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Seismic activity parameters of the Finnish potential repository sites

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SEISMIC ACTIVITY PARAMETERS OF THE FINNISH POTENTIAL REPOSITORY SITES

Tiivistelmä – Abstract

Posiva Oy has started a project for estimating the possible earthquake induced rock movements on the deposition holes containing canisters of spent nuclear fuel. These estimates will be made for the four investigation sites, Romuvaara, Kivetty, Olkiluoto and Hästholmen.

This study deals with the current and future seismicity associated with the above mentioned sites. Seismic belts that participate the seismic behaviour of the studied sites have been identified and the magnitude-frequency distributions of these belts have been estimated. The seismic activity parameters of the sites have been deduced from the characteristics of the seismic belts in order to forecast the seismicity during the next 100,000 years.

The report discusses the possible earthquakes induced by future glaciation. The seismic interpretation seems to indicate that the previous postglacial faults in Finnish Lapland have been generated in compressional environment. The orientation of the rather uniform compression has been NW-SE, which coincide with the current stress field. It seems that, although the impact of postglacial crustal rebound must have been significant, the impact of plate tectonics has been dominant.

A major assumption of this study has been that future seismicity will generally resemble the current seismicity. However, when the postglacial seismicity is concerned, the magnitude-frequency distribution is likely different and the expected maximum magnitude will be higher. Maximum magnitudes of future postglacial earthquakes have been approximated by strain release examinations.

Seismicity has been examined within the framework of the lineament maps, in order to associate the future significant earthquakes with active fault zones in the vicinity of the potential repository sites.

Avainsanat - Keywords
seismic belts, magnitude-frequency relation, strain release, glaciation, potential active fracture zones, Romuvaara, Kivetty, Olkiluoto, Hästholmen

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SEISMISTÄ AKTIIVISUUTTA KUVAAVIA PARAMETREJÄ SUOMEN KÄYTETYN YDINPOLTTOAINEEN POTENTIAALISILLA SIJOITUSPAIKOILLA

Tiivistelmä – Abstract

Posiva Oy on käynnistänyt projektin, jonka tarkoituksena on arvioida maanjäristysten aiheuttamia kallioliikuntoja loppusijoituskapselia ympäröivässä kalliossa. Nämä arvioinnit on tarkoitus tehdä neljälle tutkimuspaikalle, jotka ovat Romuvaara, Kivetty, Olkiluoto ja Hästholmen.

Tässä tutkimuksessa arvioidaan yllämainittujen paikkojen nykyistä ja tulevaa seismisyyttä. Työn aluksi selvitään mitkä Suomen seismisyyden alueelliset vyöhykkeet liittyvät tutkimuspaikkojen seismisyyteen. Näiden vyöhykkeiden maanjäristysten magnitudi-lukumäärä relaatiosta johdetaan sijoitusalueiden seismistä aktiivisuutta kuvaavat parametrit. Pyrkimyksenä on esittää arvio seuraavan 100,000 vuoden seismisestä aktiivisuudesta kullakin neljällä paikalla.

Työssä tarkastellaan tulevan jääkauden mahdollisesti aiheuttamia maanjäristyksiä. Seismisen tulkinnan mukaan Lapissa olevat edellisen jääkauden jälkeiset siirrokset ovat syntyneet olosuhteissa, joissa vaakapuristus on ollut vallitsevana. Tämän puristuksen suunta on ollut yleensä sama kuin nykyisin: luode-kaakko. Näyttäisi siltä, että vaikka jääkauden jälkeisen maankohoamisen vaikutuksen on täytynyt olla huomattava, laattatektoniikka on myös tuolloin ollut kallioliikkeiden pääasiallinen syy.

Tutkimuksessa oletetaan, että tuleva seismisyys on pääpiirteissään nykyisenkaltaista. Kuitenkin, jääkauden jälkeisenä aikana maanjäristysten magnitudi-lukumäärä jakauma on luultavasti erilainen ja maanjäristykset ovat suurempia. Jääkauden jälkeisten maanjäristysten suuruuden ylärajaa on arvioitu tarkastelemalla maanjäristyksissä vapautuvia jännityksiä.

Romuvaaran, Kivetyn, Olkiluodon ja Hästholmenin alueiden lineamenttikartoilta on pyritty tunnistamaan sellaisia ruhjevyöhykkeitä, joissa saattaisi tapahtua merkittäviä maanjäristyksiä.

Avainsanat - Keywords
seisminen vyöhyke, magnitudi-lukumäärä suhde, jännityksen vapautuminen seismisesti, jääkausi, seismisesti aktiivinen ruhjevyöhyke, Romuvaara, Kivetty, Olkiluoto, Hästholmen

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1. INTRODUCTION

This study is part of the proposed project "Estimation of rock movements due to future earthquakes at four Finnish candidate repository sites". The four sites are Romuvaara, Kivetty, Olkiluoto and Hästholmen. The purpose of the project is to approximate possible rock movements due to future earthquakes in fractures intersecting the disposal holes containing spent nuclear fuel. The outlines of the project are suggested by La Pointe & Cladouhos (1999).

The project is divided in several tasks to be made by different organisations. The aim of this study is to approximate the future seismicity related to the repository sites. The regional seismicity is studied in relation to the seismicity and fault configuration in the regions within a radius of 100 km of the four potential repository sites. These regions are called here *target areas*. The task is divided into four subtasks:

1. Identification and characterisation of seismic belts that might participate the seismic behaviour of the sites.
2. Estimation of the magnitude-frequency relation of seismicity within the target areas.
3. Evaluation of the possible impact of the postglacial faulting.
4. Attempt to associate the future earthquakes with the faults of the target areas.

The very core of the calculation of the seismic activity parameters is to find a representative and statistically reliable data set. One fundamental task is to combine the magnitudes reported from various agencies into one homogeneous magnitude scale, which actually has been the goal of the earthquake catalogue for Northern Europe (Ahjos & Uski 1992). The study is based on the latest updating of this catalogue (FENCAT) available in the beginning of the study. At that time, FENCAT included seismic history from 1375 to 1998. The later seismicity (1.1.1999-30.9.2000) fits well the results of this study.

2. CALCULATION OF EARTHQUAKE PARAMETERS

2.1 Seismic Belts and Subregions

With the scarce data in FENCAT it is not possible to establish statistically reliable parameters for each of the target areas. Scaling parameters of larger regional seismic belts to represent the target area solves this problem. In case where the target area contains more than one seismic belt, the quota of each zone will be taken into account.

The potential repository sites are within regions, where earthquakes are sparse and small (M< 5.0). The approximated location accuracy of macroseismically and instrumentally located earthquakes in Finland are 10-100 km and 5-10 km, respectively (Ahjos & Arhe 1983). In southern Finland, the clear majority of the events (75%) are macroseismically located. Due to the insufficient location accuracy, it is mainly not possible to associate the epicenters accurately with certain individual zones of weakness. Instead, the seismic belts characterised by different levels of potential seismicity can be distinguished.

The nearest seismic belts are outlined in Figures 2-1 and 2-2. The most active belts of seismicity are the Swedish coast from the Bothnian Sea to the Bothnian Bay, western Lapland and the northern Bothnian Bay-Kuusamo region. The potential repository sites are south from the northern Bothnian Bay-Kuusamo seismic zone, where the belts of higher seismic activity are not as pronounced. The northern NW-SE oriented zone (B-L) of higher activity runs through central Finland from the southern part of Bothnian Bay to Ladoga. The other active belt (Å-P-P) runs from the Ålands archipelago to Estonia, where it extends from Paldis to Pskov (Saari 1998a).

The borders of the belts are open to various interpretations. For example, two relatively large earthquakes (1626, M=4.6 and 1902, M=4.7) in the Lake Oulujärvi area, are outside the presented belts of higher activity (Fig. 2-1). The surrounding of the epicenters was largely unpopulated, especially in 1626, and the location accuracy of these events is, therefore, rather poor. There has been only one earthquake (1977, M_L =2.6) in that area since the beginning of the 19th century. Apparently, the true locations of these previous events are more closer to the instrumentally-located epicenters, like in the northern Bothnian Bay-Kuusamo belt. However, the seismotectonic analysis of the area indicates that these earthquakes cannot be ignored when the seismic risk of the Romuvaara site is considered (see details Saari 1999 and Anttila et al. 1999).

Generally, the belts of lower activity are outlined by the belts of higher seismicity. The southeastern borders of lower seismicity are difficult to define, which adds uncertainty to the interpretation. Therefore, the subregions H and R (Fig. 2-2) are introduced to give realistic or conservative approximations of the real seismicity between the active belts.

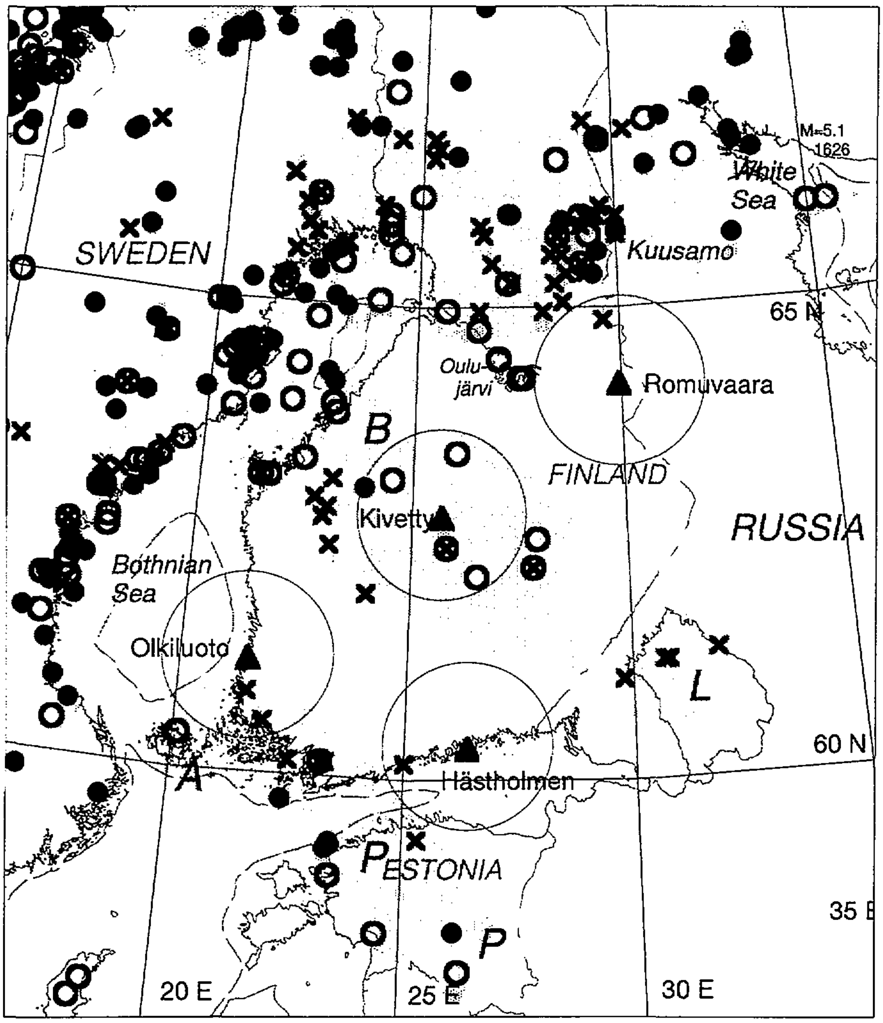


Figure 2-1. Belts of higher seismic activity (shaded areas). Historical events (1375-1964) with magnitude M ≥ 3.5 and instrumentally located (1965-1998) events with magnitude M ≥ 3.0 are shown by open and filled black circles, respectively. Crosses denote earthquakes during the period 1920-1941. Red circles, with midpoints on the potential repository sites (triangle), show the target areas.

The activity parameters of the target areas are deduced from the characteristics of the seismic subregions. Kivetty is completely inside the B-L zone and Hästholmen inside subregion H. About 2/3 of the Olkiluoto target area belongs to the subregion H and about 1/3 to the Å-P-P Seismic Zone. Subregion R includes a small strip of the northern Bothnian Bay-Kuusamo belt. Although, the seismotectonic analysis of the area doesn't support the idea (Saari 1999), it is assumed that the chain of epicenters running from Oulujärvi through the Romuvaara target area towards the White Sea (Fig. 2-2) might be associated with the same zone of weakness.

