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FAULT MECHANISMS OF FINNISH EARTHQUAKES, CRUSTAL STRESSES AND FAULTS

by

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Abstract

Fault mechanisms of nine Finnish earthquakes with local magnitudes from 2.0 to 3.8 were studied with the method developed by Slunga for Swedish earthquakes. The first motion directions and the amplitudes of *P* and *S* waves of the digital data at six stations of the Finnish Seismic Array were used.

Dynamic source parameters were calculated giving seismic moments 0.1–10 E+13 Nm, fault radii 60–300 m and static stress drops 0.4–8 MPa. The estimated stress directions gave the maximum horizontal compressions in NW-SE quadrants. This orientation is in good agreement with the results from southern Sweden and with the source mechanism of the major Estonian earthquake in 1976. These results together with other seismological observations, geological and direct stress measurements relate Fennoscandian seismicity to global tectonic processes.

A detailed quantitative analysis of the relations between the resulting fault planes and the observed surface faults has not been done due to the scarce geological and geophysical fault data. Some qualitative judgements are made between fault plane solutions and lineament studies, in Finland. There exists a good fit between surface lineaments and the fault planes of the earthquakes.

Key words: Finland, earthquake, source mechanism, crustal stresses, faults.

1. *Introduction*

Globally Finland is a low seismicity area. However, a number of earthquakes are felt each year and many more can be detected and recorded by seismometers. Fig. 1 shows earthquakes during the years 1610–1983 (AHJOS and KORHONEN, 1984). So far very little has been published about their source mechanisms and about the crustal stresses producing these earthquakes. Here we give some results from a study, which includes of nine earthquakes, and we consider that earthquake data give unique opportunities for geophysical studies, if the earthquakes are adequately recorded. A similiar study has been made for Swedish earthquakes by SLUNGA *et al.* (1984a), who studied more than 150 earthquakes in southern Sweden. Their studies and this study include a large part of the Baltic Shield area.

2. *The data*

Fig. 2 shows the epicenters of the earthquakes we have included in this study, together with the seismological stations that have recorded these earthquakes. The date and the time of the earthquakes are given in Table 1. Digital data from six of the stations of the Finnish seismic array were available for these nine earthquakes. Fig. 3 shows a typical recording of an earthquake. The largest earthquake in this study, number one in Table 1, generated stronger elastic pulses than the station instruments are adjusted to record. This prevented the complete analysis of that event.

3. *The analysis*

The elastic waves generated by the earthquakes and recorded at the seismological stations can be used for analysis of the seismic source. For instance, the orientation of the fault plane and the direction of slip on the fault determine the first motion directions of the recorded wave pulses at the stations. This method used in earthquake fault mechanism studies is, however, of limited value in this case. We have very few clear first motion observations, which means that only few restrictions on the range of possible fault mechanisms are imposed by this method. Instead we have used the method developed by SLUNGA (1981, 1982) in his studies of Swedish seismicity. This method makes use not only of the first motion directions but also of the amplitudes (*e.g.* low frequency spectral levels) of both the compressional (*P*) and the shear (*S*) waves, at each recording stations. The fault plane orientations can then be estimated even if no first motion observation is available. How-

