TECHNICAL REPORT

90-30

The earthquakes of the Baltic shield

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June 1990

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THE EARTHQUAKES OF THE BALTIC SHIELD

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Information on SKB technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32) and 1989 (TR 89-40) is available through SKB.

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ABSTRACT

More than 200 earthquakes in the Baltic Shield area in the size range ML 0.6-4.5 have been studied by dense regional seismic networks. The analysis includes focal depths, dynamic source parameters, and fault plane solutions. In southern Sweden a long part of the Protogene zone marks a change in the seismic activity. The focal depths indicate three crustal layers: upper crust (0-18km in southern Sweden, 0-13km in northern Sweden), middle crust down to 35km, and the quiet lower crust. The fault plane solutions show that strike-slip is dominating. Along the Tornquist line significant normal faulting occurs. The stresses released by the earthquakes show a remarkable consistency with a regional principle compression N60W. This indicates that plate-tectonic processes are more important than the land uplift. The spatial distribution is consistent with a model where the earthquakes are breakdowns of asperities on normally stably sliding faults. The aseismic sliding is estimated to be 20000 times more extensive than the seismic sliding. Southern Sweden is estimated to deform horizontally at a rate of 1mm/year or more.

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SUMMARY

The Baltic shield area is a low seismicity area with few seismic events exceeding ML=4. Since 1979 dense regional seismic networks have been operated and allowed accurate locations including focal depths and fault plane solutions of more than 200 earthquakes in the size range ML=0.6-4.5. The location of the southern Sweden seismicity shows that a long part of the Protogene zone, the border between the younger western and older eastern crustal rocks, marks a change in seismic activity. The focal depths of the earthquakes indicate three seismically different crustal layers: upper crust (0 - 13km in northern Sweden, 0-18km in southern Sweden), middle crust down to 35km, and the seismically quiet lower crust. The Gutenberg b-value is smaller for the middle crust than for the upper crust. The fault plane solutions show that strike-slip is dominating. Along the Tornquist line (the southwestern border line of the Baltic shield area) normal faulting occurs. In northern Sweden reverse faulting is more common than normal faulting. The stresses released by the earthquakes show a remarkable consistency considering the small sizes of the earthquakes. The data are consistent with a N60W direction of the regional principal compression, this supports the view that the Baltic shield seismicity is related rather to plate-tectonic processes than to the land-uplift. The spatial distribution of the Baltic shield seismicity is consistent with a model where the earthquakes are sudden breakdowns of asperities on normally stably sliding faults. The aseismic sliding is estimated to be more than 20000 times more extensive than the seismic sliding. The rate at which southern Sweden presently deforms horizontally is estimated to be 1 mm/year or more.

1 INTRODUCTION

Since Dec 1979 the National Defence Research Institute in Stockholm has operated networks of seismic stations for recording the Baltic shield area earthquakes. Figure 1 shows the station locations, up to 24 stations have been operated at the same time. All seismometers have been placed on Precambrian bedrock. The detection threshold has been in the range ML=0.6-1.3 for the areas covered by the networks. The favourable crustal conditions and dense spacing of the stations have allowed accurate locations and depth determinations. In addition the use of spectral amplitudes together with the first motion directions has significantly improved the fault plane solutions for the detected earthquakes, Slunga (1981b, 1982). Results from detailed studies of about 200 Swedish earthquake source mechanisms are now available, Slunga (1981a), Slunga et al (1984a,b), Slunga (1985,1989b), and Slunga and Nordgren (1987,1990). The sizes range from ML=0.7 to ML=4.5. In addition fault plane solutions have also been reported for nine Finnish earthquakes, Slunga and Ahjos (1986), and for the major, ML=4.9, earthquake in the Gulf of Finland Oct 26 1976, Slunga (1979). The earthquake epicenters are shown in figure 2.