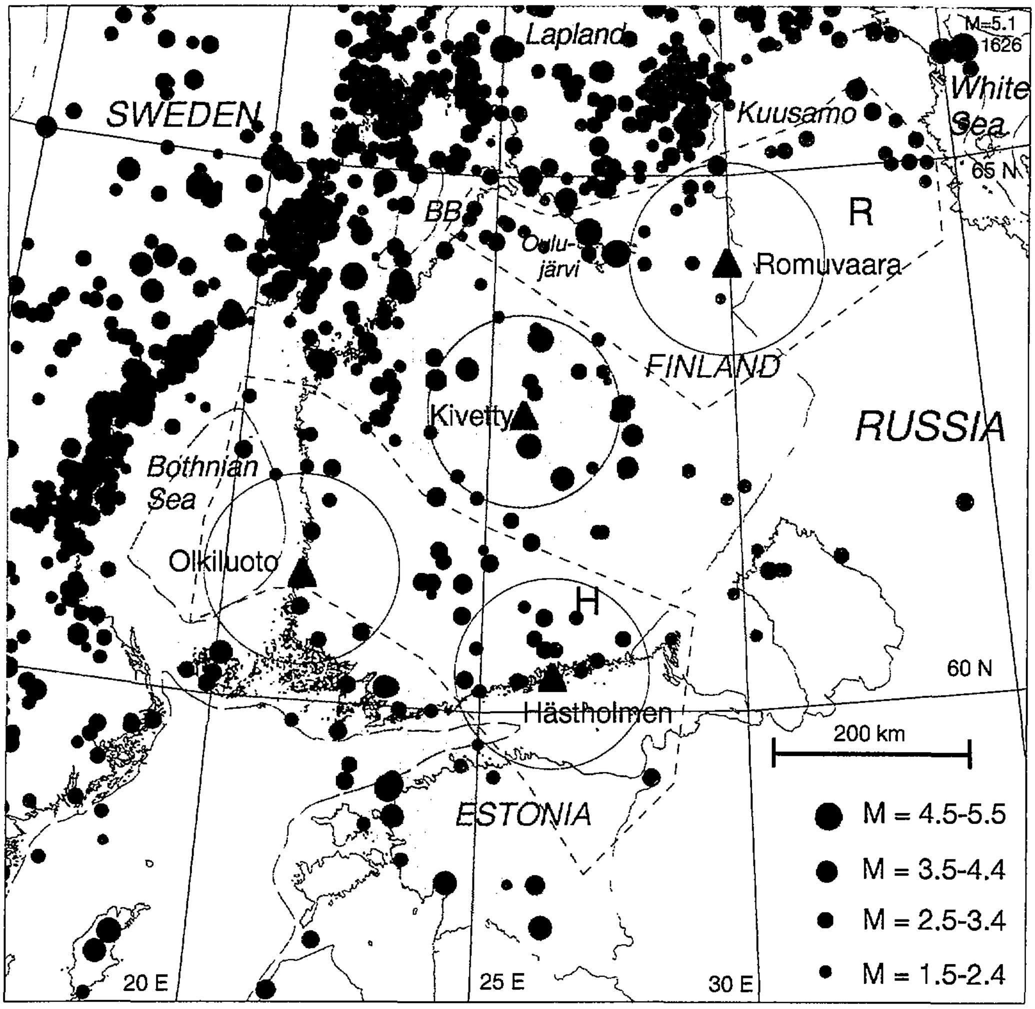


Figure 2-2. Epicenters of earthquakes in 1375 - 1998 (M ≥ 1.5) according to the catalogue of the earthquakes in northern Europe (Ahjos & Uski 1992). The potential repository sites for the final disposal of spent nuclear fuel are shown by triangles. BB = Bothnian Bay. Red circles around the repository sites show the target areas. The dashed lines outline the borders of the subregions H and R.

2.2 Magnitude-Frequency Distribution for Future Earthquakes

Owing to the long recurrence interval of Finnish earthquakes, the forecasting of future seismicity will rely strongly on historical data. There are temporal gaps in FENCAT and its subrecords (Figs. 2-3). Some of these gaps are likely natural. For example, in spite of the digital seismic network, there are not any observations of earthquakes ($M_L \geq 1.5$) in the southernmost subrecords (Å-P-P and subregion H) from 1992 to 1998. On the other hand, the lack of reported earthquake observations from 1942 to 1951 in Finland is probably related to the Second World War. In subrecords the break is longer. The period (1942-1951) is disregarded when the annual numbers of events is approximated.

According to FENCAT, the first known earthquake in Finland occurred in 1610. Since 1750, the number of felt earthquakes in each decade fluctuates but shows a certain continuity of reporting. The beginning of systematic mapping in Fennoscandia in the 1880's clearly improved the location accuracy and number of observations. The influence of the installation of the regional seismic network since 1950's is clearly seen in FENCAT and in Figures 2-3 as well. The events in Finland have been predominantly instrumentally located since the mid 1960's. The utilisation of digital instruments in 1980's caused the latest stepwise increase of the number of observations. Most of the events smaller than M=2 are recorded during this period.

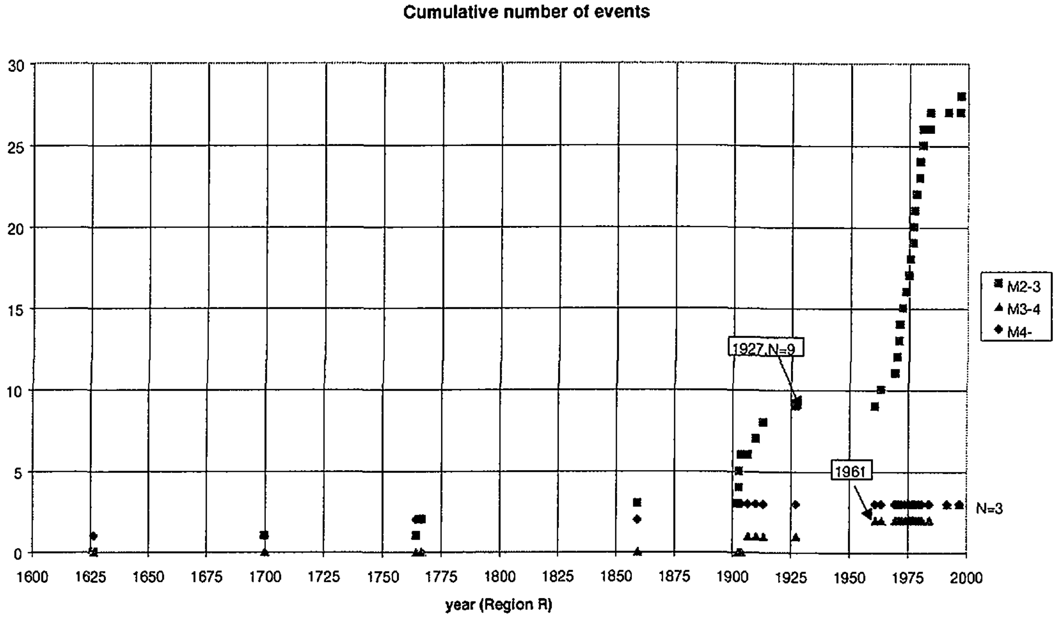


Figure 2-3a. Number of observed earthquakes in subregion R.

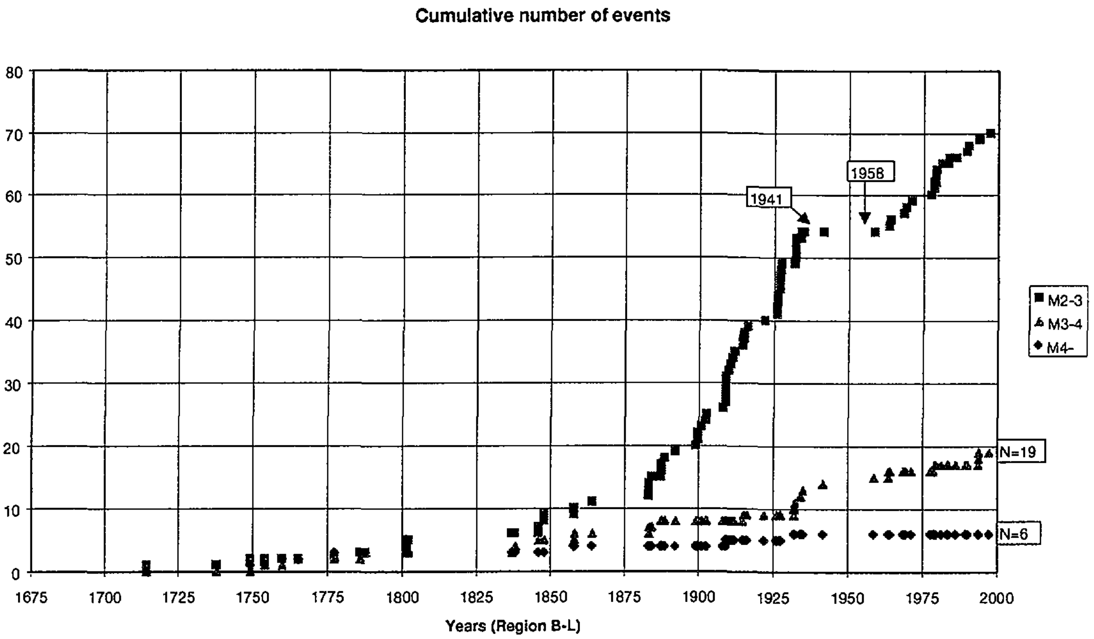


Figure 2-3b. Number of observed earthquakes in subregion B-L.

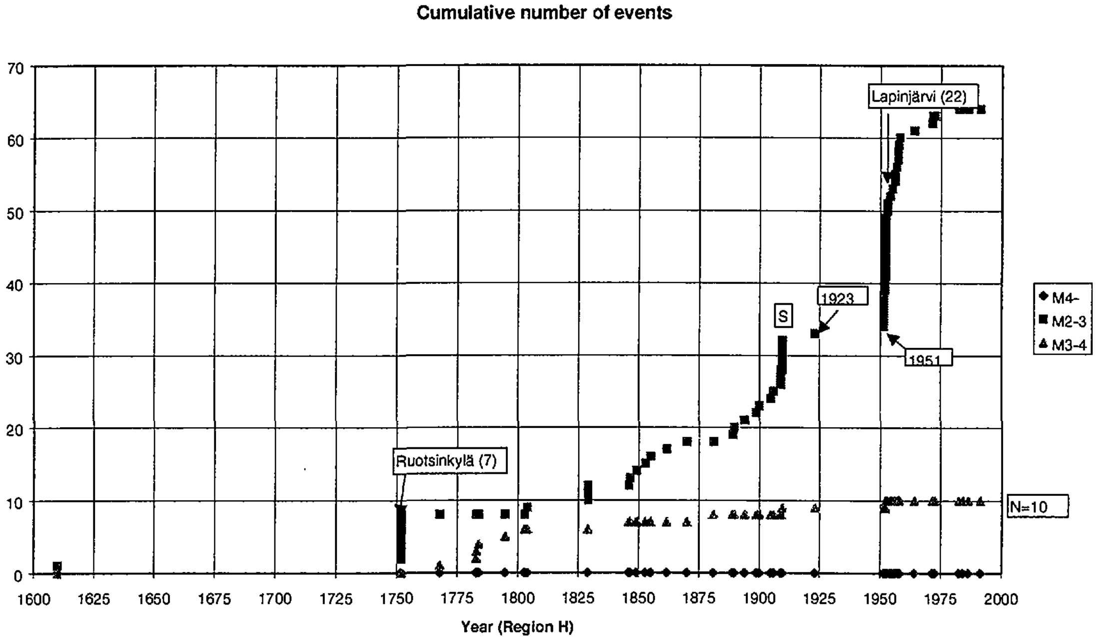


Figure 2-3c. Number of observed earthquakes in subregion H.

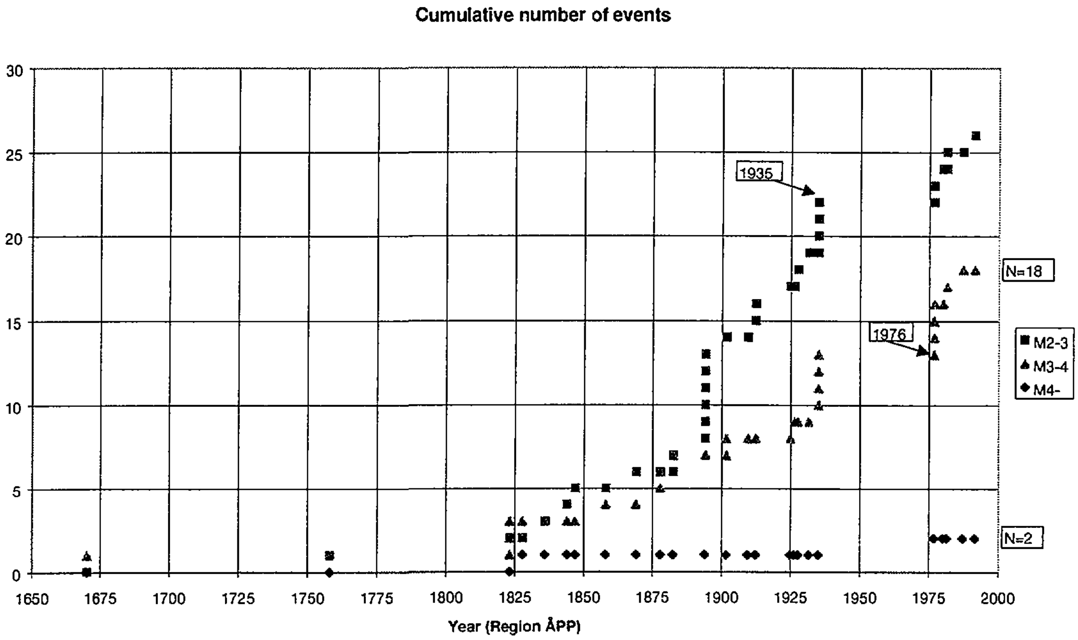


Figure 2-3d. Number of observed earthquakes in subregion Å-P-P.

