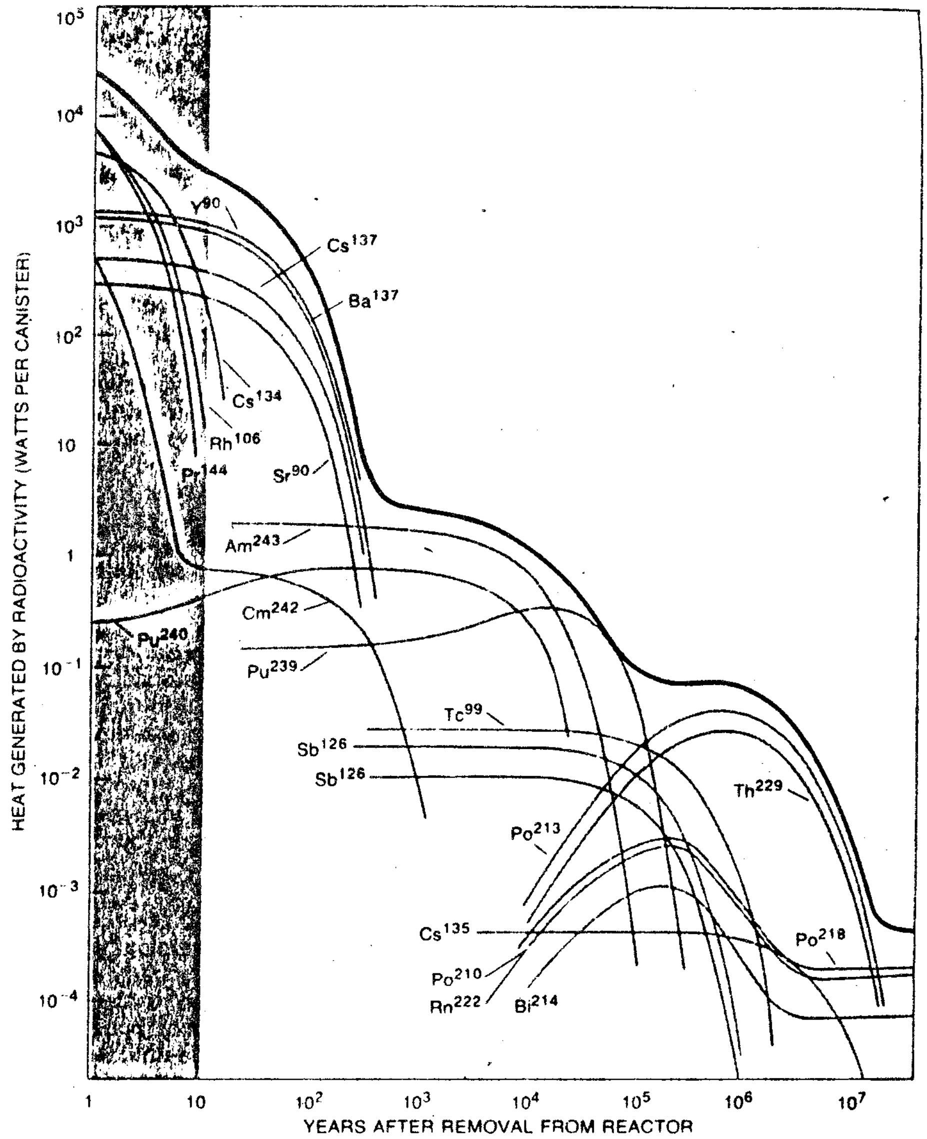

Fig. 2.1 Heat generated by the various radioactive isotopes in the spent fuel from a nuclear power plant must be allowed to dissipate safely, which means that in any long-term storage plan the canisters containing the high-level wastes must be spread out over a fairly large area. The problem can be substantially alleviated by resorting to an interim-storage period of about 10 years (colored panel at left), after which the heat generated by each canister will have fallen off to about 3.4 kilowatts. The gray curves trace the contributions of the more important radioactive isotopes to the overhall heating effect, which in turn is indicated by the black curve. (Figure after Cohen, 1977).

would be delayed by the same amount. Although we do not have exact figures available, such a lifetime does not appear unreasonable and furthermore even longer lifespans may well be feasible. An argument sometimes used for long lifespan of glass is its existence in natural form. In the subsequent geotectonic risk analysis of waste storage, a time interval of 10^4 years will be used as the standard time period during which to compute the probability of breakage due to geotectonic factors.

Suggested prototypes for canisters most often are cylindrical with height substantially longer than 'width or diameter'. If this is the case, a vertical storage mode of the canisters is recommended, since as will be shown later, geotetonic movements in Sweden are predominantly vertical. Moreover, the canister location pattern should be slightly irregular.

2.3 Types of Geotectonic Risk Factors

The type of canister damage to be considered here is that of a relative dislocation of one part of the storage area with respect to the other part. During earthquake faulting (predominantly normal faulting within stable shield areas like Sweden), this movement takes place within a few seconds. However, a dislocation may also take place over a considerable time span (e.g., a few tenths of millimeter a year), and in such cases the movement is classed as a creep process. What we do not know exactly is the extent of canister damage as a function of the amount of dislocation as well as rupture velocity. Laboratory experiments bearing on this type of problems have been conducted by Pusch (1977), but the outcome of this study relates mainly to 'creep' movements and is not considered entirely relevant for movements due to earthquakes.

2.4 Depth of Burial of Nuclear Wastes in Presumed Stable Geological Formations

The proper bedrock depth appears to be around 5-600 m although factors governing this choice are seldom stated. What we know is that the depth parameter would not be critical for the effect of increased transport time of radioactive elements due to ground water circulation, nor to the

2.1 a Parameters of the geologic formations.

Geologic formation	Darcy's permeability (m/sec)	Hydraulic gradient	Effective porosity (%)	Resulting velocity of water: Darcy's (m/sec)	Resulting velocity of water: Mean pore (m/sec)
1	10^{-6}	1/10	2	10^{-7}	5×10^{-6}
2	10^{-6}	1/50	2	2×10^{-8}	10^{-6}
3	10^{-7}	1/50	5	2×10^{-9}	4×10^{-8}
4	10^{-8}	1/50	10	2×10^{-10}	2×10^{-9}
5	10^{-10}	1/50	20	2×10^{-12}	10^{-11}

2.1 b Step function responses of each element

Geologic formation	Mean pore water velocity (m/sec)	Transmission rate of the formation (%)	Duration of transfer (years)
	*Iodine-129 (half-life 1.6 × 10^7 years)**		
1	5×10^{-6}	100	6
2	10^{-6}	100	29
3	4×10^{-8}	100	725
4	2×10^{-9}	99	14,500
5	10^{-11}	93	2,840,000
	Neptunium-237 (half-life 2.13 × 10^6 years)†		
1	5×10^{-6}	99.7	10.500
2	10^{-6}	99	52.500
3	4×10^{-8}	91	505,000
4	2×10^{-9}	43	14.9×10^6
5	10^{-11}	10^{-16}	3.3×10^7
	Plutonium-239 sorbed (half-life 2.44 × 10^4 years)‡		
1	5×10^{-6}	8×10^{-6}	1.4×10^6
2	10^{-6}	3×10^{-21}	6×10^6
3	4×10^{-8}	0	
4	2×10^{-9}	0	
5	10^{-11}	0	
	*Plutonium-239 not sorbed (half-life 2.44 × 10^4 years)**		
1	5×10^{-6}	100	6
2	10^{-6}	100	29
3	4×10^{-8}	99	725
4	2×10^{-9}	80	14.500
5	10^{-11}	6×10^{-11}	2,840,000

*Distribution coefficient, 0. †Distribution coefficient, 15 ml/g. ‡Distribution coefficient, 2000 ml/g.

2.1 c Concentration of elements in the water reaching the human environment expressed as ratios to the maximum permissible concentrations in drinking water. Hypothesis 1 refers to the case of no canister damage, diffusion only. Hypothesis 2 refers to the case of canisters remaining intact for the first 10,000 years, the breaking and leaking taking place for the next 5,000 years.

		Hypothesis 1		Hypothesis 2	
Geologic formation	Transmission rate of the formation (%)	Ratio of concentration to the maximum permissible concentration	Time when maximum is observed (years)	Ratio of concentration to the maximum permissible concentration	Time when maximum is observed (years)
		*Iodine-129 (half-life 1.6 × 10⁷ years)**			
1	100	1.4×10^{-2}	5	0.58	10,000
2	100	7×10^{-2}	25	2.9	10,000
3	100	0.7	600	28.0	10,700
4	99	5.1	10,000	250.0	20,000
5	93	5.3	1.7×10^{6}	170.0	1.45×10^{6}
		Neptunium-237 (half-life 2.13 × 10⁶ years)†			
1	99.7	1.6×10^{-4}	10,000	0.67	18,000
2	99	7.7×10^{-4}	47,500	1.13	40,000
3	91	6×10^{-3}	380,000	1.13	275,000
4	43	1.3×10^{-2}	3,000,000	0.57	2,400,000
5	10^{-16}	3.6×10^{-19}	87×10^{6}	6.2×10^{-18}	83×10^{6}
		Plutonium-239 sorbed (half-life 2.44 × 10⁴ years)‡			
1	8×10^{-6}	7×10^{-12}	475,000	3×10^{-9}	460,000
2	3×10^{-21}	5×10^{-27}	1,200,000	1.4×10^{-24}	1,150,000
3	0	0		0	
4	0	0		0	
5	0	0		0	
		*Plutonium-239 not sorbed (half-life 2.44 × 10⁴ years)**			
1	100	4.7×10^{-4}	5	1.3	10,000
2	100	2.3×10^{-3}	25	6.0	10,000
3	99	2.3×10^{-2}	600	66.0	10,700
4	80	0.16	11,000	470.0	20,000
5	6×10^{-11}	1.7×10^{-12}	730,000	8.5×10^{-10}	700,000

*Distribution coefficient, 0. †Distribution coefficient, 15 ml/g. ‡Distribution coefficient, 2000 ml/g.

Fig. 2.1 Simulation experiment for transmission rates, durations of transfers, relative concentrations and time of maximum for radioactive elements constituting a significant portion of the fuel waste from light water reactors. Notice that the permeability and absorption of the geological environment is of critical importance. Data taken from de Marsity et al (1977).

'stability' of the bedrock itself. To our knowledge, after searching both the available KBS-reports and relevant literature, we have been unable to find strong arguments for particular parameters which in turn should govern the depth of burial of the nuclear wastes. Intuitively, we do consider that the arguments in favor of the 5-600 m canister burial depth run as follows: In anticipation of future human activities a certain minimum depth of burial is mandatory, say of the order of 100 m. Furthermore, the permeability is likely to decrease with depth, while absorption of leaking radioactive material increases with depth. On these grounds a minimum depth of around 400 must be ensured but by greatly exceeding this depth (say larger than 800 m) the gain would probably become marginal. Anyway, we recommend that KBS undertake a detailed study of this problem.

We note that Båth (1977) has indicated that depths exceeding 1000 m are preferable in view of a slight increase of compressional P-wave velocity with depth as observed in a small experiment in the Bergslagen district, central Sweden. In our opinion, correlating depth of burial of waste canisters with local seismic velocity anomalies is rather an oversimplification of the risk problem at hand.