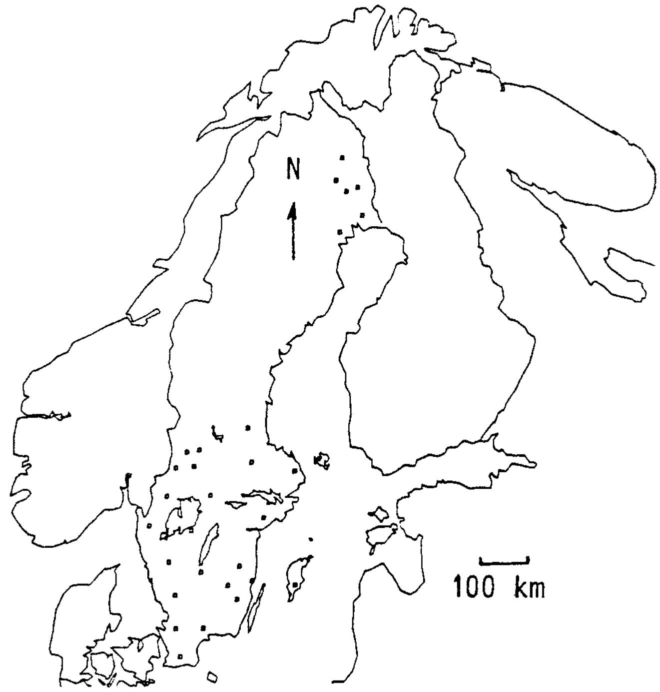

Figure 1. The squares show the seismometer positions of the regional seismic networks since the end of 1979. Up to 24 stations have been in operation at the same time. The northern network was established 1987 and was operated together with 8 stations of the southern network.

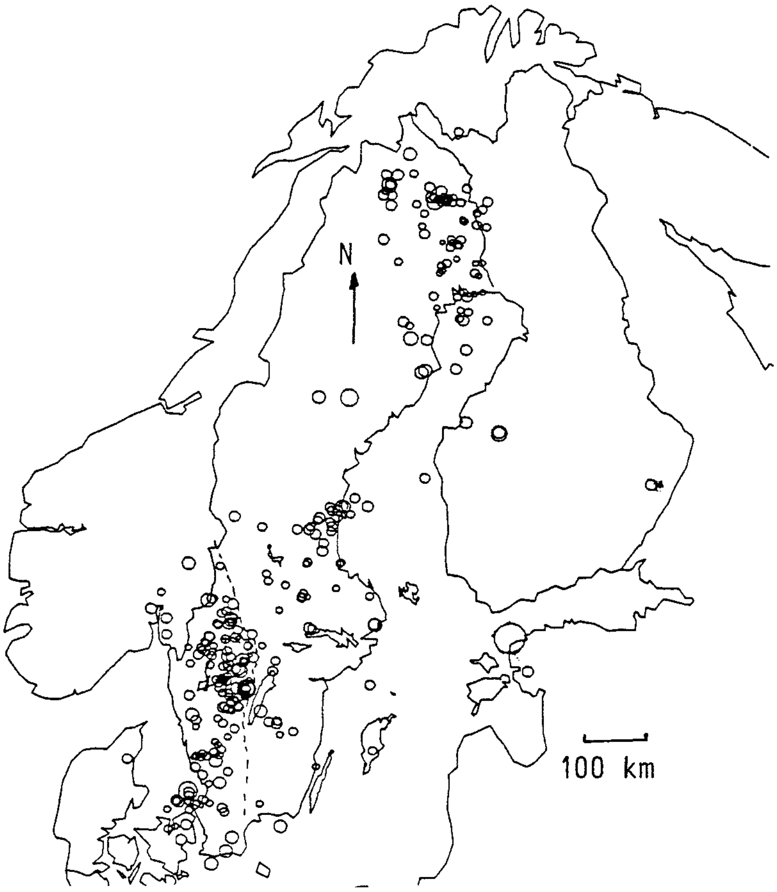

Figure 2. The epicenters of the earthquakes that so far have been analysed in detail at Foa. All but three events are from the years 1980-1988. This is a seismicity map only for the parts covered by the two networks of figure 1 (southern and northern Sweden). Note how well the Protogene zone, the dashed line, defines the eastern boundary of the higher seismicity in the lake Vänern area. The size of the circles scale with magnitude in the range ML=0.6-5.

2 FAULT PLANE SOLUTIONS

The dominating type of faulting is strike-slip at subvertical fault planes (transpression). The earthquakes along the Tornquist line (the fault zone through Scania beeing the southern limit of the shield area) show normal faulting while the remaining earthquakes have more components of reverse faulting than of normal faulting. The largest Baltic shield earthquake so far studied, the Oct 26 1976 earthquake in the Gulf of Finland, Slunga (1979), ML=4.9, was also a strike-slip earthquake at a depth of 12-14 km. In figure 3 the type of faulting mechanisms are shown.