The Finnish earthquake data has been considered to be satisfactory after 1880. This time window has been generally applied to the magnitude range 2≤M<4. However, for larger events (M≥4.0) this period is considered too short in relation to the recurrence time of events. For those events the earthquake catalogue is regarded as quite representative since 1750. Due to a relatively long history of dense population in the area of the Å-P-P belt, a time period of 1820-1998 has been applied (see Fig. 2-3d) to the magnitude range 3≤M<4.

The number of earthquakes as a function of magnitude for a specific region often conforms to the equation (Gutenberg & Richter 1944):

$$Log\,N = a - b*M \qquad (2\text{-}1)$$

N is the number of earthquakes whose magnitude is $\geq M$ occurring in a specified time interval and a and b are constants.

The constant b describes the relative proportion of larger earthquakes to smaller earthquakes. As b increases, the proportion of large earthquakes decreases. As a increases, the number of earthquakes increases for earthquakes of all magnitudes.

Figures 2-4a, b, c, d show the annual number of earthquakes as a function of magnitude for each of the subregions. The least squares fit to the presented data determines the constants a and b (Table 2-1).

The b-values and the standard errors of the subregion H are significantly larger than in general. Since 1880, only 53 earthquakes (M ≥ 2.0) have occurred within this belt, and 45% of those belong to the Lapinjärvi sequence 1951-1956 (see Fig. 2-3c). The events of this sequence, mainly of the magnitude 2.4 (13 events), are dominating the magnitude-frequency distribution of the subregion H. The sequence contains two internal swarms (1951 and 1952) followed by one event per year from 1953 to 1956. In this study, only the main shocks of the 1951 (M=2.8) and 1952 (M=3.1) Lapinjärvi swarms and the individual events occurred in 1953-1956 are included in the subregion H. The fit to the re-estimated values is shown in Figure 2-4e. This arrangement lowers considerably the b-value and the standard error in comparison to the original data (Table 2-1).

Earthquake sequences are a characteristic of the subregion H (Saari 1998a) and larger b-values are expected in the area of relatively low seismicity. However, the result based on original data is probably underestimating the relative number of larger events. When the Lapinjärvi sequence is taken into account as described above, the seismicity parameters of the subregion H give a more conservative approximation of the seismic hazard in the area.

In Table 2-1, the parameters a and N are dependent on the area of the subregion. The seismic activity of the four subregions can be compared when parameters a are normalised to represent equal areas. The parameters a_n are comparable values adjusted for a common area of 31,416 km^2, which corresponds to a circle with radius equal to 100 km. The scaling parameters k vary from 0.25 (in B-L) to 0.4 (in Å-P-P).

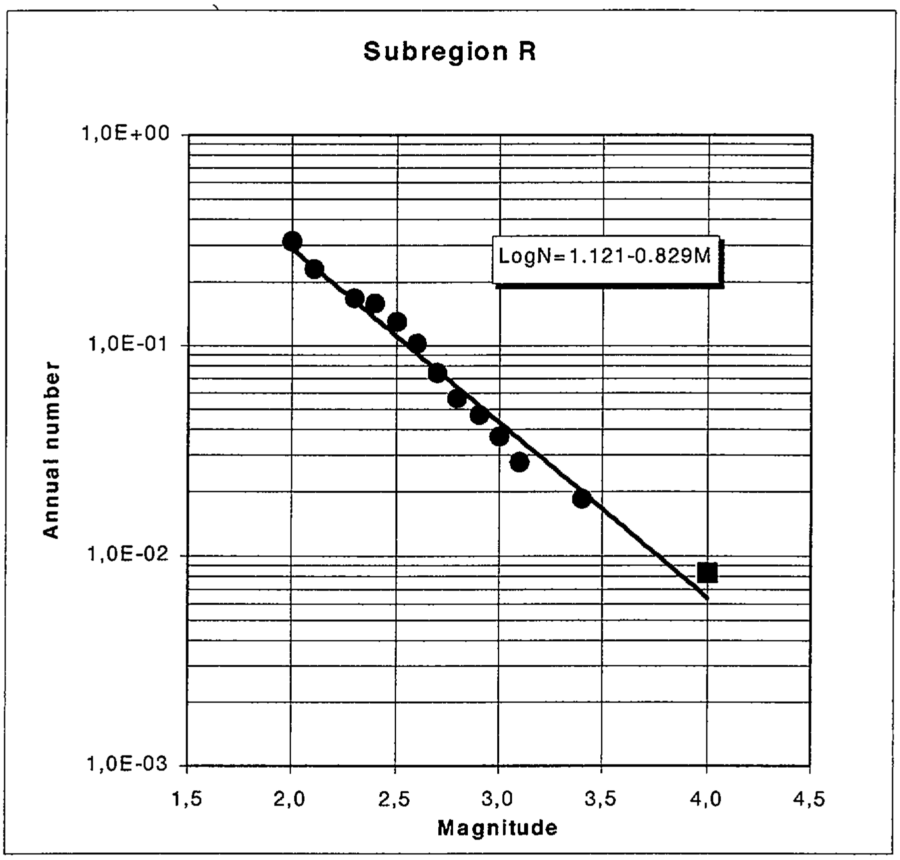


Figure 2-4a. Annual frequency of earthquakes versus magnitude (see Eq. 2-1) for the subregion R.

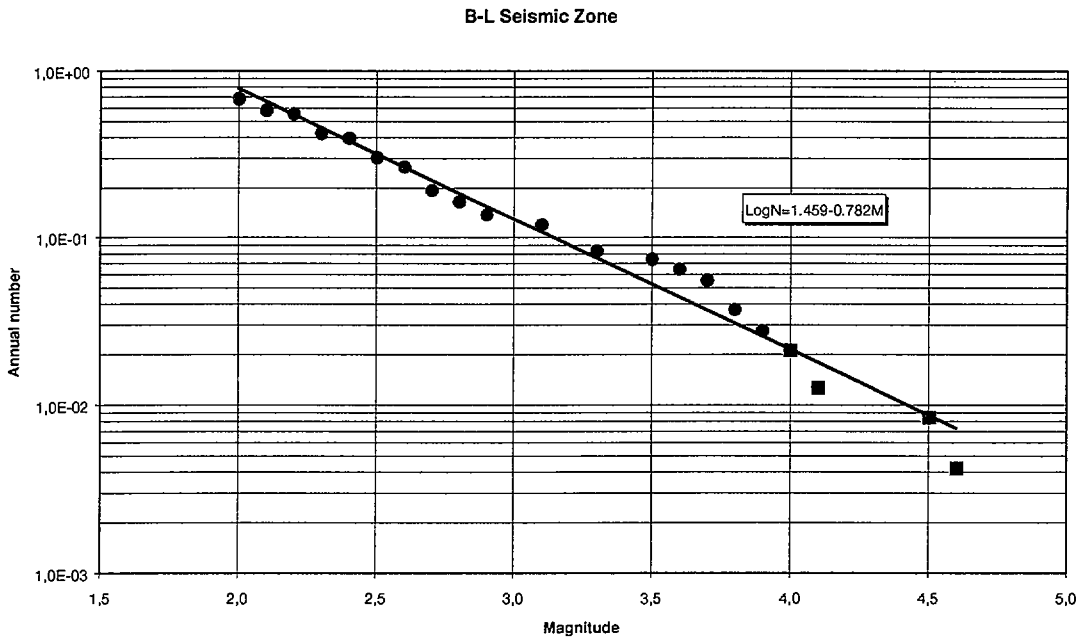


Figure 2-4b. Annual frequency of earthquakes versus magnitude (see Eq. 2-1) for the subregion B-L.

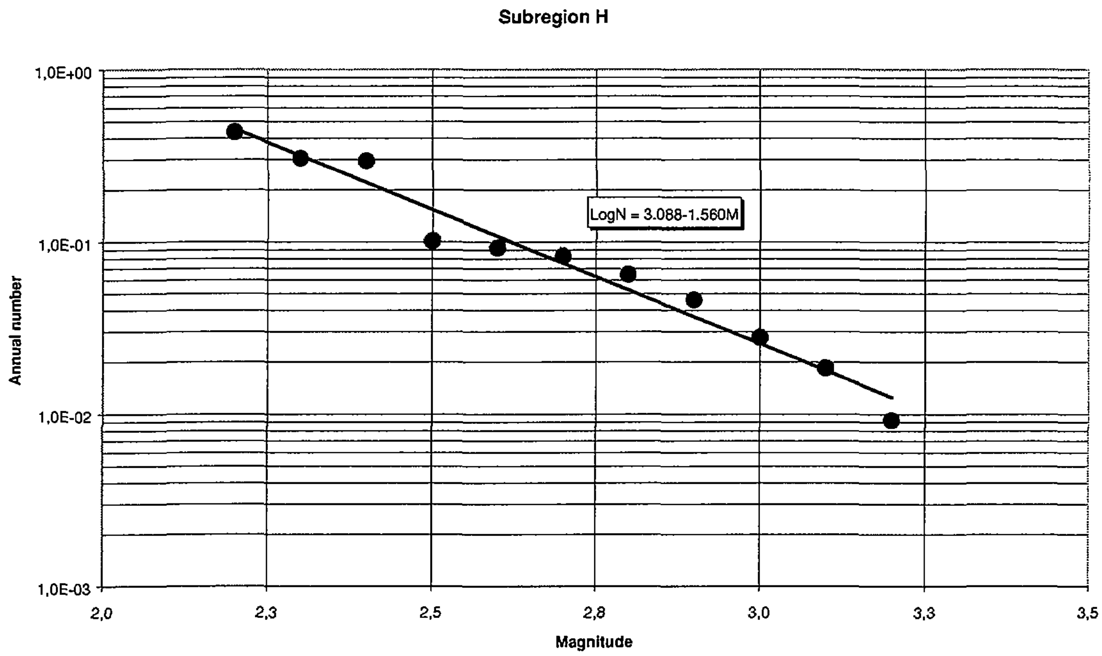


Figure 2-4c. Annual frequency of earthquakes versus magnitude (see Eq. 2-1) for the subregion H.

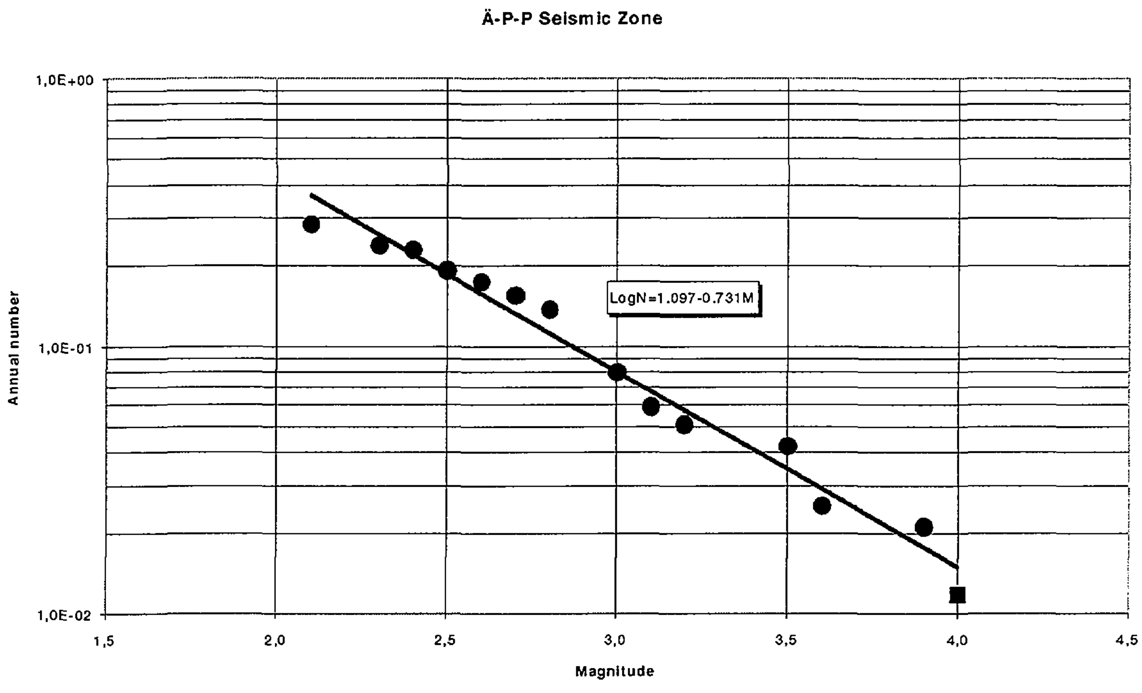


Figure 2-4d. Annual frequency of earthquakes versus magnitude (see Eq. 2-1) for the subregion Å-P-P.