3. GEOTECTONICS OF FENNOSCANDIA

Fennoscandia constitutes the western part of the Baltic Shield which is rated as a stable area from a geological point of view. The Baltic Shield in turn is part of the Eurasian plate, which is moving slowly northeastwards at a rate of only about 2 cm/year. The nearest plate boundaries (generally characterized by rather strong earthquake activity) are the mid-oceanic ridges and fracture zones in the Norwegian Sea (for a comprehensive discussion of the tectonics of the latter area, see Husebye et al, 1975).

The topic of this section is to discuss the geotectonic stability of Fennoscandia with particular attention to the potential of damage to deeply embedded nuclear waste canisters due to geotectonic forces.

3.1 Geotectonic Development of Fennoscandia

The geological history of Fennoscandia covers a time span of more than 2 billion years during which period this region has been through several orogenic cycles. One of the most prominent is the Caledonian folding period which took place some 500 million years ago. What actually happened here was that the North American plate including Greenland collided with the Eurasian plate, a process which subsequently 'generated' the coastal mountains in Norway. Another major tectonic event in the past was the formation of the Oslo Rift and the Oslo graben which took place during Permian time and was associated with strong magmatic activity. This area is of particular interest in seismo-tectonic studies, as the largest earthquakes felt in southern Scandinavia during the last 500 years are located on the Oslo Rift and its 'branches' in the Skagerrak and Kattegat seas as shown in Fig. 3.1 (see also Husebye and Ringdal, 1977; and Husebye and Ramberg, 1977). Another geotectonic fault zone of interest in the present context is the Fennoscandian Border Zone which marks the boundary between Fennoscandia and the relatively mobile North Sea area, and furthermore can be recognized as a major structural feature during much of the post-Caledonian history of northwest Europe. This border zone is rather broad and besides is characterized by block faulting. The horst and grabenlike depressions in Skåne (Hallandsås-Kullen towards

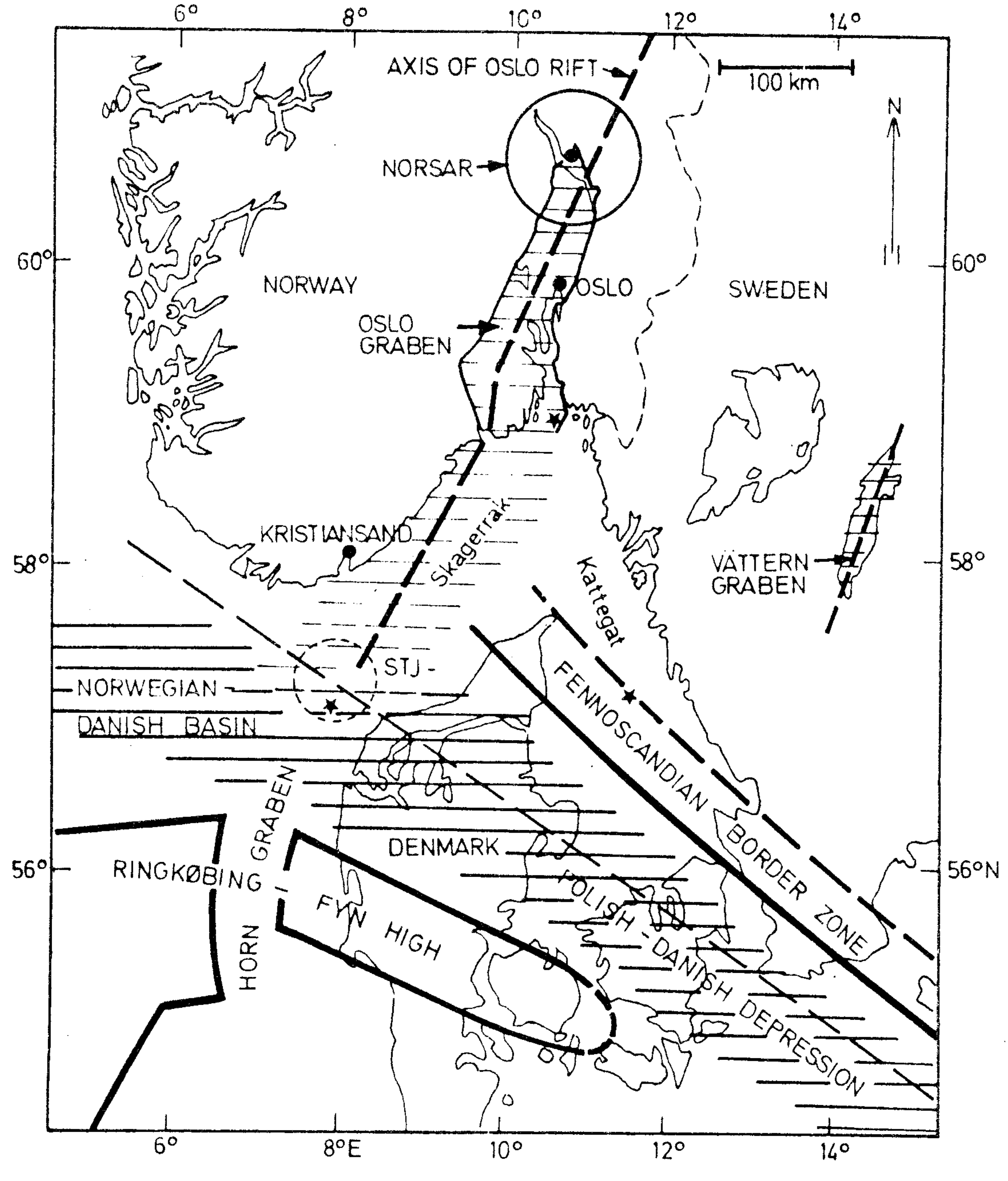

Fig. 3.1 Tectonic setting of the general Oslo Graben - Oslo Rift area. The diameter of the NORSAR array is indicated by a circle, while the presumed locations of the 3 largest recorded earthquakes are marked by stars. STJ - presumed location of the Skagerrak triple junction. (Figure redrawn from Husebye and Ramberg, 1977).

NW and Ystad-Simrishamn towards SE) are generally interpreted as manifestations of the border zone which also appears to 'cross' Bornholm (Sorgenfrei and Buch, 1964). We remark that the Fennoscandian Border Zone is not very active seismically with the exception of the 1759 earthquake. However, it should be mentioned that the Fennoscandian Border Zone does appear to be associated with seismic, gravimetric and magnetic anomalies.

In the foregoing we have commented in some detail on the youngest geotectonic features reasonbly close to Sweden. Naturally, large-scale tectonic movements took place prior to Cambrian times and their geological manifestations are also indicated in Fig. 3.2. These developments are discussed in some detail by Stephansson and Carlsson (1976, 1977). We refrain from further comments on the associated geotectonic features as the 'coupling' between present day creep movements and earthquake activity for all practical purposes seldom amounts to more than pure speculation in view of the scarcity of relevant observational data. What we know, however, is that part of the stresses generated during orogenetic cycles with ages of the order of 10^8-10^9 years ago may still be 'stored' in the bedrock in the areas most strongly affected by the associated movements. This simply means that borderlines between geotectonic provinces and areas intersected by megafaults in general should be avoided as nuclear waste storage areas.

3.2 Stress Measurements in Fennoscandia

A large number of stress measurements have been undertaken in Fennoscandia, notably by Hast (1969, 1973) and some of these are indicated in Fig. 3.2. Recently Ranalli and Chandler (1974) have published a critical review of available stress measurements on a global basis and concluded that many of reported observations were not particularly reliable and furthermore not easily correlated with intraplate earthquake observations. This does not necessarily imply that this type of observations are not important for mapping stress anomalies but only indicates that further refinement of measurement techniques as well as theoretical studies are needed before more widespread usage can be made of such data for mapping 'active' fault zones with a given area.

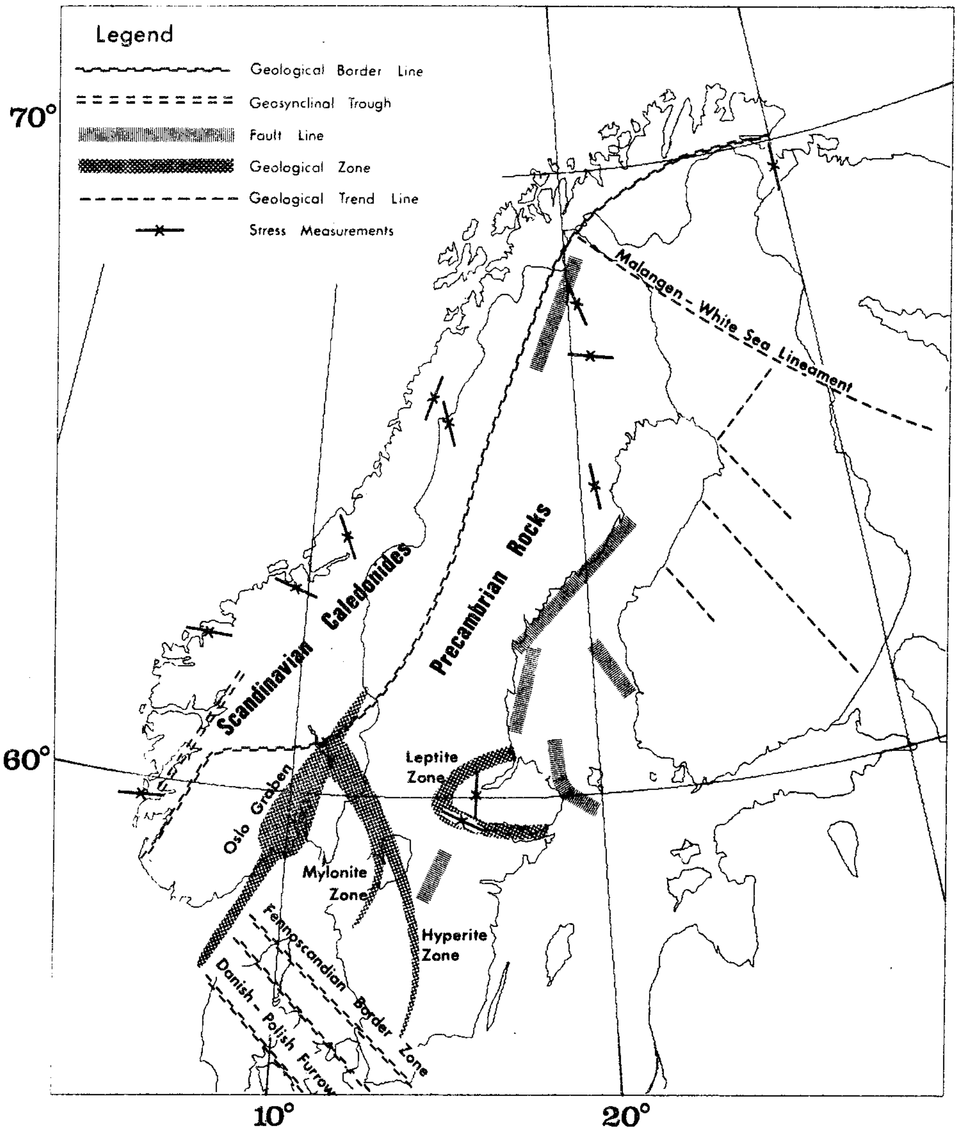

Fig. 3.2 Sketch map showing geological and tectonic trends and structures which are considered relevant for our Fennoscandian seismicity study. The in-situ stress measurements plotted are taken from Hast (1973) and Ranalli and Chandler (1975). The Oslo Graben continues both northward and southward as the Oslo Rift Zone. The mylonite, hyperite and leptite zones with ages of the order of 1000 million years or more are redrawn from Stephansson and Carlsson (1976), while the fault lines in the Baltic Sea are redrawn from Flodén (1973). The Vättern graben structure in S. Sweden (Lindh, 1972) and the holozen Pärve fault in N. Sweden (Lagerbäck and Henkel, 1977) are also shown. The geological trend lines in Finland are after I.B. Ramberg (1973), while the Malangen-White Sea lineament is after Tuominen et al (1973).