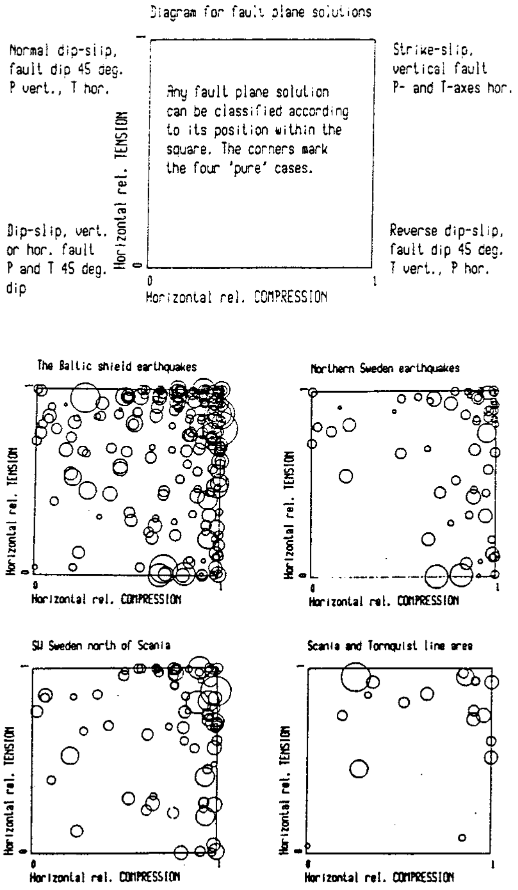

Figure 3. The fault plane solutions of different parts of the Baltic shield areas. Each circle marks one earthquake. The size of the circle scales with the magnitude, ML=0.6-5. Note the dominance of strike-slip. The four diagrams show in the upper left all data (the Baltic shield), and for comparison the parts northern Sweden, SW Sweden north of Scania, and the Tornquist line area.

3 FOCAL DEPTHS

The depth distribution of the earthquakes, figure 4, indicates at least three seismically different layers in the crust of southern Sweden: the upper crust 0-18 km having the highest earthquake frequencies, the middle crust 18-35 km, and the seismically quiet lower crust.

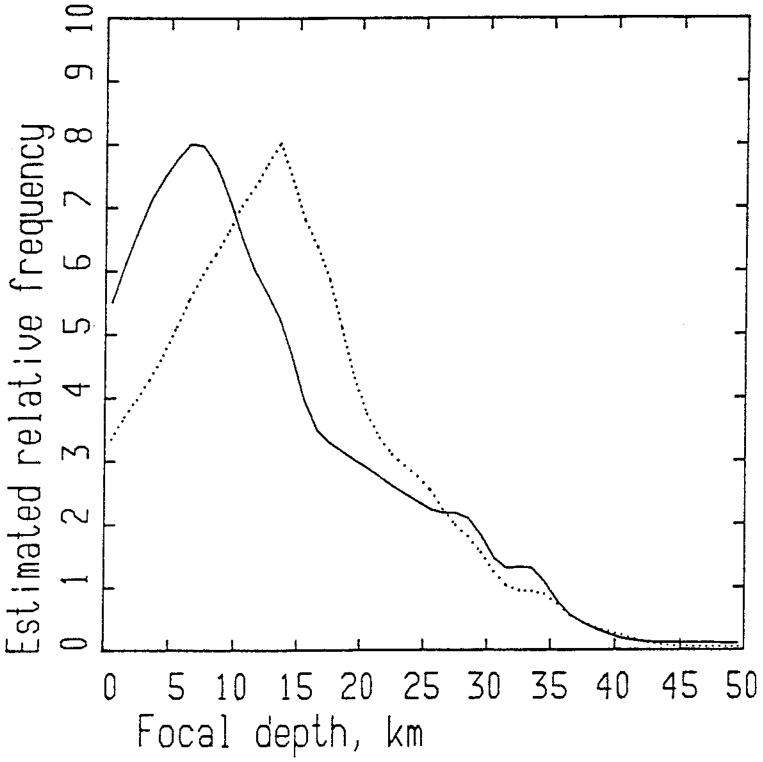

Figure 4. The estimated relative frequencies of the focal depths of the northern (solid line) and southern (dotted line) Sweden earthquakes. The seismic boundary at 35 km depth is most probably a temperature effect (ductility), the 5 km difference between the upper crustal peaks may be due to different depths of lithological boundaries. The mean crustal depth is 45km.

The upper and middle crust have different size distributions (b-values), the upper crust has a larger portion of small earthquakes (larger b-value), see figure 5. The ML 4.5 event at Skövde July 14 1986 had a focal depth of 25-30 km, Slunga and Nordgren (1987), while the ML 4.4 Kattegatt earthquake June 15 1985 occurred at about 15 km depth. Figure 4 gives the focal depth distributions of the earthquakes in northern and southern Sweden. It is interesting to note that the drop of the earthquake frequency is 5 km shallower (13 km instead of 18 km) in northern Sweden. One possible explanation is that this seismicity boundary is due to a lithological boundary (the Conrad) and that this is more shallow in the older northern crust (possibly due to erosion).