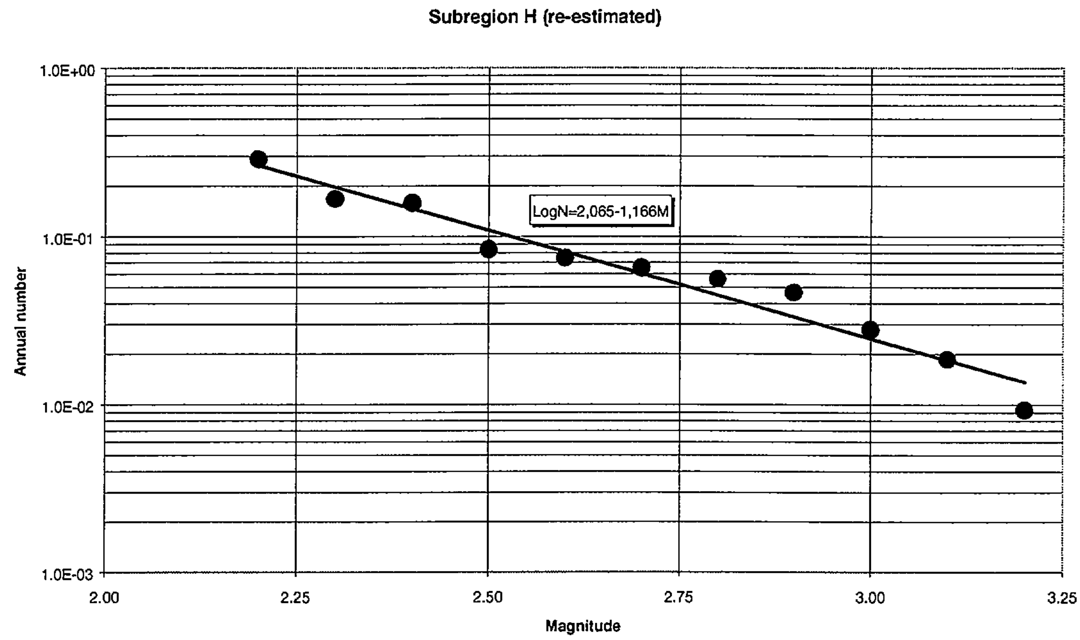


Figure 2-4e. Re-estimated annual frequency of earthquakes versus magnitude (see text) for the subregion H.

*Table 2-1. Annual seismicity parameters (**a** and **b**) for subregions and the total number of events N(M≥1.5) in FENCAT (Fig. 2-2). In the last column (a_n) parameter a is normalised for a common area of 31,315 km². The scaling parameter **k** is determined by dividing the common area by the area of the subregion.*

Subregion	*b*	*a*	N	a_n	*k*
R	0.829 ± 0.035	1.121 ± 0.099	36	0.692 ± 0.099	0.37
B-L	0.782 ± 0.028	1.459 ± 0.090	99	0.860 ± 0.090	0.25
H (original data)	1.560 ± 0.097	3.088 ± 0.263	78	2.659± 0.263	0.29
H (re-estimated)	1.166 ± 0.066	2.065 ± 0.179	32	1.521 ± 0.179	0.29
Å-P-P	0.731 ± 0.033	1.097 ± 0.101	48	0.695 ± 0.101	0.40

The expected number of earthquakes over a period of 100,000 years greater or equal to a magnitude M is shown in Figure 2-5 and in Table 2-2. The target areas Romuvaara, Kivetty and Hästholmen are inside the subregions R, B-L and H, respectively. When the Olkiluoto target area is concerned, it is approximated that 1/3 of the seismic activity origin from the Å-P-P Seismic Zone and 2/3 from the subregion H. The re-estimated parameters of the subregion H are applied.

Table 2-3 gives an impression of the accuracy of the extrapolation conducted. The estimates are based on standard errors presented in Table 2-1. Generally the ratios of the upper limits to the lower limits vary from 1.5-2 to 4-6depending on the target area and magnitude interval. Larger magnitudes show higher ratios. However, the ratio in Hästholmen for M≥8 is even 26.

The error ranges in Table 2-3 do not take into account the issue how uncertain it is to extrapolate current earthquake parameters to much larger earthquakes and to much longer time period. The magnitude-frequency distributions of 500,000 - 3,000,000 earthquakes are deduced from only 30 to 100 observations. It is supposed that the data acquired during the time interval, which is 0.1 - 0.2% of the time window of the extrapolation is representative and that the physical behaviour of the Finnish bedrock will not change. In addition, the current earthquakes are generally from magnitude two to magnitude four, when the extrapolation covers magnitudes from zero to eight. In the subregion H, where the amount of data is smallest and the standard errors are largest, also the magnitude range (M=2-3.2) is most insufficient.

Table 2-2. Number of earthquakes expected in different seismic target areas in Finland over 100,000-year interval normalised for the target areas of 31,416 km².

M	Romuvaara	Kivetty	Hästholmen	Olkiluoto
0.0-0.5	302 269	430 391	2 454 050	1 729 942
0.5-1.0	116 384	174 929	641 037	467 834
1.0-2.5	44 812	71 099	167 449	129 078
1.5-2.0	17 254	28 898	43 740	36 680
2.0-2.5	6 643	11 745	11 426	10 858
2.5-3.0	2 558	4 774	2 985	3 387
3.0-3.5	985	1 940	780	1 122
3.5-4.0	379	789	204	395
4.0-4.5	146	321	53	147
4.5-5.0	56	130	14	57
5.0-5.5	22	53	3.6	23
5.5-6.0	8.3	22	0.95	10
6.0-6.5	3.2	8.7	0.25	4.0
6.5-7.0	1.2	3.6	0.06	1.7
7.0-7.5	0.48	1.4	0.017	0.7
7.5-8.0	0.18	0.59	0.0044	0.31
≥8	0.11	0.40	0.0016	0.044

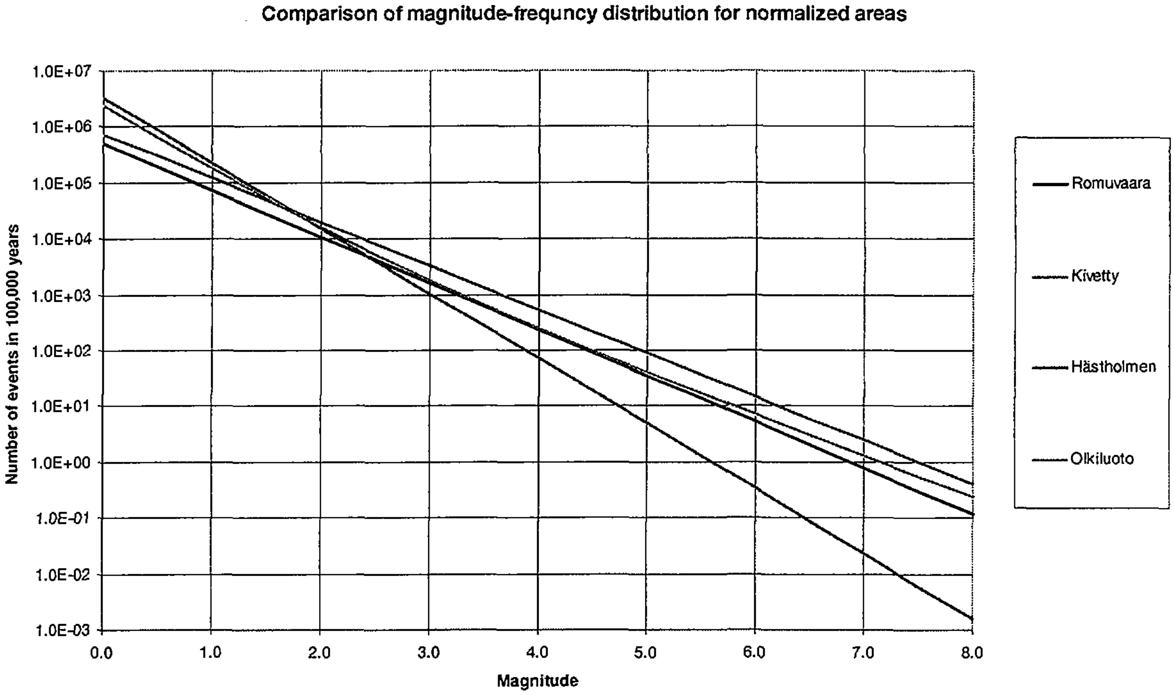


Figure 2-5. Normalised magnitude-frequency distributions of the four Finnish target areas over 100,000-year interval.

Table 2-3. Estimates for upper and lower limits for the values presented in Table 2-2, according to the standard deviation of the a- and b-values.

M	Romuvaara		Kivetty		Hästholmen		Olkiluoto	
	upper limit	lower limit	upper limit	lower limit	upper limit	lower limit	upper limit	lower limit
0.0-0.5	370 169	246 605	517 618	357 434	3 602 370	1 667 156	2 516 602	1 187 961
0.5-1.0	148 218	91 201	217 275	140 668	1 015 286	403 623	728 352	300 835
1.0-2.5	59 347	33 729	91 203	55 360	286 146	97 718	213 819	78 321
1.5-2.0	23 763	12 474	38 283	21 787	80 647	23 658	64 086	21 239
2.0-2.5	9 515	4 613	16 070	8 574	22 729	5 728	19 774	6 087
2.5-3.0	3 810	1 706	6 745	3 374	6 406	1 387	6 340	1 866
3.0-3.5	1 525	631	2 831	1 328	1 805	336	2 130	614
3.5-4.0	611	233	1 189	523	509	81	754	216
4.0-4.5	245	86	499	206	143	20	281	80
4.5-5.0	98	32	209	81	40	4.8	110	31
5.0-5.5	39	12	88	32	11	1.2	45	12
5.5-6.0	16	4.4	37	13	3.2	0.28	19	5.0
6.0-6.5	6.3	1.6	15	4.9	0.90	0.068	8.1	2.0
6.5-7.0	2.5	0.60	6.5	1.9	0.26	0.016	3.5	0.84
7.0-7.5	1.0	0.22	2.7	0.76	0.072	0.0040	1.5	0.35
7.5-8.0	0.40	0.08	1.15	0.30	0.020	0.0010	0.68	0.14
≥8	0.27	0.05	0.83	0.20	0.0079	0.00031	0.11	0.017

3. FUTURE GLACIATION AND SEISMICITY

3.1 General

Two alternative principles can be applied to the studies of current and future seismicity in Finland. The above presented magnitude-frequency distributions for earthquakes permit unlimited upper magnitudes. However, in seismic hazard studies it is often assumed that a certain region has an upper magnitude limit. According to statistical analysis based on the latter principle, the maximum magnitude of Finnish earthquakes is $M_L = 5.0$ (Ahjos et al. 1984).

It seems that, under the seismic circumstances prevailing in Finland, the bedrock is able to release strain without major earthquakes. However, because the period of known seismicity is much shorter than the forecasting period of seismicity the possibility of earthquakes larger than M=5.0 cannot be definitely excluded. Usually, in an earthquake hazard analysis 0.5 magnitude unit is added to the maximum calculated or observed magnitude, reflecting the assumption that a short catalogue may not have captured the largest possible earthquake.

The push from the North Atlantic Ridge in the NW-SE direction seems to be the major earthquakes generating force. Other factors of seismicity are glacial rebound and the structural characteristics of the bedrock. The current seismicity is a combination of these factors. In the future the factors remain basically the same, but the next ice age will change the way they interact and increase the expected magnitude extreme.

The following description of seismicity and bedrock movements related to glaciations in Finland is based on several studies, which are reviewed more in details by Forsström (1999), Kuivamäki et al. (1998) and Saari (1992).

3.2 Past and Future Glaciation

The past ice age lasted about 60,000 years. Soon after deglaciation, the crust adjusted itself strongly to the new circumstances. The most pronounced impact of this intense relaxation period occurred in a periglacial environment. The largest earthquakes in Fennoscandia during the past ten thousand years have likely occurred immediately after deglaciation 10,000-8,000 years BP. After that phase, the seismic activity seems to have decreased rather close to the current level.

The overall finding is that postglacial fault movements have occurred in old, reactivated fault zones. In Finland, the most obvious evidences of postglacial (PG) fault movements are found in western Lapland. The lengths of these faults are 4-36 km and the scarp heights 0-12 m. If the faults were generated by a single event, the estimated magnitudes of the earthquakes would have varied from 5.3 to 7.5 (Kuivamäki et al. 1998). The horizontal displacement of PG-faults is not known. The horizontal slip rates of present earthquakes seem to be 1-3 times larger than the vertical ones (Saari 1998a).

Small PG-faults located in ice polished bedrock outcrops and with scarp heights 0-20 cm have been found in southern Finland (Kuivamäki et al. 1998). PG-faults cutting quaternary soil layers have been found only in Lapland, but it is likely that similar movements have occurred elsewhere in Finland as well. The main part of Finland has been below the postglacial water bodies, which have redeposited soils. That is why geologic evidences of PG-faults are difficult to find in those areas.

The lowland faults in Lapland tend to be shorter and more irregular in geometry than the higher elevation faults (Muir Wood 1993). Perhaps, the late-glacial water body has moderated and inhibited the "earthquake pulse" in lowland areas. In addition, shorter duration of ice loading and thinner ice sheet give reasons to believe that the fault movements have been smaller in southern than in northern Finland. Also the seismotectonics of western Lapland makes the region suitable for exceptional PG-activity (see e.g. Saari 1992).

The origin and strength of the reactivation can be related to two main causes. It is suggested that, consistent with the current aseismicity beneath Greenland and Antarctica, the ice sheet suppress earthquakes. The "pulse" of seismic activity in the immediate postglacial period could be explained by the release of stored tectonic forces through the long ice age and by the release of stresses from the strong glacial unloading (Johnston 1989). Anomalous shear stresses are generated when the uniform isostatic rebound is hindered by a steep ice edge. The release of the stored stresses results that the period of retreating ice edge is characterised by much more seismic activity than the period of its advance. The other apparent cause is the intense crustal uplift immediately after deglaciation.