In general, the stresses on a system are usually specified with respect to an orthogonal set of axes, referred to as the principal axes of stress. These axes are chosen such that the stresses along the axes are purely compressive, there being no shear stress. The stress components relative to these axes are called the principal stresses and are designated by σ_1 (maximum), σ_2 (intermediate) and σ_3 (minimum). It can be shown that when failure occurs, it occurs along a plane in the direction of the intermediate stress and is independent of the value of the intermediate stress. Thus, for consideration of failure criteria, it is necessary to consider only the values of maximum and minimum compressive stresses. In the Earth the direction of the principal stresses with respect to the surface can be used to determine the type of faulting environment Normal faulting occurs where the vertical stress component is the maximum principal stress; thrust faulting where the vertical stress is the minimum principal stress and strike slip faulting where the vertical stress is intermediate principal stress. Within tectonic plates the vertical stresses (loading effects) are usually largest at depths where earthquakes occur, thus normal faulting is commonly observed in such areas. Occasionally strike slip faulting is reported (Sbar and Sykes, 1973). To summarize, for regions located within plates like the area of Sweden, tectonic movements are likely to be predominantly vertical.

3.3 Current 'Tectonic' Forces Acting on the Area of Sweden and Neotectonic Movements

As mentioned previously, Sweden is part of the Eurasian plate, which moves in a generally northeasterly direction at a rate of about 2 cm/year. The decoupling between the moving plates and the underlying upper mantle is assumed to take place in the (horizontal) boundary zone between the lithosphere (thickness of the order of 200 km in Fennoscandia (Ringdal and Husebye, 1977)) and the relatively high-viscosity asthenosphere. Presently, the plate driving mechanism(s) is not well understood, though it is generally assumed that they must be tied to large-scale convective movements in the mantle. A typical problem here is whether the lithosphere is sliding over the asthenosphere or, althernatively, the lithosphere is 'dragged along' by the asthenosphere. Whether this relative movement between the lithosphere and the asthenosphere generates significant

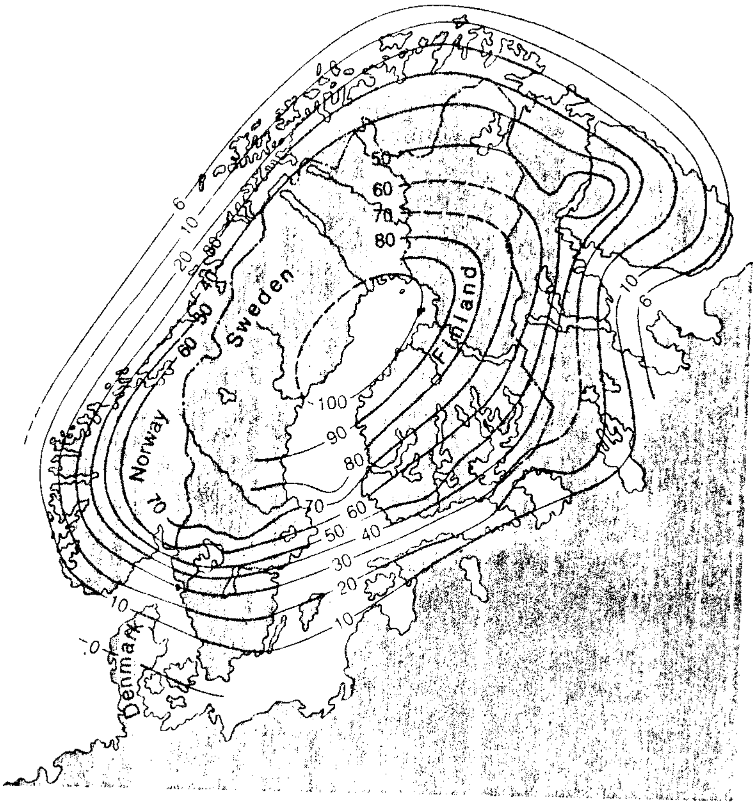

Fig. 3.3 Rate of uplift in (mm x 10)/year in Fennoscandia, redrawn from Press and Siever (1975). Notice that uplift rates presented by, for example, Mørner (1977) and Kukkamäki (1975) are slightly different reflecting the scarcity of observational data.

stress is not well known, but we remark in passing that intraplate earthquake occurrence usually takes place at depths around Moho (i.e., 30-40 km) or shallower, and is thus well removed from the lithosphere-asthenosphere boundary zone characterized by a small viscosity.

Many types of tectonic forces acting on a plate have been proposed and those most actual to Fennoscandia and Sweden have been discussed in some detail by Husebye et al (1977). From the latter work we have that the most relevant tectonic forces in the present context are:

1) Glacial rebound
2) Remnant stresses from past orogenic cycles
3) Mid-oceanic ridge push forces.

Let us add here that in the future (time span of the order of 10^4-10^6 years) we do not foresee that Fennoscandia should be subjected to other, more adverse types of tectonic forces. A new period of glaciation is sometimes suggested (Mørner, 1977), but we do not consider that this would significantly alter the risk associated to the waste canister environment. We argue here that with the relatively gentle topographic relief of Sweden very adverse erosion is not expected and that the probability of significant new fault formation would be small (discussed in next section).

Of the tectonic forces listed above, that of glacial rebound has been studied in greatest detail (e.g., see Bjerhammar, 1977; Cathles, 1975, Tapponier, 1974), but nonetheless its coupling to present day earthquake activity and neotectonic movements remains unclear. By a combination of ancient (postglacial) shore line measurements, present day precision levellings and inclusion of eustatic effects, it has been deducted that the total uplift (reckoned from about 8000 y.b.p.) is around 800 meters while the maximum gradient now is about 1 cm/year (e.g., see Mørner, 1977; Bjerhammar, 1977). The area of Fennoscandia still being uplifted and the associated gradients are displayed in Fig. 3.3. There is one aspect of the glacial rebound of interest to the canister risk analysis, namely, whether the uplift is smooth or results in some sort of discontinuous block movements. There is no strong evidence that the

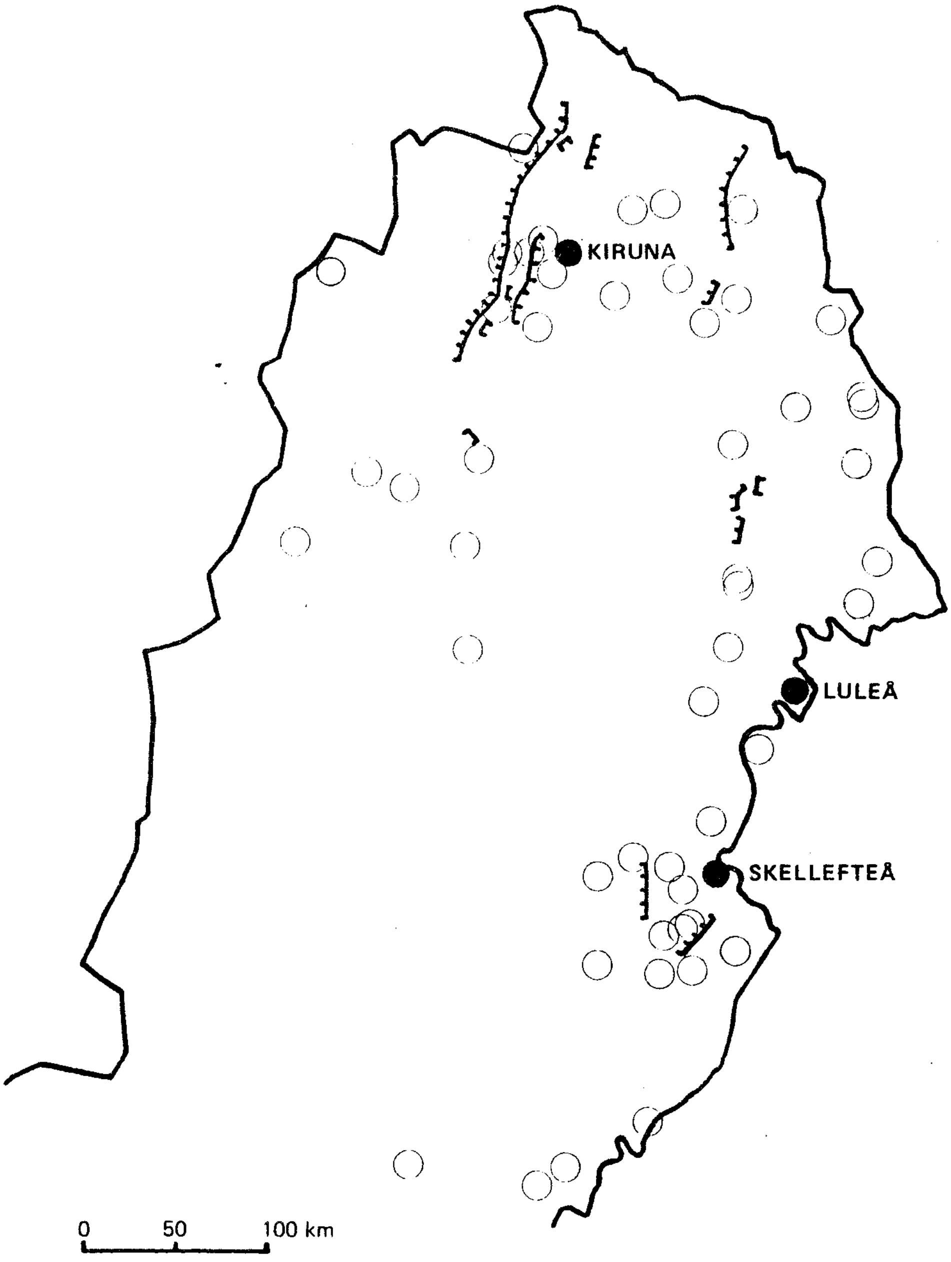

Fig. 3.4 Neotectonic movements in N. Sweden presumed to have a post-glacial origin (after Lagerbäck and Henkel, 1977). The small bars on the fault lines indicate direction of downfaulting. The dominant Pärve fault is located just west of Kiruna. The open circles mark earthquake occurrence for the period 1960-1977 (Båth, 1977).

latter hypothesis is generally valid although associated creep movements of this kind could be incorporated in the risk analysis. (As mentioned above there is no clear-cut correlation between present earthquake activity and rate of uplift.) We note that Mørner (1977) has suggested that the uplift taking place today is of tectonic origin or has a dominant tectonic component. This might possibly be so, although observational evidence for this hypothesis is indeed meager as also pointed out by Bjerhammar (1977) and Stephansson (personal communication). For the risk analysis itself the above controversy is of minor importance.