4 SEISMIC MOMENTS, SLIP SIZES, AND STATIC STRESS DROPS

The seismic moments and the sizes of the peak shear slips are shown in figure 5. Note the different general slopes (b-values) for the upper and middle crustal seismicity.

The relation used for the computation of ML from the estimated seismic moments, Mo, is for small events with ML<3.5:

ML = 10log(Mo) - 10, where Mo is expressed in Nm,

Slunga (1982). For larger events a nonlinear relation must be used, Slunga et al (1984b).

For a ML 2 event the peak slip is typically 1-10 mm. The ML 4.5 Skövde event had an estimated peak slip of about 300 mm, Slunga and Nordgren (1987). As will be discussed below the earthquake source parameter of greatest geophysical interest may be the peak slip and not the seismic moment.

Figure 6 shows the estimated static stress drops in relation to seismic moment and focal depth. One can see that there is a strong correlation between stress drop and seismic moment up to ML=2-3. It may be that the size of the smaller events primarily is determined by the size of the effective normal pressure at the hypocenter. One can also see in figure 6 that for earthquakes of the same size the stress drop is independent of focal depth. On the other hand figure 5 above showed that the size distribution (b-value) was different for the middle and upper crust, there are fewer small events in middle crust. This may be in agreement with the view that the size of the effective normal pressure determines the size of the small events, the lithostatic pressure is higher at greater depths.

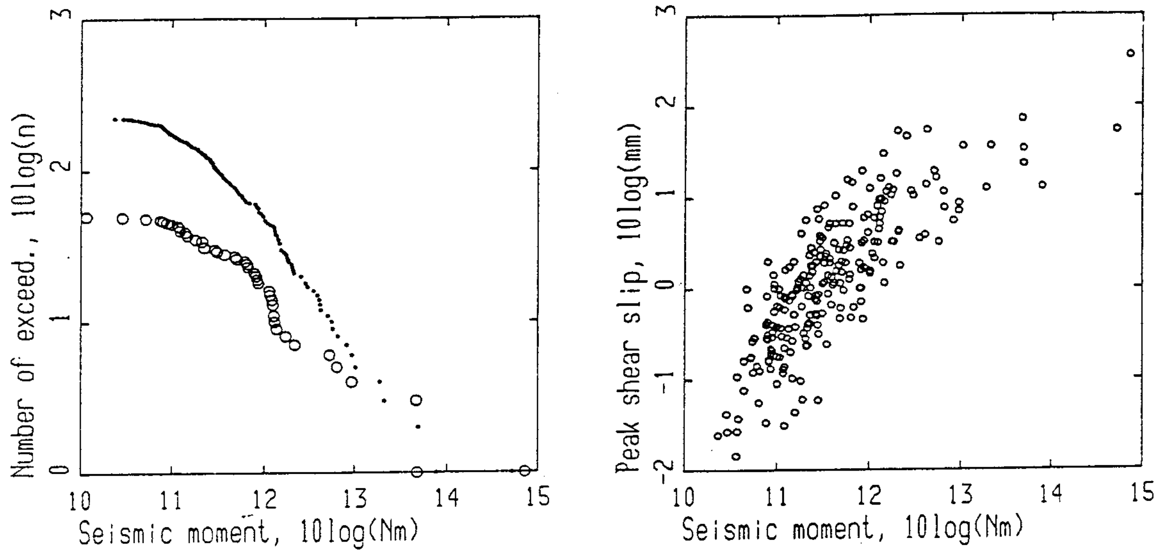

Figure 5. To the right the distribution of the seismic moment and its relation to the size of the peak fault slip. Left the number of earthquakes exceeding the seismic moment given by the x-axis is shown for earthquakes at different depths: the smaller circles denote events at 0-20km depth, the larger circles denote events deeper than 20km. Note the different general slopes of these two curves (b-values).