The PG-faults in Finland strike in SW-NE-direction and dip to SE with the exception of the Vaalajärvi PG-fault. It strikes in the NW-SE-direction. The strike direction is mainly perpendicular with the prevailing NW-SE-oriented horizontal compression. The strike direction in Vaalajärvi is interpreted as being the result of the local block structure, which possibly has given rise to a secondary stress perpendicular to the Vaalajärvi PG-fault. All these PG-fault are reverse faults (Kuivamäki et al. 1998).

Reverse faulting require compressional tectonic environment, which indicates that the release of stored tectonic forces had a significant role also in Finnish PG-seismicity. The most common seismogenic structure in compressional tectonic environment is a thrust fault (a low angle dip slip faulting). When the dip of the fault is steeper (> 45°), as usual in Finland, the reverse or strike slip faultings are expected.

Probably, near the surface, the ice cover is able to stop the vertical movement of the bedrock and the faulting is suppressed. This explanation could be applied to dip slip and strike slip faultings with a significant vertical component, but not to pure strike slip faulting. Current Finnish earthquakes seem to be mostly of the strike slip type, which indicates a dominantly horizontal movement. However, also other factors than the stress field, such as the internal friction of the faults, are involved with the seismicity and vary before, during and after the glaciation.

The observations indicate that the amount of absolute downwarping, due to the past glaciation, was around 800 m (Mörner 1979). The remaining potential uplift around the maximum has been estimated to be from 40 m - 130 m (Kakkuri 1985, Fjeldsgaar & Cathles 1991). About 80% of the uplift seem to have occurred during the first 2,000 years (Figure 3-1).

The world's climate will be dominated by growth and melting phases in the ice sheets for the next 100,000 years in the same way as it been in similar periods for the past million years. Due to general seismotectonics and factors related to generation and decreasing of the ice sheet, it is likely that the pattern of postglacial seismicity is remaining.

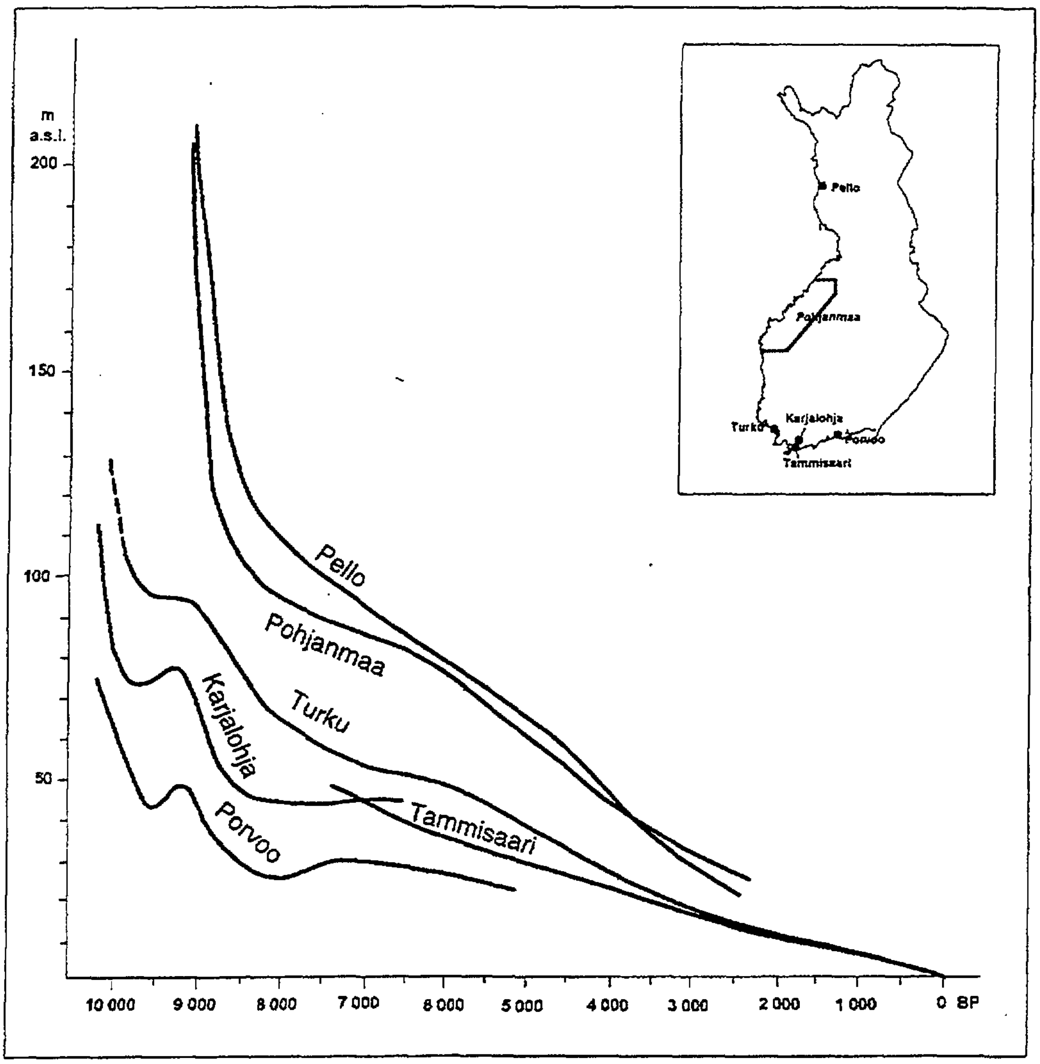


Figure 3-1. Shoreline displacement curves in different parts of Finland. Redrawn after Glückert (1994) by Kuivamäki et al. (1998). Concerning the uplift rates at the target area, the lowest rate (Hästholmen) was close to Porvoo and the highest rate (Olkiluoto) was between the Turku and Pohjanmaa curves.

Based on present knowledge, two alternative forecast (A and B) can be presented for fluctuation in climate in Fennoscandia (Forsström 1999). The glaciation scenario models do not take into account human activities, such as greenhouse effect, which may make the prevailing warm period longer. The glacial cycle includes cold episodes of advancing ice sheet (stades or stadials) and temporarily warmer periods (interstades or interstadials) with a temperature colder than nowadays. The main phases presented by Forsström (1999) are summarised below:

- Forecast A: Climate will gradually become colder, permitting the growth of glaciers in the mountainous areas of Norway and Sweden after 5,000 years. After a minor warmer period, a greater ice advance will cover a large part of Finland around 20,000 years AP (after present). The four potential repository sites are close to the edge of the ice sheet. After a new minor interstade, the ice sheet will advance again, so that c. 60,000 years AP it will extend over the whole Finland far into Baltic countries. The ice sheet will partly melt during the next interstadial phase, which will culminate about 70,000 years AP. About 80,000-115,000 years AP will be the maximum phase of the glaciation, when the ice sheet extends to northern Poland and Germany. The ice sheet will melt almost entirely during the years from 115,000 years AP to 125,000 years AP and the climate will be similar to present.

- Forecast B: The growth of the ice sheet will not begin for next 50,000 years, and Finland will be covered by ice sheet about 60,000 years AP. After a minor interstade, the ice sheet will enlarge and cover almost the whole Baltic basin. During the following ice minimum, at 120,000 years AP, the ice sheet will still cover northern Finland. At 150,000 years it will cover the whole Baltic basin, but then it will melt almost completely by 165,000 years from now.

According to the both models the glacial period will be about 80,000-100,000 years long. The climatic fluctuations are reflected in changes of a different character in different areas. In Western Lapland, the ice sheet will stay longer and be thicker than elsewhere in Finland. The minimum duration and thickness will be found in southeastern Finland around the Hästholmen site. In addition, two glacial periods (i.e. 60,000-115,000 years AP and 125,000-160,000 years AP) can be distinguished in southern Finland, if forecast B is applied. Model A predicts longer continuous glacial conditions in the site areas than B. As a more conservative forecast A is applied in the following examinations.

3.3 Future Seismicity

3.3.1 General Scenario

The current knowledge gives rather limited possibilities to assess the future postglacial seismicity. In respect of origin and strength, the current seismicity and the seismic activity following deglaciation are different. The most unchangeable factor seems to be the location of faults capable to produce major (M>7) earthquakes.

The duration of the most pronounced seismicity will presumably be of the same order than after the previous deglaciation, i.e. few thousand years or less. The release of tectonic forces and sub-ice depression will be main causes of PG-seismicity, but the strengths and quotas of these forces will differ from the present state.

An additional uncertain factor is the ice edge, its movements and thickness. However, like before, the retreating ice front will rather likely be under the water in the lowland areas (Forsström 1999). Therefore the block movements will presumably occur as smaller and "slow earthquakes" in the main part of Finland, whereas in the higher elevation faults the movements are more violent.

The current maximum rate of uplift, 9 mm/year, locates in the northern Bothnian Bay. The smallest values (1 mm/year) are close the Hästholmen site. The uplift pattern is quite regular. The residual uplift is about tenfold smaller than the total uplift. Dates and measurements from raised shorelines suggest that the rate of land uplift immediately after deglaciation was as much as 10-20 times greater than at present (Eronen & Olander 1990). In the periglacial areas the uplift is more irregular and the relative block movements can be more than 10% of the absolute value. Displacements of the order of 1-10 cm can produce earthquakes in the magnitude range from 4 to 6 (Saari 1998a, Wells & Coppersmith 1994). Larger displacements are possible in environments where extraordinary steep stress gradient is generated, like close to the ice edge.

3.3.2 Maximum Magnitude

A common opinion in seismic hazard studies is that a certain seismotectonic zone has a characteristic maximum magnitude. However, when the postglacial seismicity is concerned, the basic conditions are changed and estimate of maximum magnitude based on current data is not valid. This means that one should estimate a new maximum magnitude or utilise the data presented in Table 2-2, where the magnitude-frequency distributions are based on assumption that the magnitudes of Finnish earthquakes have not any upper limit.

The maximum magnitude could be based on calculations of seismic strain release, which is proportional to the square root of seismic energy release (Richter 1958):

$$\mathrm{Log}(E) = 2.9 + 1.9M_L - 0.024\,M_L^2 \qquad (3\text{-}1)$$

where energy (E) is expressed in J.

Currently the seismic strain release in Finland seems to be constant or close to it (Fig. 3-2). Major earthquakes dominate the cumulative strain release, but active periods of smaller earthquakes are also essential elements of the strain release pattern. The maximum strain release estimate (Fig. 3-2) corresponds to an earthquake with magnitude 5.3.

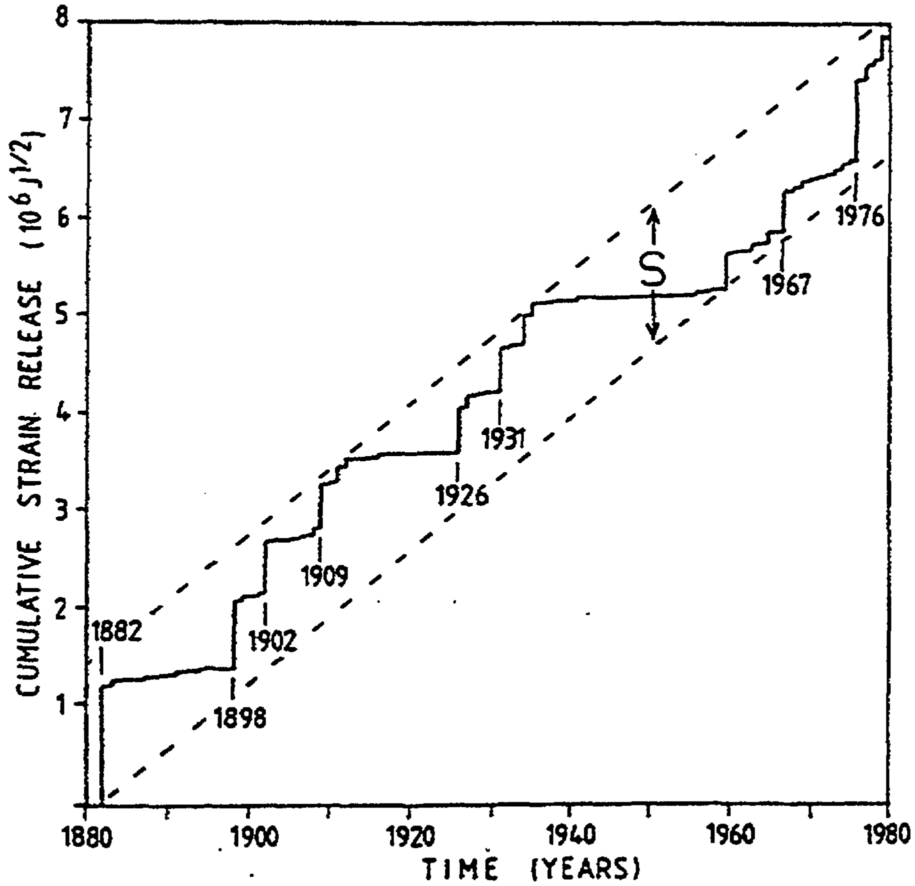
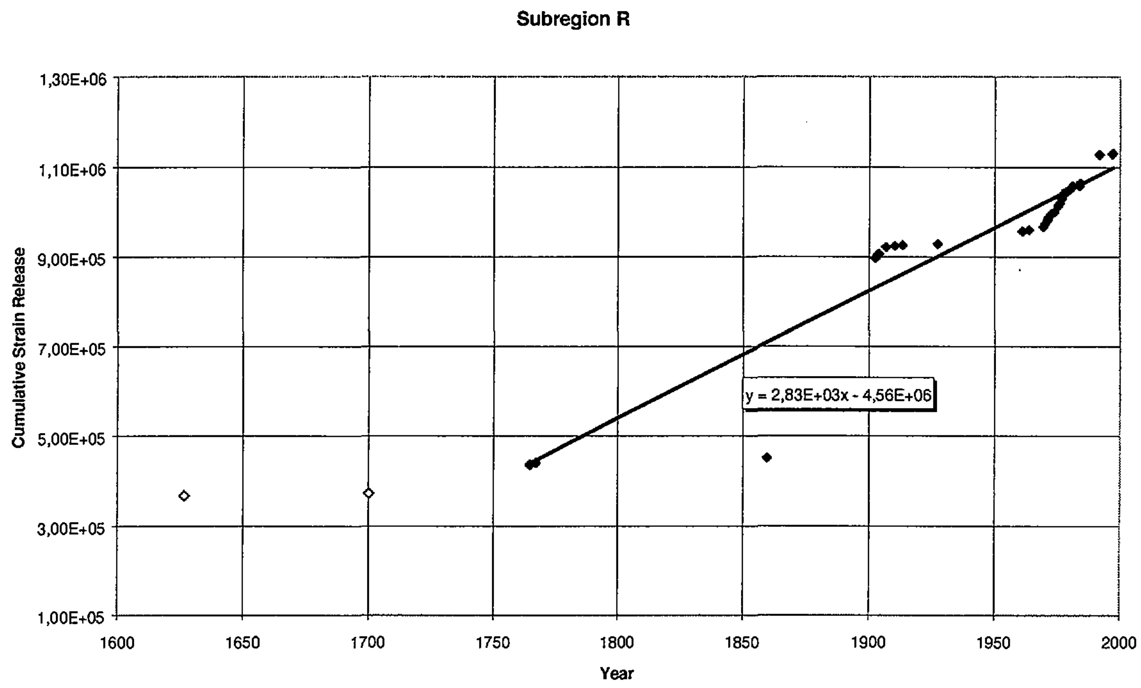