The other two types of tectonic forces considered, remnant stresses and mid-oceanic ridge push forces are not well understood, and their relevance to the stress field within the potential canister storage complex and nearby areas is very uncertain. Consequently, these kinds of effects are only indirectly incorporated in the risk analysis, that is, by the strong recommendation of avoiding selection of storage areas close to boundary zones between different tectonic provinces.

In general, shield like the Baltic one are rated as exceptionally stable areas, and evidence of clear neotectonic movements here is automatically rated as a geological sensation. Very recently, this type of movement has been reported to have taken place in North Sweden and also to be of postglacial origin (see Fig. 3.4, redrawn from Lagerbäck and Henkel 1977). Similar neotectonic movements were in fact first reported from N. Finland a decade ago (Kujansuu, 1964). Postglacial movements have also been reported from Skåne (the Kullen area) by Lagerlund, but a resurvey of the same area was not confirmative in this respect (Stephansson and Carlsson, 1977). Any dynamic rationale for the above neotectonic movements has only been vaguely suggested and would probably remain largely unexplained for years to come. For example, a puzzling feature here is that the Pärve fault and nearby parallel ones have their 'uplifted walls' facing each other, just like a horst structure.

In the context of nuclear waste storage, an obvious question to ask is how widespread have neotectonic movements been in Sweden, and furthermore why have such movements remained unreported until very recently? The Pärve fault was 'detected' less than 3 years ago, and in an area with modest vegetation which in theory should facilitate detection.

The same applies to the reported neotectonic movements in Finland (Kujansuu, 1964). We note in passing that the neotectonic faults do not appear to be associated with significant earthquake activity or other types of geophysical anomalies. This further adds to the apparent difficulty of 'detecting' neotectonic movements.

Returning to the question on how widespread neotectonic movements in Sweden might have been, we remark that conclusive evidence for such phenomena in the southern part of Sweden is lacking, despite the fact that this area has been the most thoroughly surveyed geologically. We also argue that neotectonic movements cannot be too widespread in the last several hundred years in view of the few large earthquakes reported and furthermore movements of this kind have not 'affected' populated areas to our knowledge.

3.4 Quantification of Faults in the Area of Sweden

In the previous sections we have commented upon the geotectonic history of Fennoscandia in general and Sweden in particular. Furthermore, some attention has been given to the most prominent faults within the region and in this respect we again refer to Fig. 3.1. However, from a nuclear waste storage point of view, these types of faults are easily avoided, as besides in this context we are mainly concerned with the probability of faulting and/or creep movements along unknown faults accidentally intersecting the canister area. An integral part of the modelling here, which is discussed in detail in Section 5, is to find the probability density function of fault occurrence in Sweden. Furthermore, if the fault directions are very uniform, one could take advantage of this in choosing the geometric pattern of canister storage layout. In general, comprehensive tectonic mapping of any area is seldom performed, but fortunately in this respect Sweden is an exception. On the behalf of KBS several tectonic surveys have been performed recently (e.g., see Lagerbäck and Henkel, 1977; and Røshoff and Lagerlund, 1977) and the basic material used here comes from geological publications and reprints, ordinary topographic maps, aircraft and satellite photography, and even magnetic mapping (N. Sweden only). Although the tectonic maps prepared by the above authors may be somewhat inaccurate in the sense that actual surveys in the field are modest, we do consider that this material

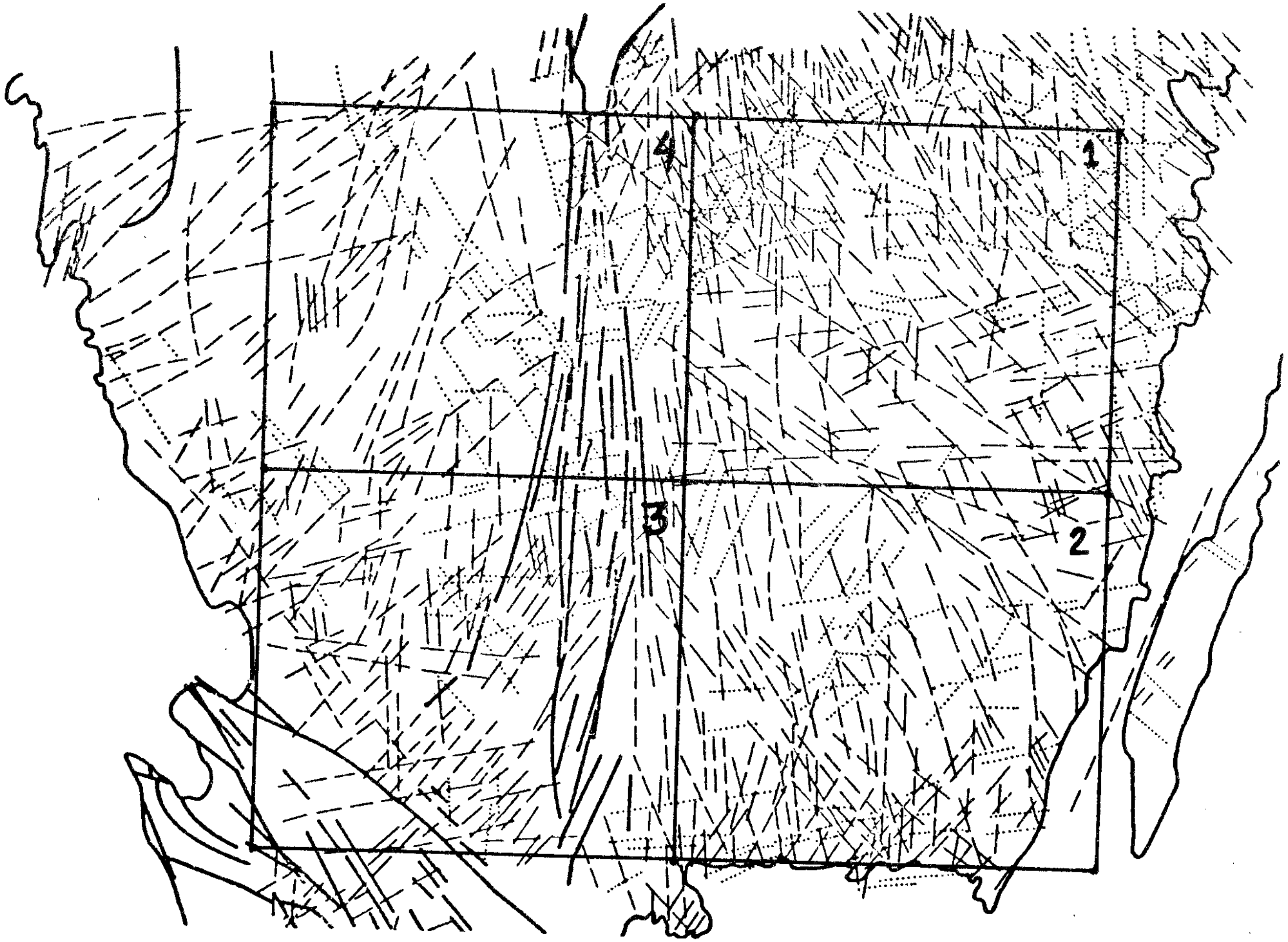

Fig. 3.5 Tectonic map over southern Sweden (after Røshoff and Lagerlund, 1977). For the fault length distribution analysis the region was subdivided in 4 areas as indicated. Map scale is approx. 1:1800 000.

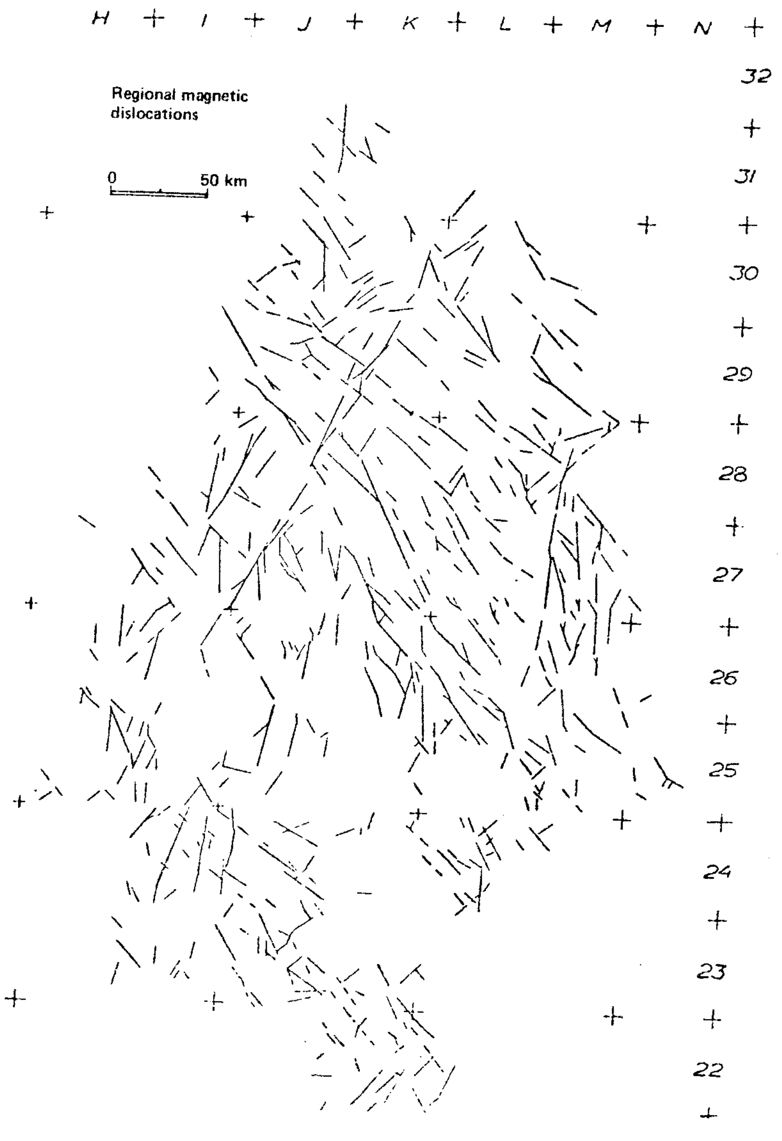

Fig. 3.6 The regional magnetic dislocation map (after Lagerbäck and Henkel, 1977) used for representing the fault length distribution in northern Sweden.

is well suited for a statistical quantization of the extent of faulting* in the Swedish bedrock. Our starting point here has been tectonic maps over southern and northern Sweden (see Figs. 3.5 and 3.6) taken from the just-mentioned reports. As shown in Fig. 3.5, we have subdivided southern Sweden into 4 areas and observed the number of first, second and third order faults falling in different length intervals. Some of the results are shown in Table 3.1 and Figs. 3.7-3.10. In case of northern Sweden the fault map was that derived from aeromagnetic anomalies shown in Fig. 3.6 (no subdivision here) and the corresponding results are displayed in Fig. 3.11.