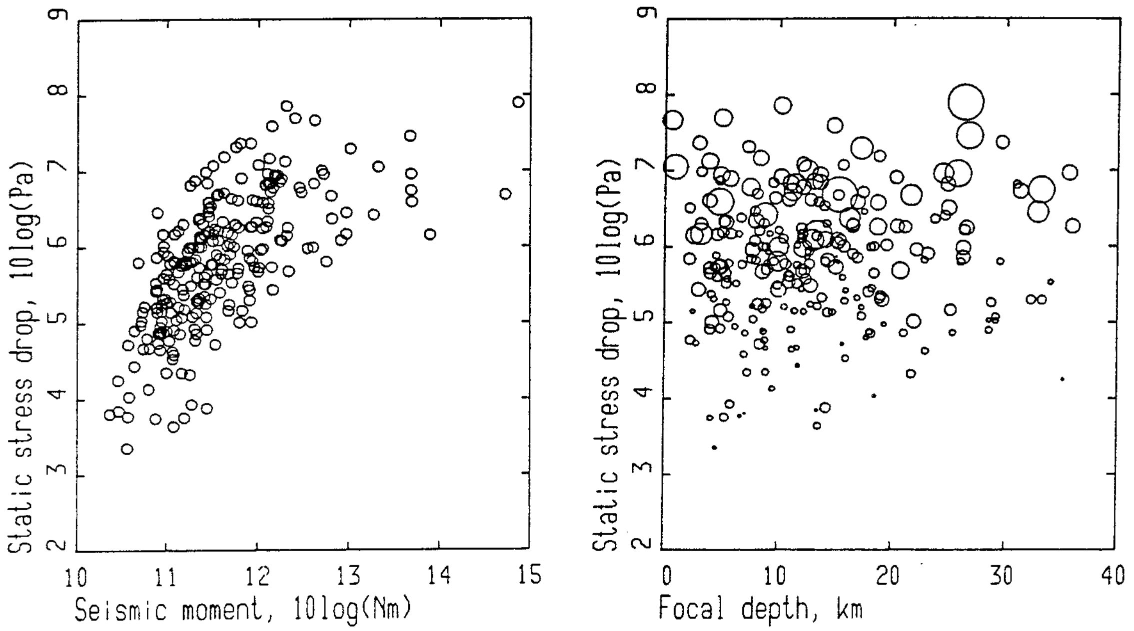

Figure 6. The estimated static stress drops. Each circle marks one earthquake, in the right diagram they are scaled according to ML (0.6-4.5). Note the strong correlation between static stress drop and seismic moment (up to ML=3) and the lack of correlation between static stress drop and focal depth for events of similar sizes. The picture one sees here is consistent with the view that the earthquakes occur in small parts of the faults of increased normal stresses (locking that part during aseismic slip).

5 HORIZONTAL STRESSES

One of the most interesting results of the analysis of the Baltic shield earthquakes is the very consistent horizontal orientation of the released stresses. The rock stresses cannot be estimated directly from the earthquakes, McKenzie (1969), only the stress release is uniquely estimated (the orientation of the P- and T-axes), see the discussion by Slunga (1981a). Figure 7 shows the orientations of horizontal principal compression for the stresses relaxed by the earthquakes in southern and northern Sweden and in Finland. It is interesting that also earthquakes below magnitude ML=1 show the same stress release orientation as the major earthquakes. The consistancy means that the seismic fault movements may all be part of the same systematic horizontal deformation of the crust. The earthquake mechanisms both from Finland, northern and southern Sweden, and Denmark are in general agreement with a regional stress field having its principal horizontal compression in the direction N60W.

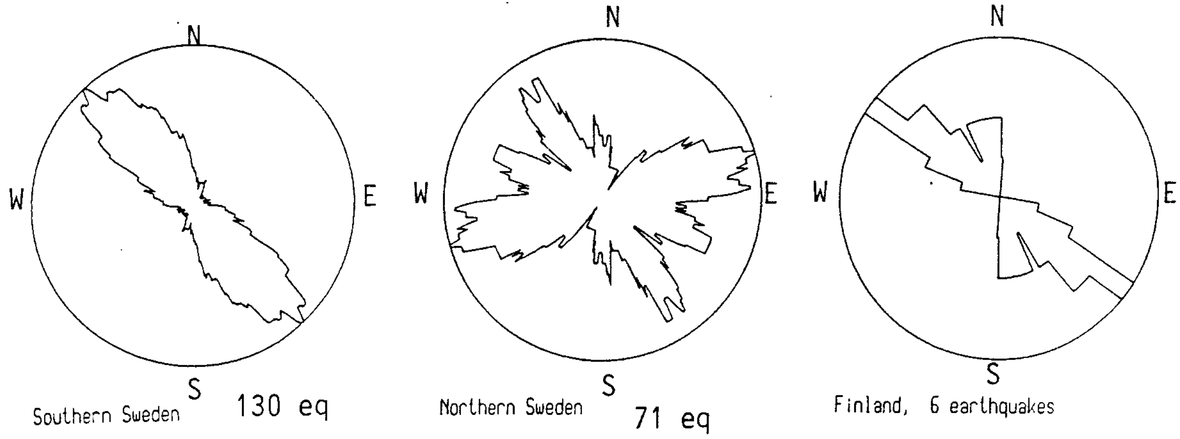

Figure 7. The distribution of the orientation of the maximum horizontal compression of the stresses released of the earthquakes. The radius gives the number of earthquakes having the principal horizontal compression within +/- 20 degrees. The circle peripheri means 46, 15, and 4 events for respectively southern Sweden, northern Sweden, and Finland. Note the remarkable consistency in southern Sweden. All three areas are consistent with a regional orientation of the principal horizontal compression in the direction N60W. The different scatter of southern and northern Sweden is possibly explained by the different pattern of fault strikes of the two areas (southern Sweden dominated by N-S and E-W faults, northern Sweden by N-S and NW-SE faults).