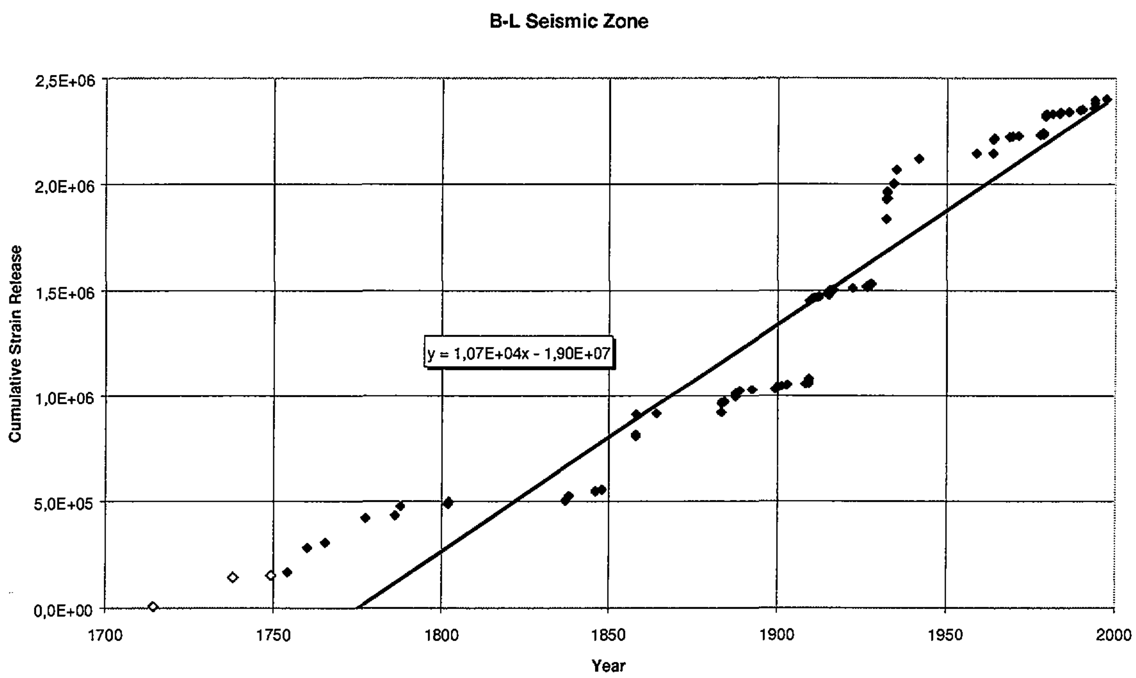
Figure 3-2. Cumulative strain release curve for Finnish earthquakes during the period 1880-1980. The major events have been marked with the year of occurrence. S is the estimate for the maximum strain (Ahjos et al. 1984).

The cumulative strain release and the slope of the average accumulation of it for the subregions are presented in Figures 3-3. The slopes and the scaling parameters of Table 2-1 give a possibility to approximate the amount of accumulated unreleased strains of the target sites over a 100,000 years interval. An earthquake, that could release the accumulated strain, determines the upper magnitude limit. The potential maximum magnitudes of the target areas are: Romuvaara M_L=7.6, Kivetty M_L=8.2, Hästholmen M_L=7.4 and Olkiluoto M_L=7.9. In practice a single earthquake does not release all the strains accumulated inside the target area. About 80,000 years long glacial period would yield about 0.2 magnitude unit smaller estimates.



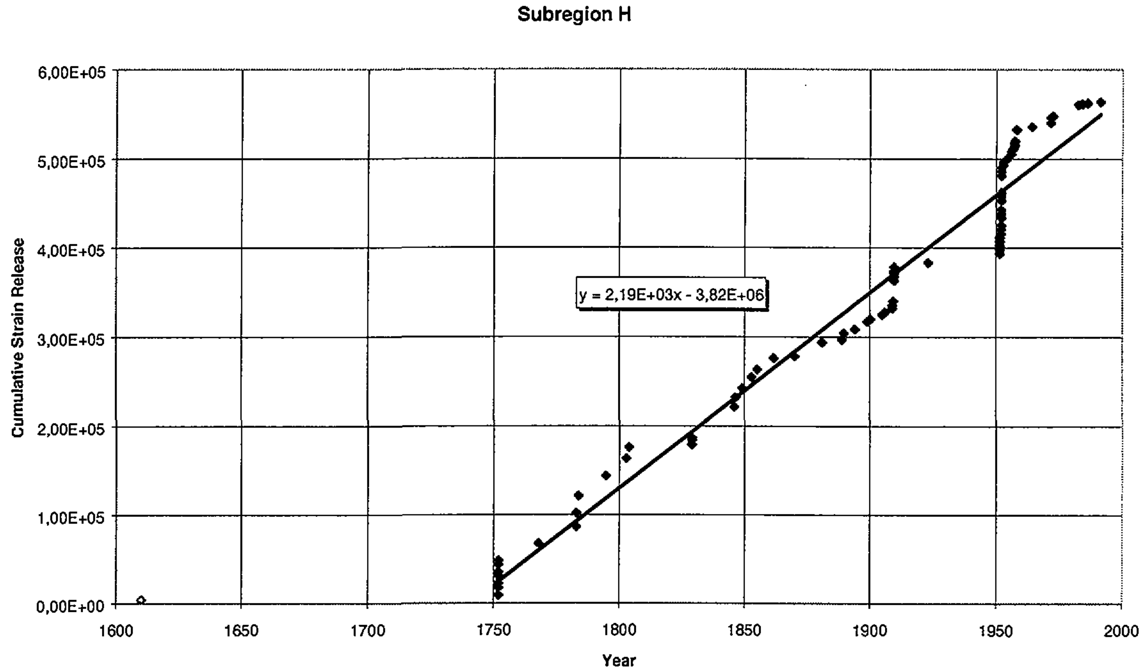
Subregion R
Cumulative Strain Release
1,30E+06
1,10E+06
9,00E+05
7,00E+05
5,00E+05
3,00E+05
1,00E+05
1600
1650
1700
1750
1800
1850
1900
1950
2000
Year
y = 2,83E+03x - 4,56E+06

a)

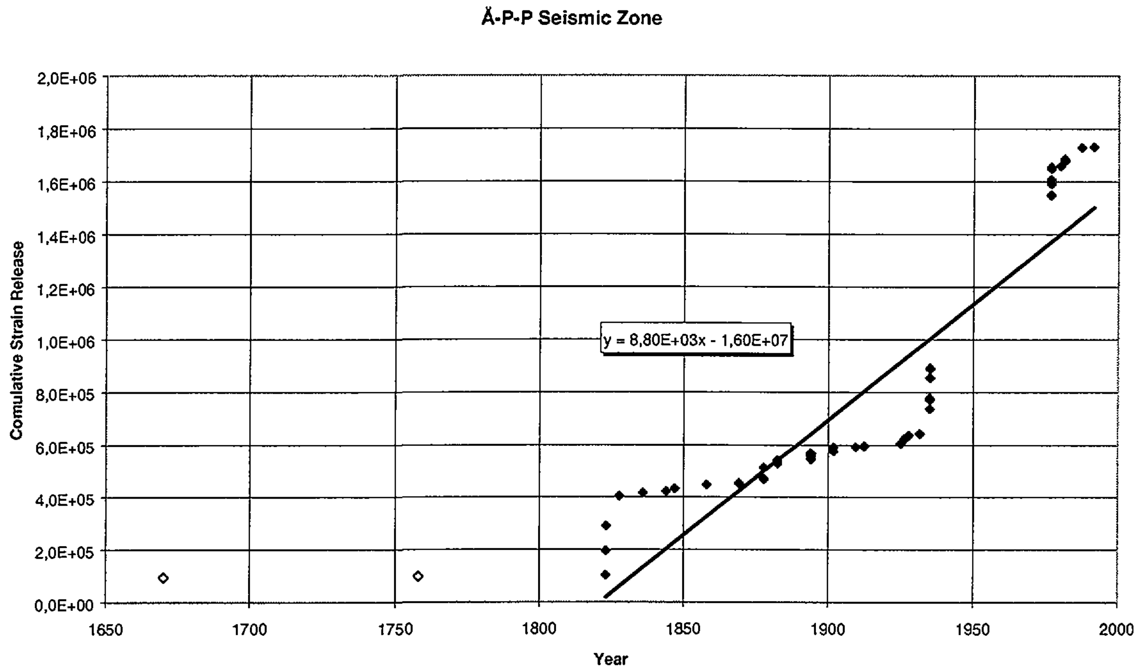


B-L Seismic Zone
Cumulative Strain Release
2,5E+06
2,0E+06
1,5E+06
1,0E+06
5,0E+05
0,0E+00
1700
1750
1800
1850
1900
1950
2000
Year
y = 1,07E+04x - 1,90E+07

b)



c)



d)

Figure 3-3. Cumulative strain release: a) Subregion R, b) B-L Seismic Belt, c) Subregion H and d) Å-P-P Seismic Belt. The least squares fit (line) is based on the same data (solid diamonds) as magnitude-frequency analysis except that the earthquake sequences of subregion H are included in this analysis. Open diamonds show the preceding incomplete data.

3.3.3 Discussion

The dominant fault type of the known PG-faults indicate that the push from the North Atlantic Ridge compression in the NW-SE direction seems to relate strongly to the seismicity immediately after deglaciation. It is rather likely that the release of the tectonic forces decreases also exponentially, but the shape of this curve is uncertain.

The approximations of the seismicity following the 80,000-100,000 years long glaciation can be based on the above presented magnitude-frequency distributions (Chapter 2.3) and maximum magnitudes (Chapter 3.3.2). In this context, at least three uncertainties should be mentioned: 1) The magnitude-frequency distribution of seismicity is likely different in PG-environment. 2) The estimates could be lower, if it is assumed (analogous to the decrease of land uplift) that about 80 % of seismic block movements will occur during the "pulse of seismic activity" and after that the expected maximum magnitude of earthquakes will be close to the current level. 3) The estimates would be higher due to the extraordinary strong crustal rebound.

The proportion of larger earthquakes is probably larger (i.e. the b-value is smaller) during the most pronounced phase of postglacial seismicity than nowadays (item one). According to the fault plane solutions of Finnish and Swedish earthquakes, the present seismicity is mainly caused by the plate tectonic ridge push. Because the present uplift rate is about 5-10% of the corresponding value during the "earthquake pulse", the statistical considerations based on current seismicity may underestimate the postglacial seismic activity.

Items two and three compensate each other, but their quotas are difficult to estimate. An important unsettled question is how much of the tectonic forces are actually stored during the ice age, and how they are released. In addition, the proportion of postglacial rebound should be approximated. However, the postglacial earthquakes in Lapland were generated in an environment of rather uniform compressional tectonics, which indicates that the impact of postglacial crustal rebound was smaller than the impact of plate tectonics. If the absolute value of strain release were 1.5 times larger than the estimates of accumulated tectonic strains, that would increase the estimates of maximum magnitude by 0.2 units.