Figs. 3.7-3.11 exhibit several interesting features which we want to comment upon in the following. First of all, the fault lengths appear to follow a lognormal distribution subject to the condition that faults have a minimum length below which the faults are classed as joints, microfractures, etc. As we shall show in the next section, this is quite reasonable from a theoretical point of view. The average fault length is of the order of 10-15 km with standard deviation of the logarithmic distribution corresponding to a factor of 2 for any part of Sweden. The number of faults per unit area (km^2) is of the order 0.01-0.02 and appears relatively homogeneous for the various areas under consideration. The fault directions are occasionally relatively uniform within limited regions, (e.g., southern Skåne) while they may vary considerably from one small area to another. Due to this variability we have in the subsequent risk analysis assumed that fault orientation exhibits no predominant direction.

There are two aspects of the tectonics of Sweden which deserve further comments, namely, i) the process of generating new faults and ii) how many faults are likely to be active at any given time. When addressing the first problem here, we argue as follows: The tectonic history of Sweden covers an interval of about 1500 mill. years as compared to the total of faults identified in the material available to us. This gives in average less than one fault per mill. years, which in turn implies that very few new faults were generated during and after the last glaciation. Not surprisingly, Lagerbäck and Henkel (1977) point out that most of the new detected neotetonic (postglacial) movements took place in ancient faults. Concerning the second problem, it is difficult to give specific numbers, as we are interested in time intervals

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* Notice that in this context the word fault is used in a rather wide sense, thus comprising prominent geological features like lineaments, valleys, breakage zones, etc.

1st, 2nd and 3rd Order Fault Distribution

Length (cm) 1 cm ~ 12.7 km		AREA 1				AREA 2				AREA 3				AREA 4				AREAS 1+2+3+4			
	log	1st order	2nd order	3rd order	Total	1st order	2nd order	3rd order	Total	1st order	2nd order	3rd order	Total	1st order	2nd order	3rd order	Total	1st order	2nd order	3rd order	Total
0.5-1	-0.30→0.0		54	22	76		39	17	56	4	37	13	54		25	22	47	4	155	74	233
1-2	0.0 →0.30		57	18	75		61	21	82	7	56	9	72	8	26	21	55	15	200	69	284
2-3	0.30→0.48		17	4	21		17	6	23	2	12	3	17	6	13	11	30	8	59	24	91
3-4	0.48→0.60		5	3	8		5	2	7	5	5	1	11	2	5	2	9	7	20	8	35
4-5	0.60→0.70		2	2	4		3		3	1	3		4	0	2		2	1	10	2	13
5-7	0.70→0.85		2		2		3		3	1	1		2	1	2		3	2	8		10
7-10	0.85→1.0		2		2										1		1		3		3
10-13	1.0 →1.11		1		1														1		1
		0	140	49	189	0	128	46	174	20	114	26	160	17	74	56	147	37	456	177	670

AREA 1 = AREA 2 = AREA 3 = AREA 4 ≈ 9000 km^2

Table 3.1 First, second and third order fault distribution in southern Sweden. The areas sampled are shown in Fig. 3.5.

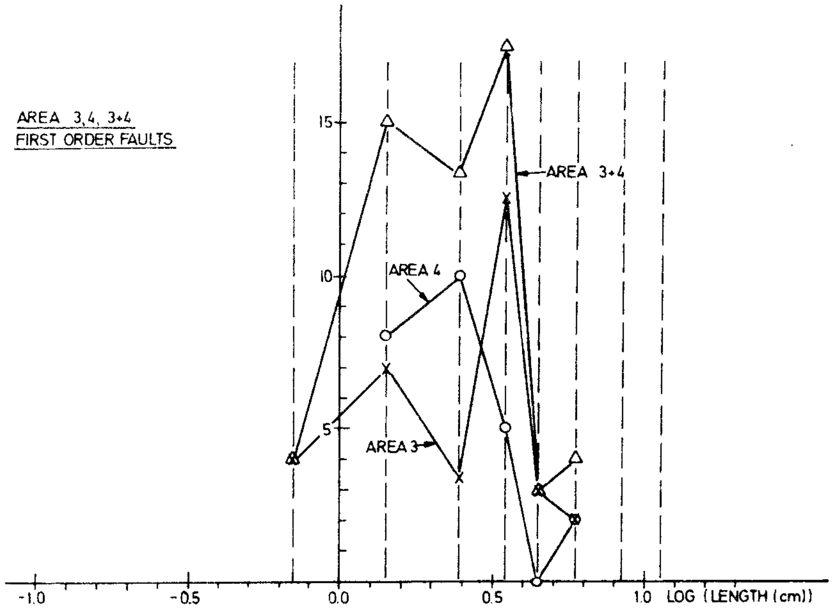

Fig. 3.7 Statistical fault length distribution for first order faults in the various areas shown in Fig. 3.5 (1 cm ~ 12.7 km).

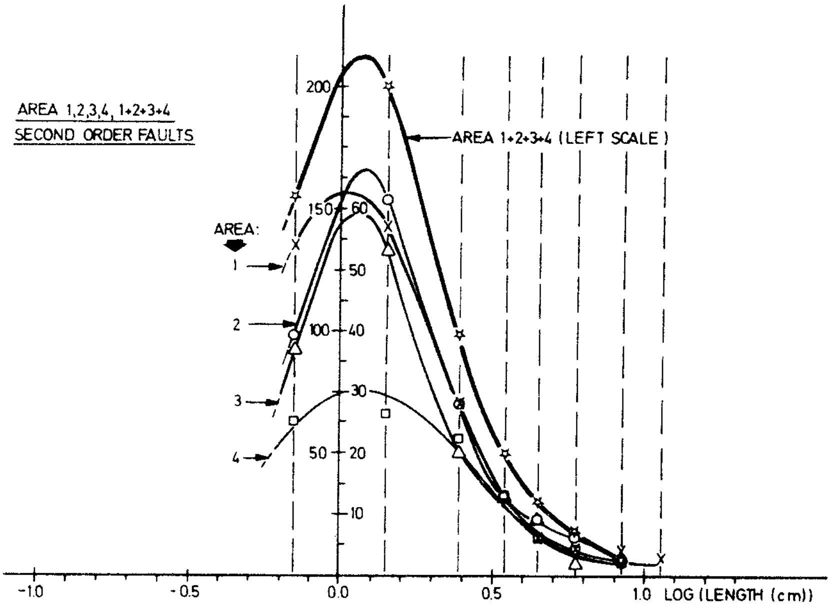

Fig. 3.8 Statistical fault length distribution for second order faults in the various areas shown in Fig. 3.5 (1 cm ~ 12.7 km).

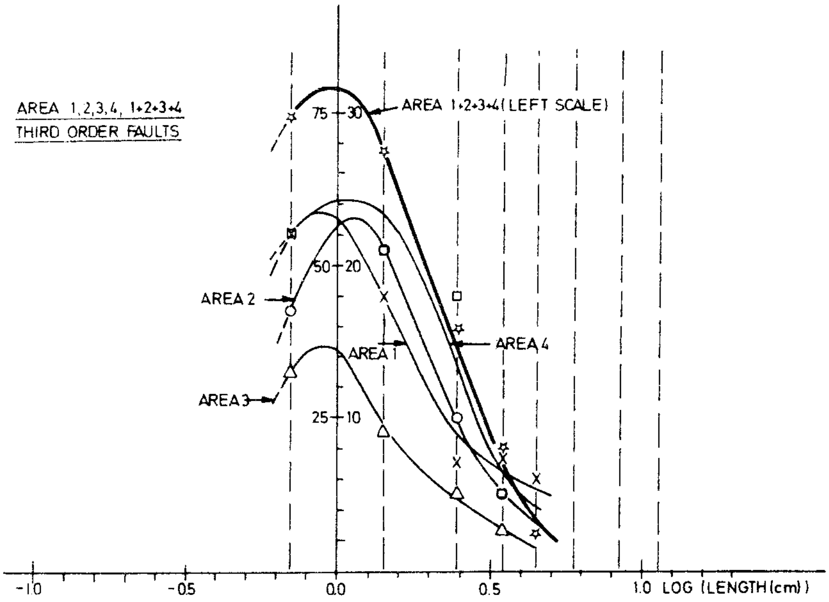

Fig. 3.9 Statistical fault length distribution for third order faults in the various areas shown in Fig. 3.5 (1 cm ~ 12.7 km).

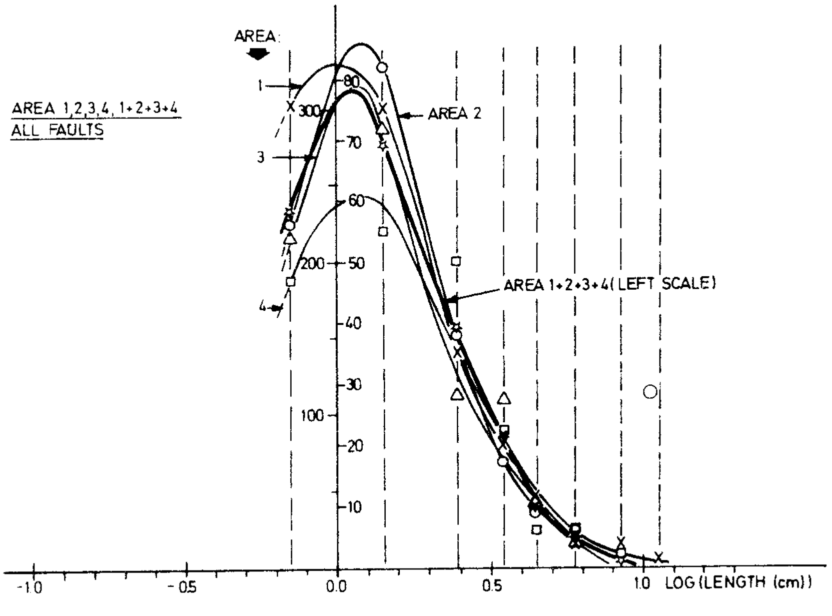

Fig. 3.10 Statistical fault length distribution for the total amount of faults in the various areas in Fig. 3.5 (1 cm ~ 12.7 km).

during which the Fennoscandian seismicity cannot be considered stationary. Based on the seismicity observed over the past few hundred years, it is possible, however, to give estimates of the 'current' activity level in this respect. We do not pursue this subject any further since it is assumed that great care will be taken in avoiding existing faults during actual storage of nuclear wastes.