6 GEODETIC OBSERVATIONS

Geodetic measurements in Finland and Norway have indicated fault movements at rates of 1 mm/year both vertically and laterally, Talvitie (1977), Veriö (1979, 1982a,b), Bakkelid (1986), Kakkuri (1988), and Anundsen (1988). Veriö stated that these fault movements occur both in seismic and aseismic areas. These geodetic fault movements are several orders of magnitudes more extensive than the summed seismic fault movements because the seismic fault movements only covers very small portions of the faults (fault radii are typically 100m or less) while the geodetic measurements indicate whole block movements with 100 km dimension.

In Estonia similar results and conclusions have been achieved by Vallner, Sildvee, and Torim (1988). They stated:

- block movements of the Estonia are proved by the geodetic measurements
- there is a definite relationship between the localities of change in vertical movement rate and the boundaries of geological structures.

The sum of the differential block movement rates is about 3 mm/year across the area. If these differential block movements are fault movements the total fault movement across Estonia corresponds to a seismic moment of the order of 1E+18 Nm/year. The largest known earthquake of the area during the last 350 years, the Oct 26 1976 event with ML=4.9, had a seismic moment of 3.5E+15. Assuming a reasonable b-value, 0.80, and assuming a Gutenberg linear relation for the smaller earthquakes one get the seismic moment release to be 1.6E+16 Nm for the last 350 years. This gives the aseismic fault movements (the geodetically observed differential block movements) to be more than 20000 times more extensive than the seismic fault movements.

In conclusion the geodetic measurements in the Baltic shield area indicate fault movements and/or block movements orders of magnitudes more extensive than the summed seismic movements of the seismicity during the same periods.

7 ASEISMIC AND SEISMIC FAULT SLIP

The stability of fault slip has been discussed in a number of papers, for instance Tse and Rice (1986). The understanding of the aseismic and seismic sliding is in fact quite promising and numerical models for fault behaviour based on laboratory results of rock sliding have been successful, Tse and Rice (1986) and Stuart (1988). The significance of the stable sliding (aseismic sliding or creep) is now generally recognised. The aseismic sliding will increase the stresses at locked parts of the faults.

In a study of the Californian seismicity Wesson and Nicholson (1988) stated that:

- larger earthquakes along faults exhibiting fault creep tend to occur at the ends of creeping sections,
- large earthquakes tend to occur adjacent to previous large earthquakes,
- the occurrence of any significant earthquake increases the intermediate-term probability of future earthquakes on adjacent fault segments.

All these three statements will be included if one accepts the following statement:

- slip (seismic and/or aseismic) on a fault segment will increase the probability (intermediate term) to have slip (earthquake and/or creep) on adjacent fault segments.

This is the basic idea behind the efforts to estimate the extension of the aseismic fault slip from the spatial distribution of the Swedish earthquakes as done by Slunga (1989).

8 ESTIMATION OF ASEISMIC FAULTING FROM THE SPATIAL DISTRIBUTION OF THE MICROSEISMICITY

In this paragraph a way to estimate the amount of aseismic slip from the microseismicity is presented and applied. The idea is based on the view that the earthquakes are sudden breakdowns of asperities on the faults to which shear stress is concentrated by stable sliding of the surrounding fault area. These are the underlying assumptions:

a) the earthquakes are due to asperities on normally stably sliding faults (the earthquake is a sudden breakdown of the asperity),

b) the asperities (and also the earthquakes) are laterally uniformly distributed over the stably sliding fault area,

c) the peak slip of the earthquake equals the size of the stable fault slip preceeding the earthquake,

d) the earthquake depth distribution is given by the estimation given above with no earthquake deeper than 35 km,

e) the size of the accumulated total fault slip is the same at all depths in the range 0-35 km.