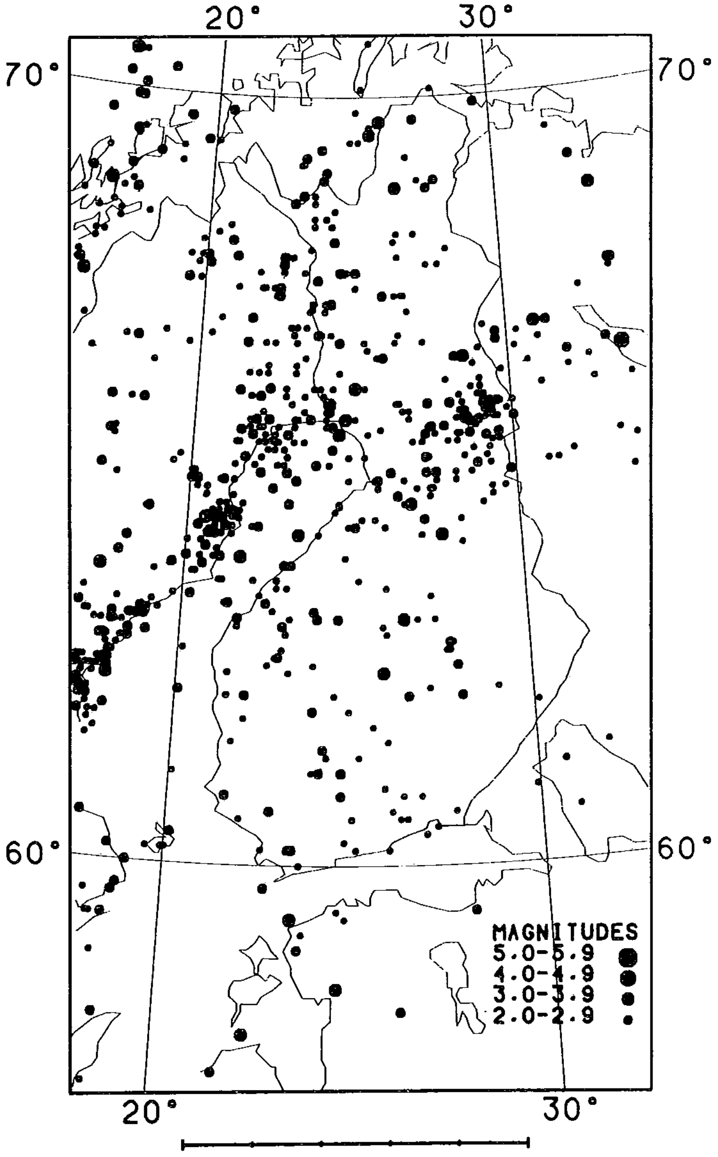

Fig. 1. Epicentral distribution of earthquakes in and near Finland, during the period 1610–1983.

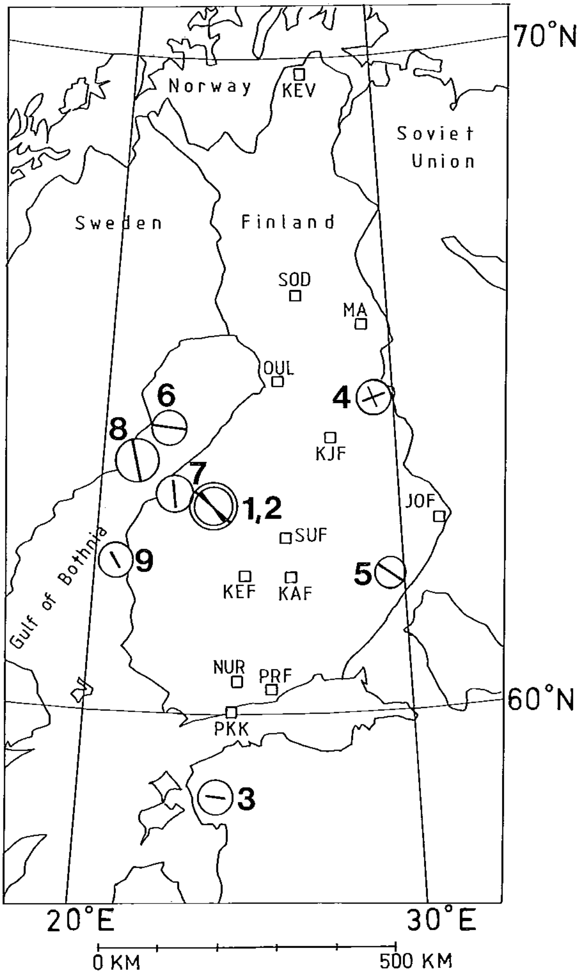

Fig. 2. The orientation of maximum horizontal compression of the relaxed stress for each earthquake is given by a line centered in the earthquake circle. Two lines are given for event 4, as it was not possible to discriminate between the two alternatives. All remaining events show maximum horizontal compressions in the NW-SE quadrants. The seismological stations are indicated by squares and name abbreviations.

ever, to get a unique estimate of the stress directions, at least one first motion observation is needed. For one of the earthquakes, number 4 in Table 1, this uniqueness was not possible to achieve, and this prevented a complete analysis of this earthquake. It should also be noted that the analysis gives generally more reliable results and a more unique fault plane solution, if a denser network of