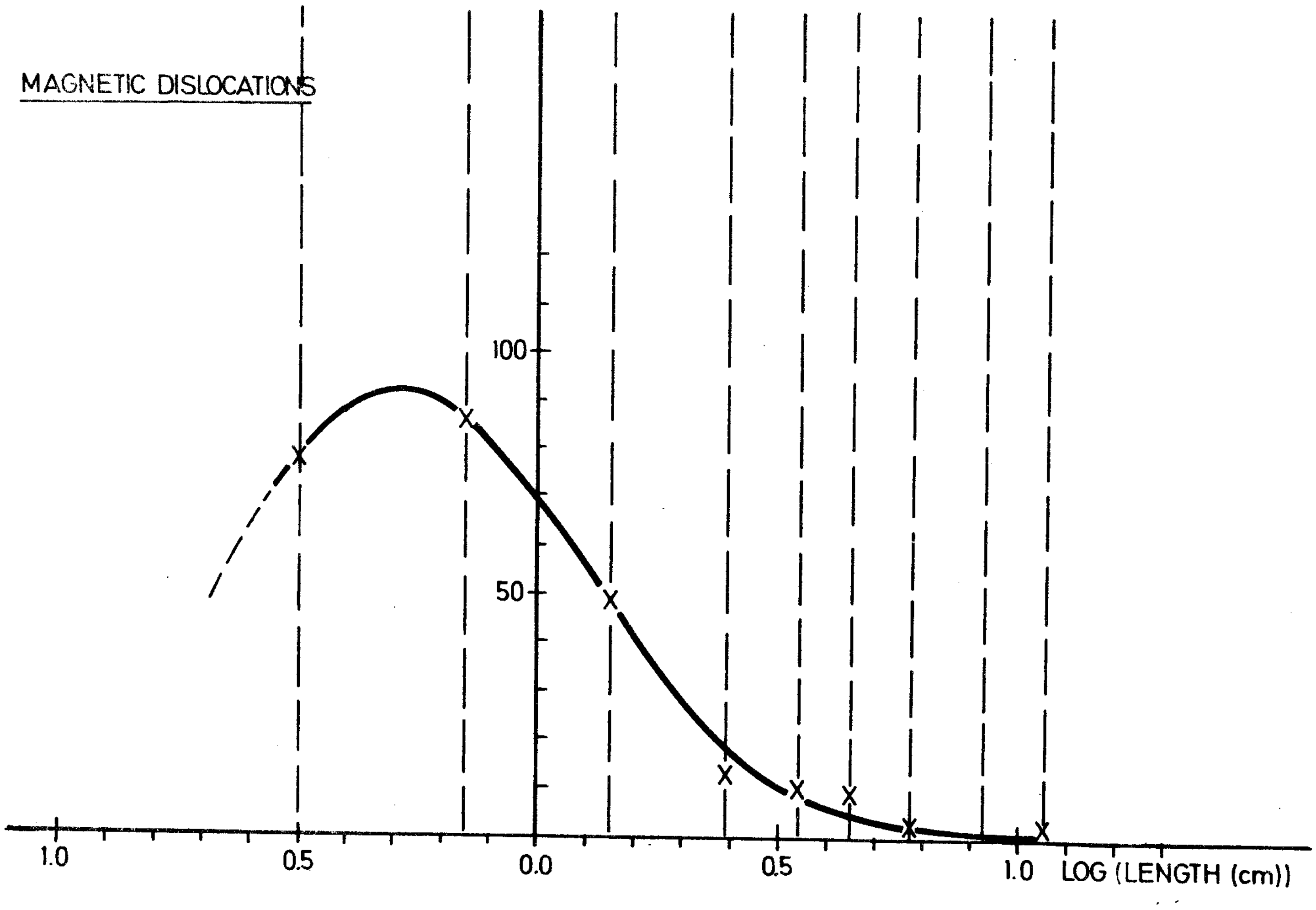

Fig. 3.11 Statistical distribution of lengths of magnetic dislocations measured from the map of Fig. 3.6 (1 cm ~ 25 km).

4. EARTHQUAKE ACTIVITY IN SWEDEN

As mentioned previously the relative movements between two blocks is manifestable by either earthquakes or sometimes by a creep process, which in turn may be associated with microearthquake activity. The latter process may be very difficult to detect unless precise levelling surveys are repeatedly performed over the area in question. From the data available now, it appears that the ongoing uplift is rather smooth, that is no creep movement along a specific (block) boundary has been reported up to now.

The earthquake occurrence has been subjected to many detailed studies in connection with seismic risk analysis for the nuclear power plants in Forsmark and Ringhals (for references, see Husebye et al, 1977; Husebye and Ringdal, 1976, 1977). In Fig. 4.1 the reported earthquake activity in Sweden and the rest of Fennoscandia is displayed covering the time interval 1497 to 1976. The largest occurring earthquakes are displayed separately. The corresponding seismicity zones are shown in Fig. 4.2. The largest earthquake occurring in recent time was that in the outer Oslofjord in 1904 with an estimated magnitude of about 6.0-6.5. The earthquake recurrence relationship parameters based on the observed seismicity of Sweden indicate that an earthquake of magnitude $M \geq 6$ takes place at intervals of about 300 years. A parameter of importance in seismic risk studies is the distribution of earthquake (focal) depths. The results obtained by Husebye and Ringdal (1977) are shown in Fig. 4.3. The depth estimates are somewhat dependent on the amount of attenuation assumed and this is also indicated in the figure. Noteworthy, however, for all considered values of the attenuation parameter, the majority of earthquakes occur at depths significantly greater than the planned depth of burial of nuclear waste canisters.

4.1 Fault Displacements as a Function of Earthquake Magnitude

The stress drop associated with earthquake occurrence which is of the order of 10-500 bar and the associated fault movements usually take place within a few seconds. What is of particular interest for assessment of tectonic risk to canister waste storage is the size of the fault area subjected to movements and the associated ground displacement.

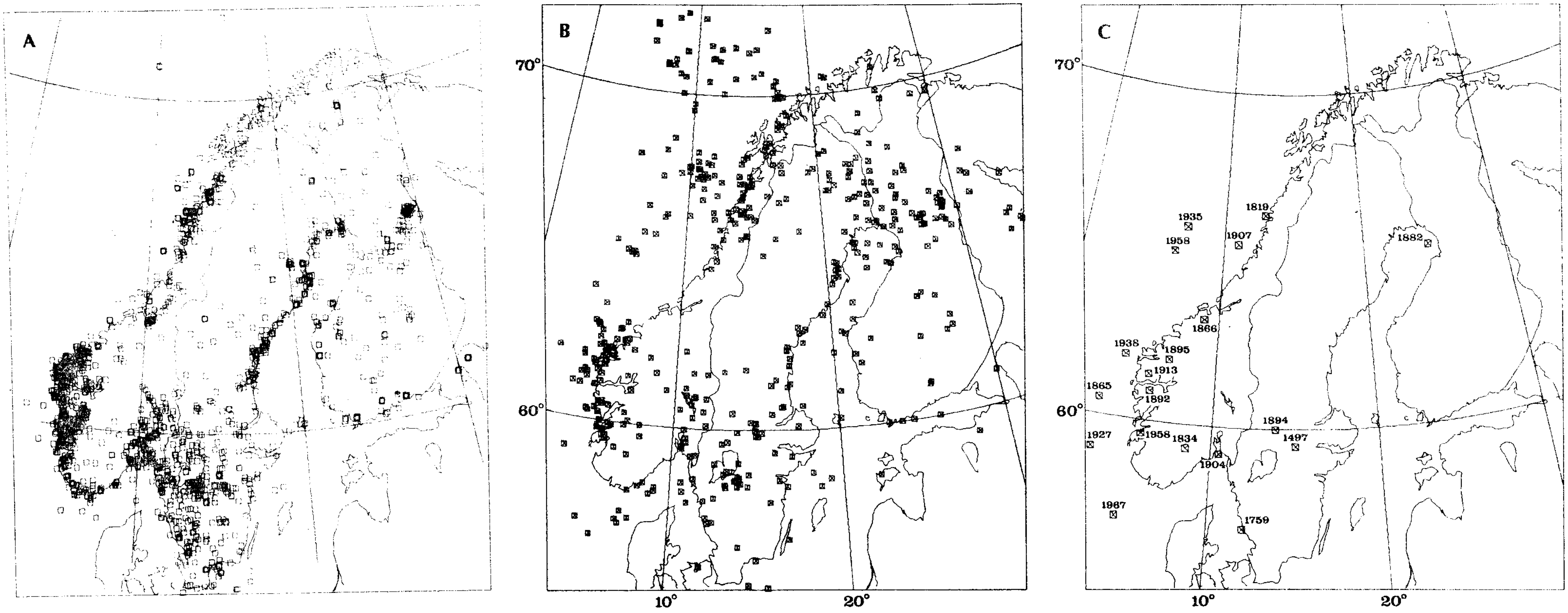

Fig. 4.1 A. Reported earthquakes in Scandinavia between 1497 and 1950 based mainly on so-called macroseismic observations.

B. Reported earthquakes in Scandinavia between 1951 and 1975 based on instrumental recordings.

C. Assumed epicenters of the largest known earthquakes in Scandinavia. Magnitude for these earthquakes is assumed to have been at least 5.0.

(Maps redrawn from Husebye et al, 1977).

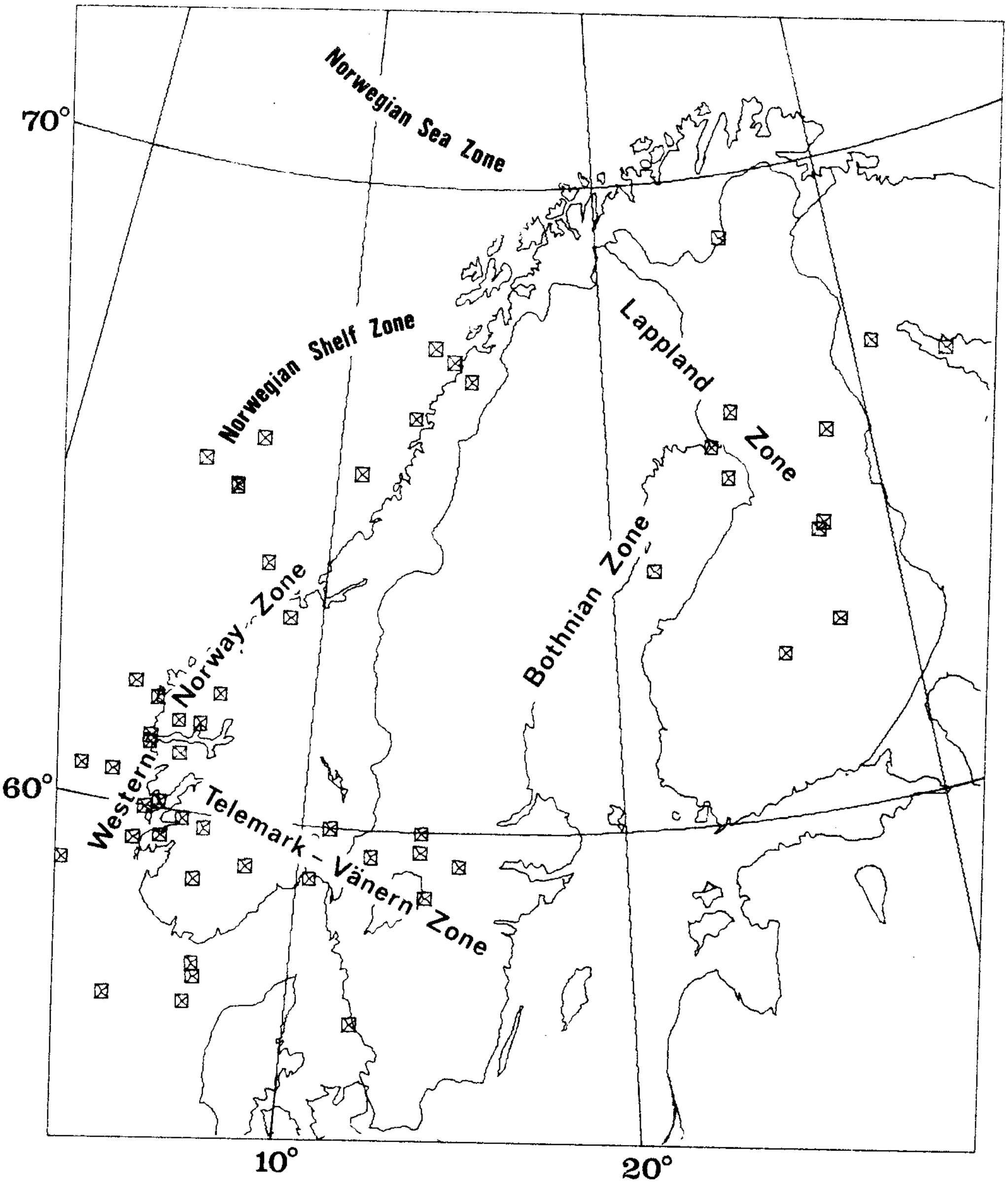

Fig. 4.2 Fennoscandian earthquakes for the time period 1497-1975 and with a magnitude greater than 4.5. An outline is also given of the seismicity zones defined by Husebye et al (1977).