The parameter to be used in the statistical analysis of the spatial distribution of the earthquakes is the distance to closest later earthquake (within the time window of the catalogue). In figure 8 the observed distributions of this parameter is shown for two earthquake catalogues, 107 events within 5 years in southwestern Sweden and 80 events within 1.5 years in northern Sweden. In fitting the two curves for the theoretically expected distributions (for laterally uniformly distributed earthquakes) to the observed curves one parameter has been adjusted: for the 3D-curve the number of earthquakes per cubic meter and year, for the 2D-curve the number of earthquakes per year and per meter of fault length (the depth distribution according to figure 4). The 3D-curves have been adjusted to fit the range 20-30 km, the 2D-curves to the range 0-20 km.

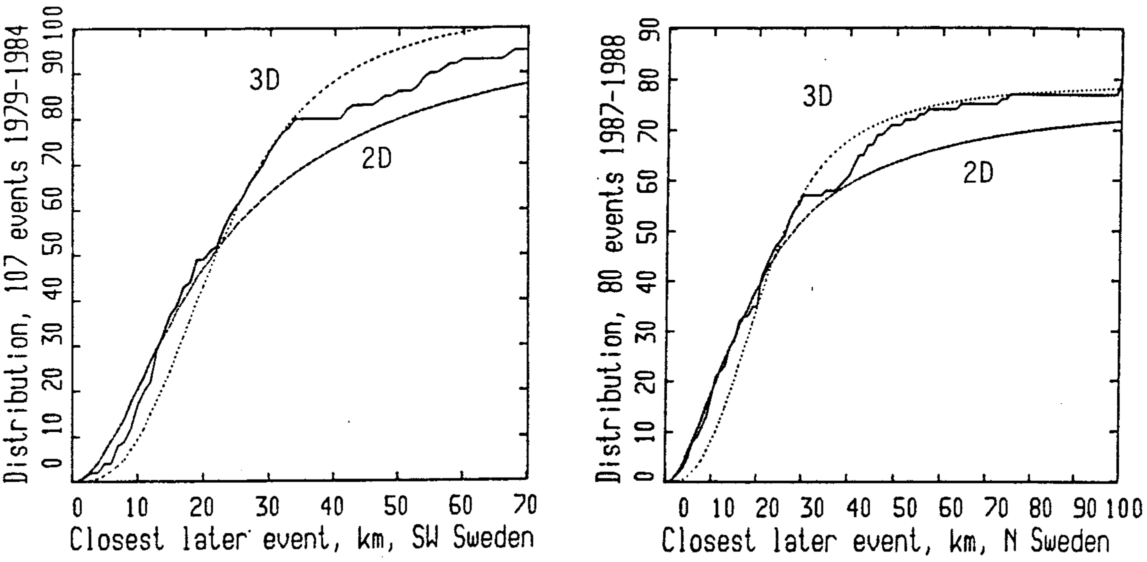

Figure 8. The spatial distribution of the closest later event distance for the seismicity 1979-1984 in south-western Sweden, lat 54-61, long 11-14 degrees, totally 107 events and northern Sweden, 80 events. The solid lines show the observed distributions. The dashed lines show the expected curves for a laterally uniform 3D earthquake distribution, and the dotted lines show the expected curves for laterally uniform 2D (vertical plane) earthquake distributions. The two populations exhibit remarkable similarities, see the text.

From figure 8 it is seen that:
- there are remarkable similarities of the two observed distributions in comparison to the expected curves for the laterally uniform populations,
- compared to the laterally uniform 3D-distribution there is an increased probability of distances ("closest later event") less than 18-20km,
- for distances less than 18-20km the laterally uniform 2D-distribution gives curves close to the observed ones,
- there is no indication at all of increased probability for small distances of the order of the location accuracy (2-4km).

The increased probability (compared to 3D) of later events within 18-20km and the lack of increased probability (compared to 2D) at very small distances are together hard to explain except by the acceptance of rather extensive stable fault sliding. This is a strong indication that these small earthquakes are really breakdowns of asperities (possibly points of increased effective normal stress) locked while stable slip takes place over large portions of the surrounding fault surface. The theoretical 2D curves in figure 8 fitting the observations correspond to a mean value of 21km (northern Sweden) - 26km (southwestern Sweden) of fault segments sliding aseismically per earthquake. The typical earthquake fault surface (the surface of the seismic sliding) is 0.03 square km as the fault radius is about 100 m. A fault length of 26 km (SW Sweden) with a thickness of 35 km (the depth of the seismic part of the crust) has undergone stable sliding (aseismic slip) for each earthquake. If the peak slip of the earthquake is assumed to equal the size of the preceeding aseismic slip this gives the aseismic fault movements to be of the order of 20 000 times more extensive than the seismic fault movements (21*35/0.03). Note that by "seismic" slip is meant the fault slip associated with the detected seismic events.