4. LINEAMENT INTERPRETATION AND SEISMICITY

4.1 General

Two fundamental elements of seismotectonics, the orientation of the main stress field and the location of fracture zones, will remain the same during the next 100,000 years. The past pattern of changes suggest that in the geological near future of Fennoscandia variations are to be anticipated in the magnitude rather than in the orientation of stresses (Muir Wood 1995). The loading and removal of the ice sheet will change the pattern in some extent.

The stress pattern in Finland has been verified by the analysis of earthquake fault plane solutions, in situ stress measurements and geodetic information. The current tectonic stress field is rather consistently in the NW-SE direction. However, in the northernmost part of Fennoscandia, the stress pattern is less uniform probably due to the increase of the ridge push from NNE- and N-directions.

Intraplate earthquakes tend to occur on old zones of crustal weakness reactivated by present stress field. The target sites are dominated by long, NE-SW oriented fracture zones (see Figs. 4-1 ... 4-4). The other orientations of N-S and SW-NE for fracture zones are less common. According to seismic soundings and fault plane solutions, the faults and fault zones seem to be predominantly vertical.

Wells and Coppersmith (1994) assembled a comprehensive database of earthquake source parameters. The database gives values for rupture area, moment magnitude, average surface displacement and surface rupture length among other parameters. The data was separated into three groups based upon fault type (normal, reverse and strike slip faults). Based on this database, empirical relationships can be presented to assess maximum earthquake magnitudes or dislocation for a particular fault zone or an earthquake source (Wells and Coppersmith 1994, La Pointe et al. 1999). The relations among some of the parameters differ based upon the fault type.

Generally, it is not possible to predict reliably whether any given fault lineament will reactivate as a normal, reverse or strike slip fault during some future earthquake event. A conservative modelling approach would be to select the worst-case parameters for any fault trace. In Sweden, this was accomplished by selecting displacement and depths based upon the regression for reverse faults if surface rupture length is less than 40 km or the magnitude is less than 7, and displacement and depths from the strike slip regressions for faults greater than 40 km or magnitude greater than 7 (La Pointe et al. 1999).

An alternative modelling approach could combine the stress pattern and the lineament interpretation of the target area. When the orientation of the main stress field is in the NW-SE direction, NW-SE- and N-S-oriented zones of weakness are advantageous for strike slip faulting whereas reverse faulting is more plausible in fracture zones perpendicular the orientation of the main stress field.

4.2 Lineament maps

In Finland, as usual in intraplate areas, the principal knowledge of larger earthquakes generally relies on macroseismic observations, whereas instrumentally located events are mainly smaller. In both cases the location error is likely to be too large in comparison to the dimensions and separation of faults. However, within the limits of location accuracy, some fracture zones can be associated with seismicity.

The future 100,000 years will certainly bring out currently unknown active faults. It is assumed that the most significant earthquakes are related to the largest fault zones or to the faults associated with present seismicity. These potentially active fault zones are suggested in the following.

The following interpretations are a compilation of the lineament maps presented by Kuivamäki (2000) and the previous seismotectonic interpretations of the target sites (Saari, 1997, 1998a 1998b and 1999). In these studies, the interpreted lineaments were mainly classified in four size categories (Table 4-1).

Table 4-1. The size classification of lineaments. Modified after Salmi et al. 1985.

Size category	Width (m) *	Length (km)
I	about 1000 m	tens - hundreds
II	several hundreds	5 - tens
III	10 - 100 m	1 - 5
IV	<< 10 m	< 1

* supposed value

Generally, only the I-class lineaments are included in the presentations. The numbers of I-class lineaments in Romuvaara, Kivetty and Olkiluoto sites are 162, 131 and 88, respectively. In the Loviisa area, where the largest classified linements are in class II, the map of unclassified lineament was applied. In each of the maps, lineaments longer than 40 km are picked up. Also some lineaments possibly associated with current seismicity are mentioned.

In the Romuvaara target area, 76 of the I-class lineaments are more than 40 km long. Most of them are NW-SE oriented. The area is characterised by low seismicity with relatively small earthquakes. The area includes 9 events with a magnitude of M = 2.2 - 3.3. The nearest event (1971, ML = 2.4) occurred 35 km west from the site. This event and the events north from it seem to be related to the N-S oriented Kuhmo greenstone belt (lineaments 131 - 133 in Fig. 4-1).

Two relatively strong earthquakes are located 115 km (1902, M=4.7) and 145 km (1626, M=4.6) west from the Romuvaara site, in the Lake Oulujärvi area. Lineament 9-12 weakness and their branches can possibly be associated with the seismic activity in Oulujärvi and NW of it (Saari 1999).

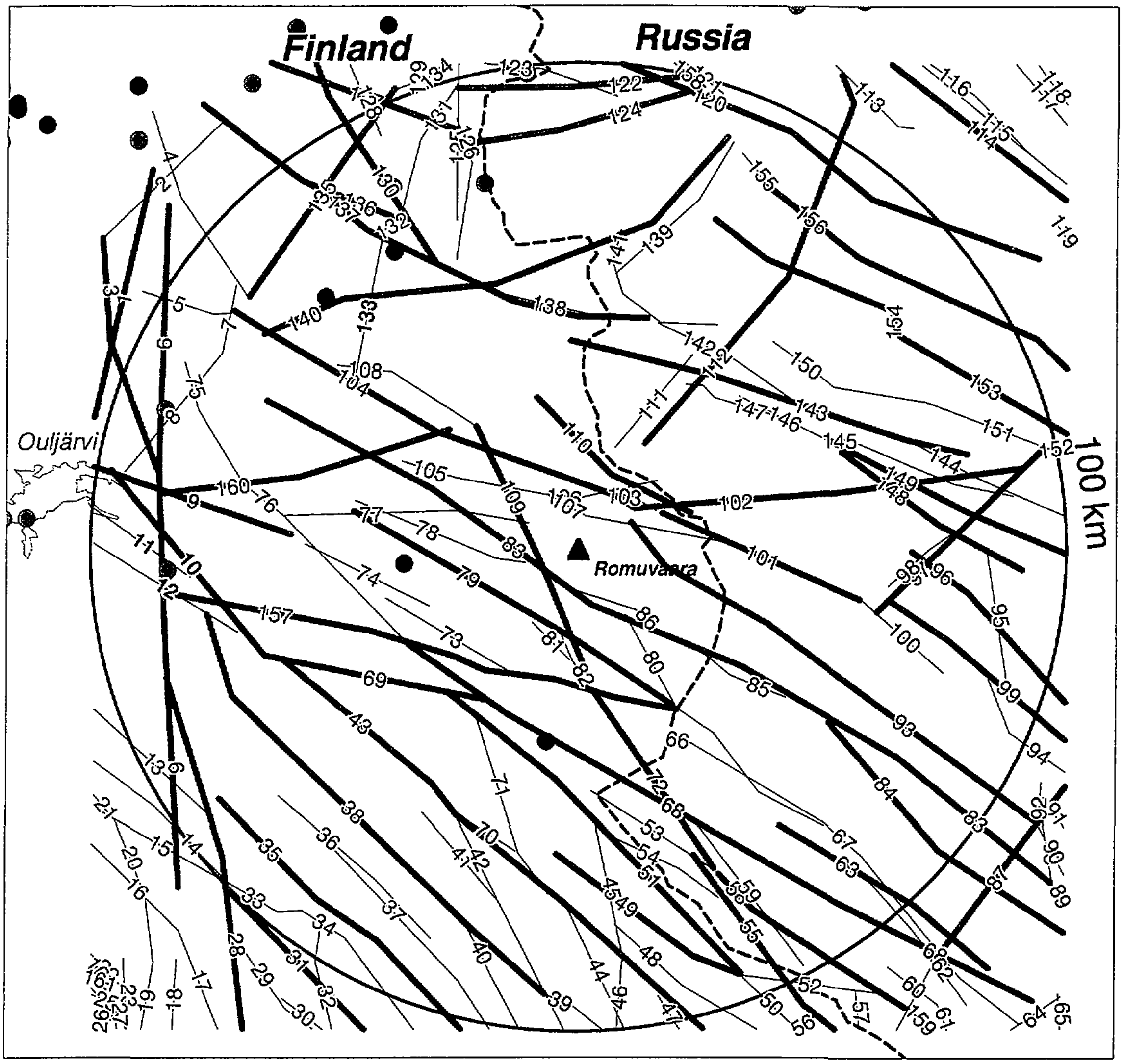


Figure 4-1. I-class lineaments of the Romuvaara target area. Lineament numbers refer to the corresponding number in the interpretation by Kuivamäki (2000). Lineaments longer than 40 km are shown by red colour. Lineaments with red numbering are mentioned in the text. Light blue dots are macroseismically (-1964) and dark blue dots are instrumentally (1965-) located earthquakes. The solid triangle shows the location of Romuvaara.

Most of the I-class lineaments of the Kivetty target area are NW-SE oriented. Altogether 63 of them are more than 40 km long. Within a radius of 100 km from Kivetty 18 earthquakes are located. Six of these events were exceptionally strong (M = 3.8 - 4.5) for Finland. The closest ones occurred in 1931 (M = 4.5 and M = 3.9) in Laukaa, 35 km from Kivetty. The remaining 12 events within this region were microearthquakes (M < 3.0) and the closest of these (1899, M=2.6) occurred 25 km north of Kivetty (Fig. 4-2).

The most significant events (M≥3.5) of the Kivetty target area can be related to two sets of I-class fracture zones oriented in a NW-SE-direction (Saari 1998b). The longer one runs SE from the Bothnian Bay region and includes lineaments 1 and 60 (Fig. 4-2). Altogether 9 earthquakes with magnitude M = 3.7 - 4.6 can be associated with this set of lineaments. The other set of active fracture zones is east of lineaments 70 and 77.

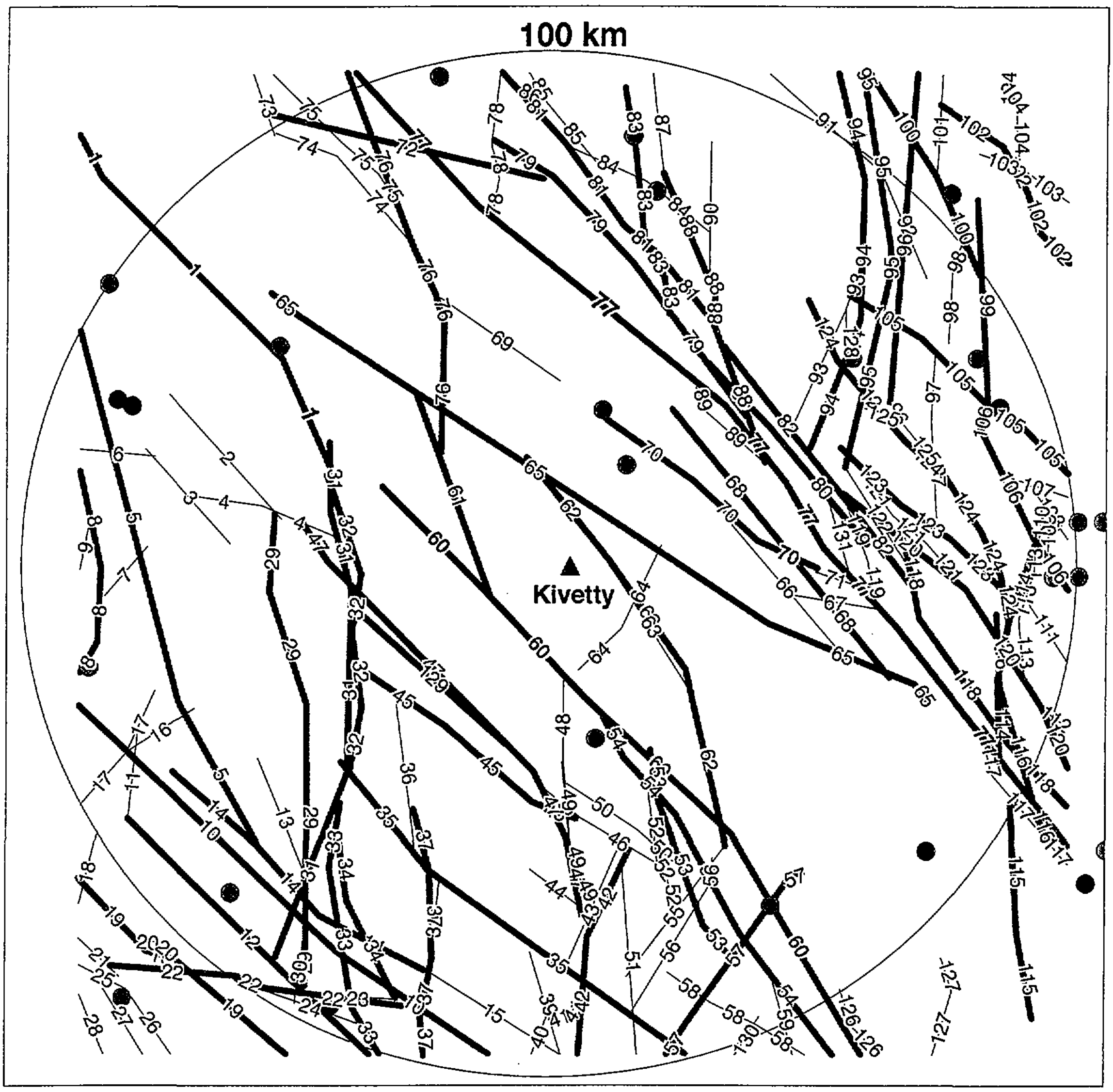


Figure 4-2. I-class lineaments of the Kivetty target area. Lineament numbers refer to the corresponding number in the interpretation by Kuivamäki (2000). Lineaments longer than 40 km are shown by red colour. Lineaments with red numbering are mentioned in the text. Light blue dots are macroseismically (-1964) and dark blue dots are instrumentally (1965-) located earthquakes. The solid triangle shows the location of Kivetty.