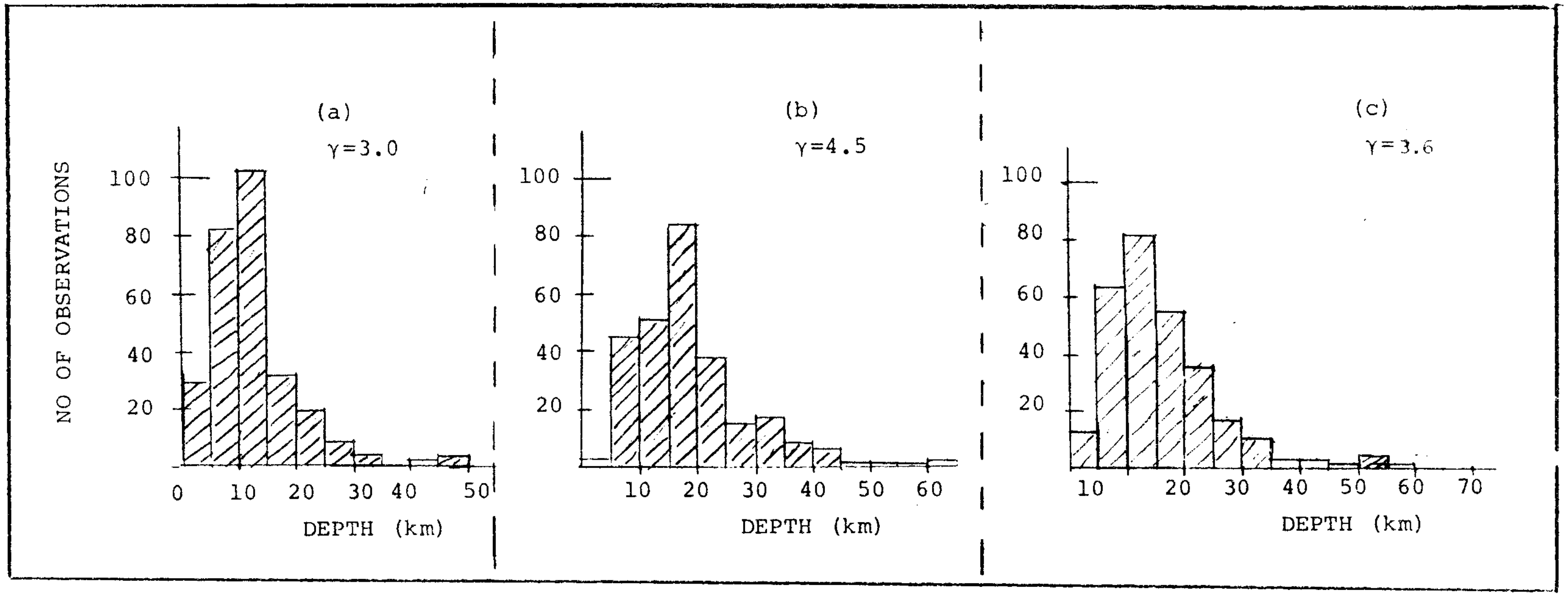

Fig. 4.3 Focal depth distribution for 274 south Sweden earthquakes as inferred from macroseismic data. The following formula has been used

$$H = r/(10^{\frac{2(I_o-2.5)}{\gamma}} - 1)^{\frac{1}{2}}$$

r is the radius of perception, I_o is maximum intensity and γ represents geometrical spreading and attenuation. (Figure redrawn from Husebye and Ringdal (1977).

Magnitude Range	Offset (meter)	Fault Width (km)	Fault Length (km)
3.5 - 4.5	0.01	1.5	7.0
5.5 - 6.5	0.1	5.0	40.0
7.5 - 8.5	10.0	30.0	300.0

Table 4.1 Dislocations and fault dimensions associated with earthquakes. The data are taken from Chinnery (1969) and refer to strike slip faulting. Notice that the values given may exhibit regional dependencies.

Little observational data are available, as surface faulting is rarely reported. Therefore, general rules have been worked out for relating the 'size' of the fault area as a function of magnitude. Using results presented by Chinnery (1969) for strike slip faulting, such a tabulation is presented in Table 4.1. Notice that since intraplate earthquakes generally are characterized by relatively high stress drops the given fault dimensions represent upper limits for the problem at hand.

4.2 Surface Faulting and Creep Movements

Most of the so-called shallow earthquakes, i.e., the depth interval 0-70 km, actually take place in the depth interval 20-40 km. This in combination with Table 4.1 explains why surface faulting associated with earthquake occurrence so seldom is observed. In other words, active faulting within the canister storage area is most likely to be associated with large magnitude earthquakes with $M \geq 6.0$, since these would have the largest fault area.

With respect to creep motion, this type of faulting may be conveniently modelled as the cumulative sum of small earthquakes. For such a process to represent a tectonic risk, this kind of movements must be confined to a first-order fault. In short, the risk of creep movements within the canister storage area may as a first approximation be taken to be equivalent to having a undetected fault within this area.

5. SEISMOTECTONIC RISK ESTIMATION

5.1 Probability Model

In Section 3 it was demonstrated that the observed distribution of fault lengths in Sweden is very well modelled by a lognormal function. This is in fact to be expected on theoretical grounds, if one views the creation of faults as the result of a crustal 'breakage' process (the actual conglomerate of forces contributing to the breakage need not be specified). The theory to model such processes (Aitchison and Brown, 1969) is briefly described as follows:

Suppose there is a set of objects or elements each of which is associated a positive measure, the dimension of the element, in our case the fault length. Let the initial distribution of the elements be $F_0(x)$, that is to say, the proportion of elements with dimension $\leqq x$ is $F_0(x)$. The elements are then subjected to a sequence of independent breakage operations. If, at the j-th breakage, $G_j(x|u)$ describes the distribution of elements arising from elements of dimension u prior to the breakage, we may, using a 'law of proportionate effects', assume that $G_j(x|u)$ depends only on the ratio x/u; i.e.,

$$G_j(x|u) = H_j(\frac{x}{u}) \tag{5.1}$$

Then

$$F_j(x) = \int_u H_j(\frac{x}{u})\, dF_{j-1}(u) \tag{5.2}$$

If X_j and T_j are the variates associated with the distribution functions $F_j(x)$ and $H_j(t)$, then (5.2) implies that

$$X_j = T_j X_{j-1} \tag{5.3}$$

so that

$$X_n = X_0 \prod_{j=1}^{n} T_j \tag{5.4}$$

or

$$\log X_n = \log X_0 + \sum_{j=1}^{n} \log T_j \tag{5.5}$$

By the Central Limit Theorem of statistics, it may then be inferred that $\log X_n$ approaches a normal distribution as n becomes large, i.e., X_n approaches a lognormal variable.

We will now assume that the distribution F(L) of fault lengths L is lognormal, and that the total number of faults over an area A is N. The following geometrical considerations will be relevant to a horizontal plane, either at the surface or at some specified depth.

First we note that the expected number of faults of length less than L in a unit area will be:

$$N(L) = \frac{N}{A} \cdot \int_0^L \frac{\log e}{\sqrt{2\pi} \cdot \sigma \cdot X} \cdot \exp\left(- \frac{(\log x-\mu)^2}{2\sigma^2}\right) dX \tag{5.6}$$

where μ, σ are the parameters of the lognormal distribution, and the logarithms are base 10.

Referring to Fig. 5.1, we next address the chance of any fault intersecting a given circular disc of radius R_B. We assume that the orientation θ of any given fault can assume any value with equal probability. By trigonometric considerations, it follows that the probability $P(r,R_B,L)$ of the disc intersecting a fault of a given length L, given that the distance from the disc center to the midpoint of the fault is r, becomes:

$$P(r,R_B,L) = \begin{cases} 1 & \text{if } r<R_B \\ 0 & \text{if } r \geq R_B \text{ and } \frac{L}{2} \leq r-R_B \\ \frac{2\theta_1}{\pi} & \text{if } r \geq R_B \text{ and } r-R_B < \frac{L}{2} \leq \sqrt{r^2-R_B^2} \\ \frac{2\theta_2}{\pi} & \text{if } r \geq R_B \text{ and } \frac{L}{2} \geq \sqrt{r^2-R_B^2} \end{cases} \tag{5.7}$$

$$\text{where } \theta_1 = \text{Arccos}\left(\frac{r^2+(\frac{L}{2})^2-R_B^2}{r \cdot L}\right) \text{ and } \theta_2 = \text{Arcsin}\left(\frac{R_B}{r}\right). \tag{5.8}$$

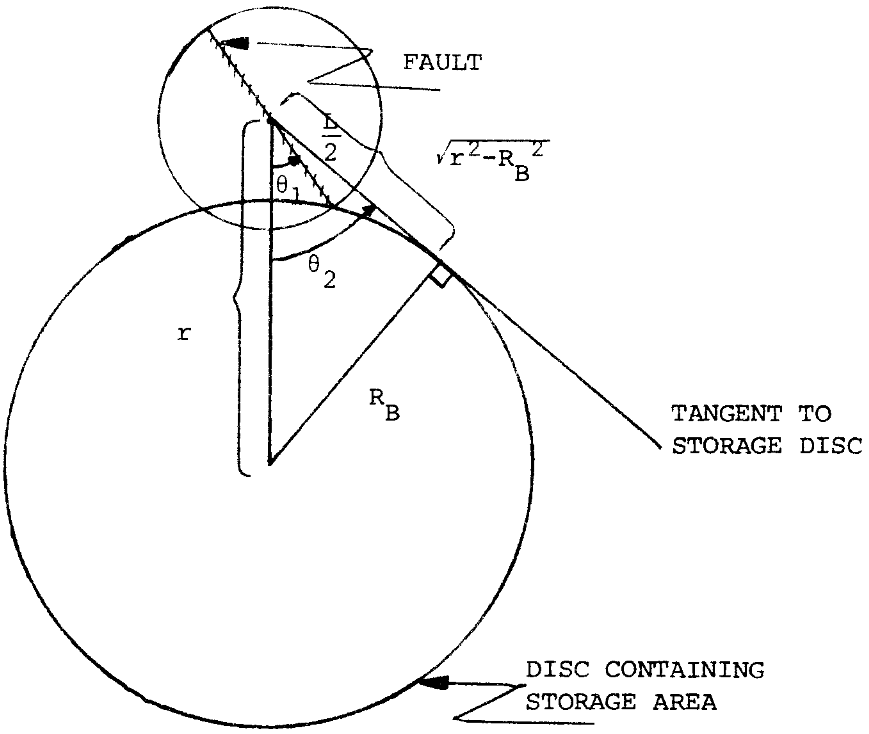

Fig. 5.1 Illustration of probability considerations relative to fault intersection of a circular disc. In case $\frac{L}{2} < \sqrt{r^2-R_B^2}$, intersection will occur if the fault angle is less than the critical angle θ_1.