From the hypothetical process of generating the Baltic shield earthquakes - aseismic sliding accumulating stress at asperities - and from the estimate of the sizes of the aseismic fault surfaces per detected earthquake given above one can estimate the aseismic (not seismically detected) crustal fault movement rate in southwestern Sweden for the time period of figure 8. We had during the years 1980-1984 about 20 earthquakes per year. If a fault length of 26 km has slided stably for each of them this means that 520 km of crustal faults moved each year. The mean of the estimated peak slips of these earthquakes is 1.2 mm. The length of the southewestern Sweden seismic area is about 650km. As stated above the earthquakes cooperate in the crustal deformations as they have similar stress release. Thus one can from these numbers conclude that the horizontal deformation rate over the seismic part of southwestern Sweden corresponds to relative movements of points at each side of about 1 mm per year.

The model for the mechanisms behind the Baltic shield earthquakes presented here means that almost all fault sliding is aseismic. Within this view it is quite possible that the Protogene zone is the major deformation zone in southern Sweden but without seismic events. One possible indication of this is the fact that parts of the zone delimits the more active western seismic part, figure 2. Geodetic measurements and geologic observations may give answers to the questions raised by this view. Finally, the high consistency of the source mechanisms of the microseismic (ML=1) events is more easy to understand if they are expressions for much more extensive fault movements.

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[1] Swedish Nuclear Fuel and waste Management Co (SKB)
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Mineralogy, petrology and geochemistry of the Poços de Caldas analogue study sites, Minas Gerais, Brazil.
II: Morro do Ferro
N Waber
University of Bern
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Isotopic geochemical characterisation of selected nepheline syenites and phonolites from the Poços de Caldas alkaline complex, Minas Gerais, Brazil
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Battelle, Chicago
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Geomorphological and hydrogeological features of the Poços de Caldas caldera, and the Osamu Utsumi mine and Morro do Ferro analogue study sites, Brazil
D C Holmes[1], A E Pitty[2], R Noy[1]
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December 1990

TR 90-15
Chemical and isotopic composition of groundwaters and their seasonal variability at the Osamu Utsumi and Morro do Ferro analogue study sites, Poços de Caldas, Brazil
D K Nordstrom[1], J A T Smellie[2], M Wolf[3]
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December 1990

TR 90-16

Natural radionuclide and stable element studies of rock samples from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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TR 90-17

Natural series nuclide and rare earth element geochemistry of waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

N Miekeley[1], O Coutinho de Jesus[1], C-L Porto da Silveira[1], P Linsalata[2], J N Andrews[3], J K Osmond[4]
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TR 90-18

Chemical and physical characterisation of suspended particles and colloids in waters from the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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December 1990

TR 90-19

Microbiological analysis at the Osamu Utsumi mine and Morro do Ferro analogue study sites, Poços de Caldas, Brazil

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December 1990

TR 90-20

Testing of geochemical models in the Poços de Caldas analogue study

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December 1990

TR 90-21

Testing models of redox front migration and geochemistry at the Osamu Utsumi mine and Morro do Ferro analogue sites, Poços de Caldas, Brazil

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December 1990

TR 90-22

Near-field high temperature transport: Evidence from the genesis of the Osamu Utsumi uranium mine analogue site, Poços de Caldas, Brazil

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December 1990

TR 90-23

Geochemical modelling of water-rock interactions at the Osamu Utsumi mine and Morro do Ferro analogue sites, Poços de Caldas, Brazil

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December 1990

TR 90-24
The Poços de Caldas Project: Summary and implications for radioactive waste management
N A Chapman[1], I G McKinley[2], M E Shea[3], J A T Smellie[4]
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TR 90-25
Kinetics of UO_2(s) dissolution reducing conditions: numerical modelling
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TR 90-26
The effect from the number of cells, pH and lanthanide concentration on the sorption of promethium on gramnegative bacterium (Shewanella Putrefaciens)
Karsten Pedersen[1], Yngve Albinsson[2]
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June 1990

TR 90-27
Isolation and characterization of humics from natural waters
B Allard[1], I Arsenie[1], H Borén[1], J Ephraim[1], G Gårdhammar[2], C Pettersson[1]
[1] Department of Water and Environmental Studies, Linköping University, Linköping, Sweden
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May 1990

TR 90-28
Complex forming properties of natural organic acids. Part 2. Complexes with iron and calcium
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July 1990

TR 90-29
Characterization of humic substances from deep groundwaters in granitic bedrock in Sweden
C Pettersson, J Ephraim, B Allard, H Borén
Department of Water and Environmental Studies, Linköping University, Linköping, Sweden
June 1990