In the Olkiluoto target area, 44 of the I-class lineaments are more than 40 km long. Most of them are NW-SE oriented. The target area includes 6 events with a magnitude of M = 2.5 - 3.1. The nearest events occurred about 35 km south (1926, M=3.1) and about 40 km north (1804, M=2.9) from the site (Saari 1997). Lineaments 12, 23, 24, 27, 36 and lineaments intersecting them within the active Å-P-P seismic belt (Fig. 4-3, shaded area) are likely the most potential active lineaments. Another, less active but noteworthy set of lineaments is north of Olkiluoto (numbers 5-15).

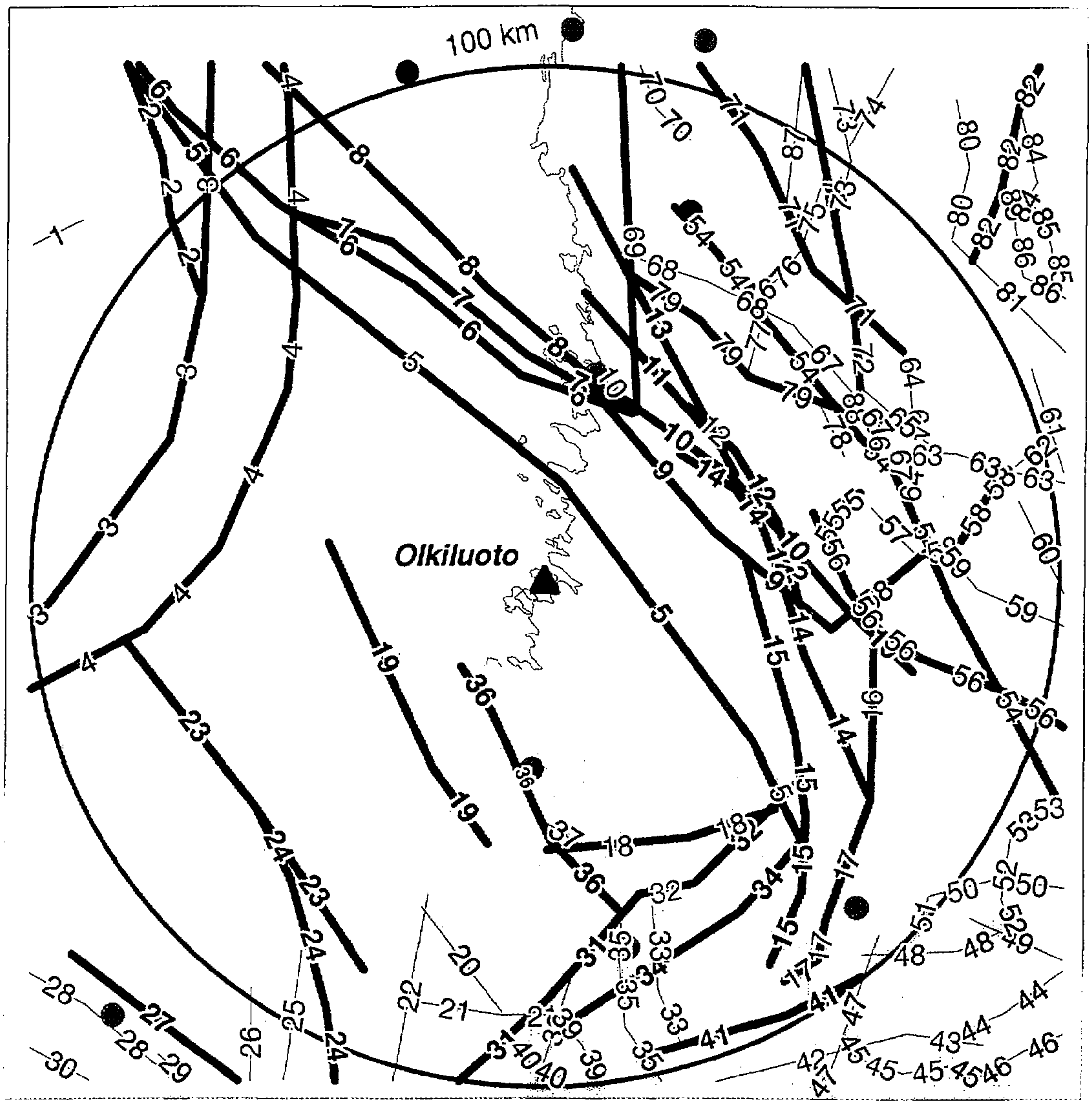


Figure 4-3. I-class lineaments of the Olkiluoto target area. Lineament numbers refer to the corresponding number in the interpretation by Kuivamäki (2000). Lineaments longer than 40 km are shown by red colour. Lineaments with red numbering are mentioned in the text. Light blue dots are macroseismically (-1964) and dark blue dots are instrumentally (1965-) located earthquakes. The solid triangle shows the location of Olkiluoto.

In the Hästholmen target area, only four of the lineaments are more than 40 km long. One of them (270) runs nearly towards Hästholmen. The area contains two dominant fault directions: SW-NE and NW-SE (Fig. 4-4).

The area within a distance of 100 km from Hästholmen includes 51 events with a magnitude of M = 2.2 - 3.1, and all except one, were macroseismically observed. These events were felt not more than 10 - 20 km from their epicentres and the majority (29) occurred during two earthquake sequences (1751-1752 and 1951-1956) about 25 km north from Hästholmen. The macroseismic data, representing location accuracies of the order of 20-100 km, is difficult to associate with the local tectonics. However, some potentially active fault zones are suggested in Figure 4-4. The interpretation is supported by a microearhquake study (Saari 1998b).

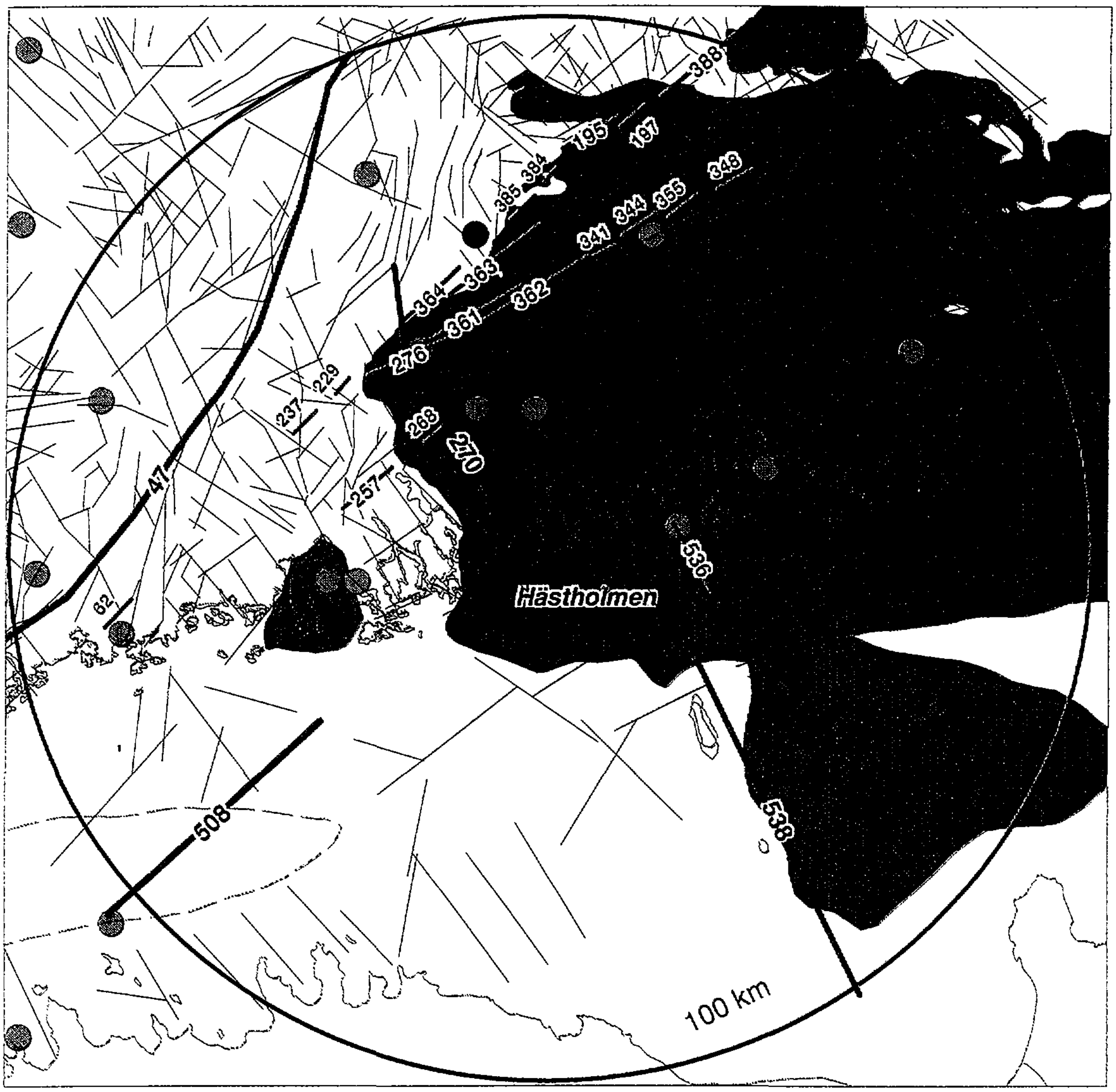


Figure 4-4. Unclassified lineaments of the Hästholmen target area. Lineament numbers refer to the corresponding number in the interpretation by Kuivamäki (2000). Lineaments longer than 40 km are shown by blue colour. Shorter green lineaments are likely related to current seismicity (Saari 1998b). Light blue dots are macroseismically (-1964) and dark blue dots are instrumentally (1965-) located earthquakes. The solid triangle shows the location of Hästholmen. Red = rapakivi granite (Koistinen 1994).

5. CONCLUDING REMARKS

The aim of the study has been to approximate the future seismicity associated with the fourinvestigation sites for final disposal of spent nuclear fuel. The four sites are Romuvaara, Kivetty, Olkiluoto and Hästholmen.

The study of regional seismicity indicated that southern Finland contains two seismic belts of higher and lower seismic activity. The magnitude-frequency relations of these belts were scaled to represent the seismicity of the target areas, i.e. the areas within a radius of 100 km of the sites. The proportion of larger earthquakes to smaller ones seems to be smaller in Hästholmen site than in three other sites.

In Finland, the most obvious evidences of postglacial fault movements are found in western Lapland. All these faults are reverse faults, which require compressional tectonic environment. It seems that the impact of postglacial crustal rebound was smaller than the impact of plate tectonics.

The postglacial earthquakes in Lapland were generated in an environment of rather uniform NW-SE oriented compressional tectonics, which indicates that, as the present seismicity, the seismicity immediately after deglaciation seems to relate strongly to the push from the North Atlantic Ridge.

When the dip of faulting is steep, as usual in Finland, also strike slip faulting is expected in compressional environment. Postglacial strike slip faults are difficult to identify, but current Finnish earthquakes are mainly of that type.

A common opinion in seismic hazard studies is that a certain seismotectonic zone has a characteristic maximum magnitude. The Finnish bedrock seems to be able to release strain with earthquakes less than M=5.0. However, because the period of known seismicity is much shorter than the forecasting period (100,000 years) the possibility of larger earthquakes cannot be definitely excluded. Usually, in an earthquake hazard analysis 0.5 magnitude unit is added to the maximum calculated or observed magnitude, reflecting the assumption that a short catalogue may not have captured the largest possible earthquake.

However, when the postglacial seismicity is concerned, the basic conditions are changed and the estimate of maximum magnitude based on current data is not valid. This means that one should estimate a new maximum magnitude. The accumulated unreleased strains of the target sites over a 100,000 years interval give an estimates of maximum magnitude: Romuvaara M_L=7.6, Kivetty M_L=8.2, Hästholmen M_L=7.4 and Olkiluoto M_L=7.9. One can also utilise the magnitude-frequency distribution, which is based on the assumption that the earthquakes do not have any upper magnitude limit.

The target sites are dominated by long, NE-SW oriented lineaments. In the Hästholmen site also SW-NE orientations are common and lineaments are shorter than in the other three areas. Potentially active fault zones are suggested in the study. It is assumed that the most significant earthquakes are related to the largest fault zones or to the faults associated with present seismicity.

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