The expected number of faults of length $\leq L_0$ intersecting the disc is then found by integrating with respect to r and L:

$$E_I(R_B, L_0) = \int_0^{L_0} \int_0^{R_B+\frac{L}{2}} P(r, R_B, L) \cdot \frac{d}{dL} [N(L)] \cdot 2\pi r \, dr \, dL \tag{5.9}$$

This double integral may be evaluated, and its value depends, of course, not only on the disc radius R_B and length L_0, but also on the parameters N, A, μ, σ of equation (5.6) used to characterize the fault distribution and density.

5.2 Estimation Results

The problem of canister damage due to tectonic risk is not solved by consideration of fault distribution alone. The appropriate forces and their effects must of course also be taken into consideration. A simple model may be established as a first approximation to consider these combined risk factors:

Risk due to earthquake faulting

$$P(\text{risk}) = P(F) \cdot P(A/F) \cdot P(E\geq?/AF) \cdot P(B/E) \tag{5.10}$$

Risk due to creep movements

$$P(\text{risk}) = P(F) \cdot P(A/F) \cdot P(C\geq?/AF) \cdot P(B/C) \tag{5.11}$$

where

- $P(\text{Risk})$ = probability of canister damage (per unit time and canister)
- $P(F)$ = probability of at least one fault within storage area
- $P(A/F)$ = probability of a given fault being active
- $P(E\geq?/AF)$ = probability of earthquake of a given size on active fault (per unit time)
- $P(B/E)$ = probability of breakage given earthquake occurrence (per canister)
- $P(C\geq?/AF)$ = probability of significant creep on active fault (per unit time)
- $P(B/C)$ = probability of breakage given creep movements (per canister).

We will initially confine the discussion here to the first factor P(F), i.e., the probability of having a fault sufficiently close to the storage area. Two considerations are appropriate to point out.

a. Firstly, it must be assumed that all possible effort is being spent on attempting to locate and identify zones of weakness in any potential storage area. During the drilling of the holes in which to place the canisters, stress measurements will be continually made in order to identify possible unknown faults. One must therefore assume that the chance of actually overlooking a fault of any significance is very close to zero.

b. Secondly, one must be aware of the possibility of new faults being created during the span of several thousand years for which the canisters must be safely stored.

For this second probability, under b. above, a reasonable and conservative assumption, as discussed in Section 3, must be that the rate of creation of fault lines has been constant over an age period of 1500 million years, which is approximately the age of the oldest Swedish bedrock. This period includes several orogenic cycles, e.g., the formation of the Caledonides some 500 million years ago. More recently, the glaciations of Fennoscandia and subsequently the elastic and isostatic rebound would have contributed to the formation of new faults, although the neotectonic component of the total fault pattern in Sweden must be considered very small. It is even open to some doubt whether future glaciations would indeed create any significant new fault zones, as the great majority of crustal displacements following uplifts would be confined to the already existing numerous weakness zones.

Based on these considerations, we make the following assumptions in our risk model

- The future fault creation process is modelled as occurring at a constant rate, which is obtained by extrapolating the rate considered above to the next few tens of thousands of years.

- The probability distribution of future fault lengths is assumed to be similar to that of existing faults documented in Section 3.
- The spatial distribution and orientation of future faults is assumed to be homogeneous (i.e., following a 'rectangular' probability density).
- The expected probability of fault occurrence is supposed to be independent of depth, so that the statistics developed for surface storage locations would be equally applicable at a depth of e.g., 500 m.

Table 5.1 shows the expected number of existing faults of length $\leq L$ intersecting a circular disc of radius R_B for various values of R_B. Formula (5.9) has been used in these computations. By our assumption of constant breakage rate, these numbers may be easily converted to the expected probability of new faults created during the next, e.g., 10,000 years intersecting a similar disc, by applying a constant factor of $10{,}000/(1500 \cdot 10^6)$. Table 5.2 lists the resulting probabilities when no restriction on fault lengths is assumed. The associated probability for a disc of 1 km radius is on the order of 10^{-6}. For disc radii small enough to affect a given canister, i.e., 0.01 km or less, the probability is below 10^{-7} of a fault created during the next 10,000 years intersecting this area.

5.3 Additional Considerations

The formulae (5.10) and (5.11) include additional factors that may contribute to further reduce the risk of breakage. Mostly, these factors would need to be considered only when discussing existing faults, since the creation of a new fault is by itself a major tectonic event that one would clearly not expect the canisters to withstand. We therefore do not intend to discuss these in detail at this stage. However, a few qualitative remarks are in order, since the risk resulting from existing faults cannot be entirely ignored. Conservatively, one must assume that a fair percentage of the faults are potentially active, although present uncertainties in earthquake locations makes it difficult to associate observed seismicity to known fault structures. Furthermore, in order for an earthquake to produce significant damage to a canister, it must most likely result in a fault displacement of several cm, i.e., be on the order of magnitude 4 or higher. The rate of occurrence of such earthquakes

	Disc Radius R_B (km)						
	0.01	0.02	0.05	0.1	0.2	0.5	1.0
Expected no. of faults intersecting the disc	$8 \cdot 10^{-3}$	$1.6 \cdot 10^{-2}$	$4 \cdot 10^{-2}$	$8 \cdot 10^{-2}$	$1.6 \cdot 10^{-1}$	$4 \cdot 10^{-1}$	$8 \cdot 10^{-1}$

Parameters characterizing fault distribution (eq. (5.6))

$\mu = 1.2$
$\sigma = 0.3$
$N/A = 0.02$

Table 5.1 Expected number of faults intersecting a horizontal, circular disc of radius R_B for various values of R_B. The density and distribution of faults is set to values typical of southern Sweden.

	Disc Radius R_B (km)						
	0.01	0.02	0.05	0.1	0.2	0.5	1.0
Expected no. of new faults created during next 10^4 years intersecting the disc	$5 \cdot 10^{-8}$	$1 \cdot 10^{-7}$	$2.5 \cdot 10^{-7}$	$5 \cdot 10^{-7}$	$1 \cdot 10^{-6}$	$2.5 \cdot 10^{-6}$	$5 \cdot 10^{-6}$

Parameters characterizing fault distribution (eq. (5.6))

$\mu = 1.2$
$\sigma = 0.3$
$N/A = 0.02$

Fault creation rate assumed constant as if all existing faults were created during the past 1500 million years.

Table 5.2 Estimated number of new faults created during the next 10,000 years intersecting a horizontal, circular disc of radius R_B for various values of R_B.

in Sweden is low, certainly less than 1 per year, for all of the country, and of course considerably lower for any given active fault. Moreover, the depths of Fennoscandian earthquakes are generally estimated to be in the range 10-15 km or deeper (Husebye and Ringdal, 1976). Consequently, any fault movement occurring as close to the surface as 0.5 km would have to be assigned a very low probability. Thus, as far as present-day seismicity is used for estimation, the risk factors would be considerably diminished by including the additional factors in (5.10). However, if a reglaciation should occur, these probabilities would of course be significantly altered.

For the risk due to creep movement (5.11), it appears hardly likely that such an occurrence should have any significant potential to damage a canister embedded in a material that is assumed to behave in a plastic mode under slow deformation. This point of view is supported by the experiments of Pusch (1977). We therefore do not consider it necessary to consider this case in more detail.

6. CONCLUSIONS

In the following the main conclusions of this study are summarized.

Tectonic Risk Factors

The problem studied concerns the risk of breakage of specially designed canisters to contain nuclear wastes. The canisters are assumed to be stored underground at depths of about 500 m in the Swedish bedrock, and embedded in tunnels filled with a clay-like material. The geotectonic events causing potential damage can be classed as (i) earthquakes and (ii) creep motion. Such movements will predominantly occur along already existing zones of weakness in the crust; nonetheless, the possibility of new faults being created during the next few thousands of years must be considered.

Geotectonics of Fennoscandia

Fennoscandia is generally rated as a stable area from a geological point of view. The numerous existing faults observed in Sweden are in general the results of past orogenic cycles, dating several hundred million years back in time. Only a few faults have shown surface movements after the most recent glaciation (ending about 8000 years b.p.), and in most cases such neotectonic movements have occurred along already existing zones of weakness.

Tectonic Forces

The most relevant tectonic forces presently acting on the Fennoscandian region are due to (i) glacial rebound, (ii) remnant stresses from past orogenic cycles and (iii) mid-oceanic ridge push forces. The dominant force appears to be that of (i), although data are too scarce to allow a reliable separation of the components. The uplift of Fennoscandia is very smooth, and this implies that the probability of differential movements (or faulting) in this connection is low.

Statistical Distribution of Faults

A statistical analysis of the lengths and orientations of major faults in Sweden has shown that (i) the distribution of fault lengths is approximately lognormal with a mean of 10-15 km and a standard deviation corresponding to a factor of two; (ii) the orientation of faults show similarity over limited areas, but may vary strongly from one region to another; (iii) the spatial density of occurrence of significant faults is 0.01-0.02 per square km; (iv) the fault density and distribution is quite similar over all of the Swedish area.

Seismicity of Sweden

The present seismicity of Sweden and surrounding areas is low, but occasional earthquakes of magnitude around 6 have been observed in historic times. Such an earthquake would be expected to occur in the Swedish area with an average return period of 300 years. Estimated depths of observed earthquakes are mostly 10 km or more, thus the expected seismic effect at the planned depths of canister storage will be small. Surface faulting of Swedish earthquakes is at present seldom, if ever, observed.

Fault Displacements during Earthquakes

Normal faulting is generally to be expected for Swedish earthquakes, although no fault plane solutions have yet been found in this area. Based on U.S. data (strike slip faulting), expected displacements for a magnitude 4 earthquake are around 1 cm, and increasing with earthquake magnitude (see Table 4.1). Based on tectonic considerations, the above numbers probably represent upper limits when considering Swedish earthquakes.

Risk Estimation: New Faults

A model has been developed to compute the probability of a storage area being intersected by a known or unknown fault. The model is based upon a lognormal distribution of fault lengths and a random orientation of the faults with all directions having equal probability of occurrence. The model is used in conjunction with the assumption that the rate of creation of new faults has remained constant over the past 1500 million years, and will remain so in the future. The probability of a new fault created during the next 10,000 years intersecting a given circular storage area of 1 km radius is then of the order $5 \cdot 10^{-6}$.

Risk Estimation: Existing Faults

Nuclear waste canisters will obviously not be deposited in the immediate neighborhood of known, existing faults. However, the above model can also be used to estimate the risk of intersecting existing (unknown) faults, if one is able to make an estimate of the proportion of such unknown faults relative to those faults that are already known. Additional considerations such as chance of earthquake occurrence, the expected amount of ground displacement during an earthquake, and the corresponding probability of damage can be considered in conjunction with the model. Of course, if one during the actual deposition of waste canisters is able to confidently identify all possible zones of weakness, then the associated risk may be neglected.

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