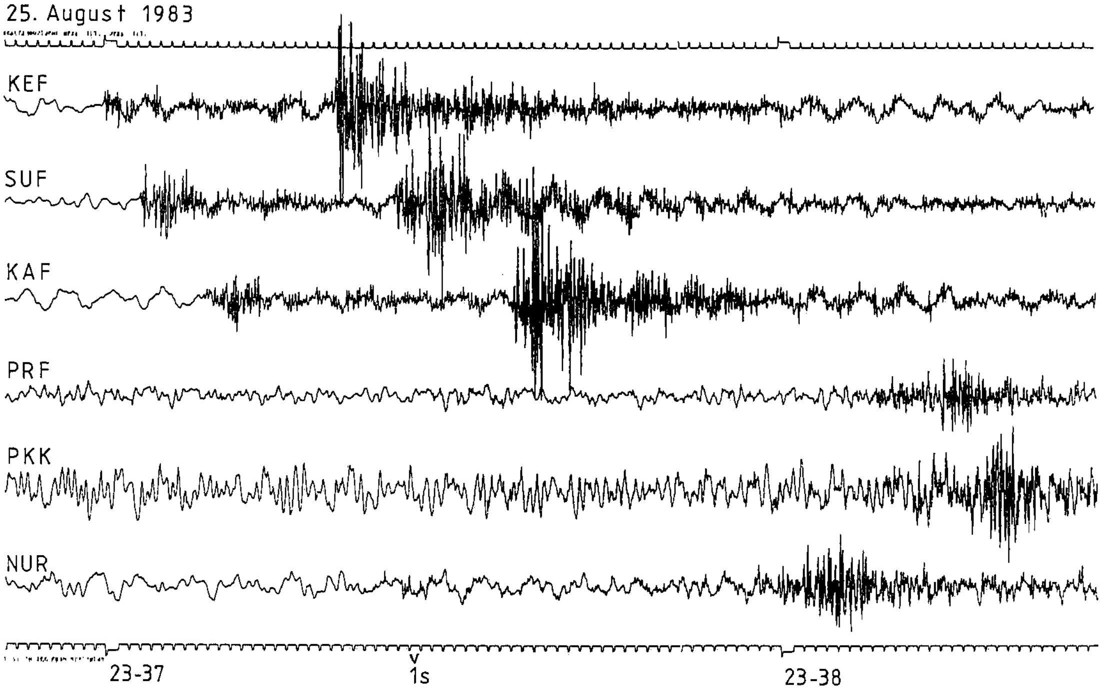

Fig. 3. An example of the digital, short-period, vertical recording of an earthquake (event 7 in Table 1) by the Finnish seismic array at Keuruu (KEF), Sumiainen (SUF), Kangasniemi (KAF), Porvoo (PRF), Porkkala (PKK) and Nurmijärvi (NUR) stations.

Table 1. The earthquake data. Estimates in parenthesis are based on incomplete data.

No	Date YMD	Time (UT) HMS	Epicenter Lat. N	Long. E	Focal depth (km)	Seismic moment (Nm)	ML	Fault radius (m)	Static stress drop (MPa)	Horizontal direction of compression (degr. N to E)
1	790217	173120.9	63.13	23.79	(13.4)	(0.10E+15)	3.8	290	1.7	131
2	790217	174057.0	63.14	23.79	(11.5)	0.51E+13	2.7	65	8.4	136
3	800119	012452.8	58.71	24.01	(10.0)	0.20E+13	2.3	(130)	(0.4)	100
4	801128	000133.2	64.75	29.32	(10.0)	0.21E+13	2.3	(125)	(0.5)	–
5	810327	220044.5	62.08	29.48	(10.0)	0.11E+13	2.0	(200)	(0.05)	129
6	830428	234814.4	64.34	22.22	(10.0)	0.13E+13	2.1	(92)	(0.7)	97
7	830825	233632.5	63.34	22.48	(10.0)	0.43E+13	2.6	120	1.1	170
8	840302	022529.0	63.80	21.15	(10.0)	0.34E+14	3.5	(60)	(67.)	166
9	840315	223806.1	62.32	20.68	(10.0)	0.14E+13	2.1	(110)	(0.5)	150
	761025	083947.4	59.36	23.34	12.0	3.5 E+15	4.9★			

★ (Slunga, 1979)

stations (giving observing distances less than 200 km) is available. In this study, most of the distances from the epicentres were rather great, which means a reduced reliability of the results. The most favourable cases were earthquakes number 2, 5 and 7 in Table 1.

4. *Orientation of the crustal stresses*

The earthquake analysis gives two possible fault planes at a normal angle to each other, for each earthquake. This is due to a fundamental nonuniqueness in most seismological source inversion methods. It should be noted that only one of these two alternatives has a geophysical meaning. As long as it is not known which one of the planes is real, the best estimate of the orientation of the deviatoric stresses causing the earthquake is simply the orientation of the stresses relaxed by the earthquake slip. SLUNGA (1981b) proposed a method for estimating the orientation of the horizontal crustal stresses from the orientation of the relaxed stresses. He computed the relaxed normal stresses on vertical crustal planes and called this the horizontal deviatoric stress. The direction of the horizontal maximum compression will be normal to the direction of the minimum horizontal compression. See further SLUNGA *et al.* (1984b). The orientation of the maximum horizontal compression can then be used to define the crustal horizontal stress directions.

All eight cases where it was possible to estimate the stress directions gave the orientation of the maximum horizontal compression to be contained in the

NW-SE quadrants. Fig. 2 shows the direction of the maximum horizontal compression of each earthquake. This orientation is in good agreement with the results from southern Sweden (SLUNGA 1981b, 1982; SLUNGA *et al.*, 1984a, 1984b), and with the source mechanism of the major Estonian earthquake in 1976 (SLUNGA, 1979).

We conclude that, together with the above mentioned results, we evidently have the same NW-SE main direction of the crustal horizontal compressions in both Finland and southern Sweden. This direction is in agreement with a number of observations in Europe north of the Alps: geological (PAVONI, 1969; SCHÄFER, 1974; JAŠKOLLA, 1979; LETOUZEY and TREMOLIERES, 1979), seismological (AHORNER *et al.*, 1972; PAVONI, 1979; SCHNEIDER, 1979) and direct stress measurements (GREINER and LOHR, 1979; FROIDEVAUX *et al.*, 1979; PAVONI, 1979). This result indicates that Fennoscandian seismicity is not caused by postglacial uplift, but is directly related to the global tectonic processes (see RICHARDSON *et al.*, 1976).

5. *Fault orientations*

As discussed above, seismological source inversions give two possible fault plane orientations. Fig. 4 shows the most likely fault directions for each earthquake. Two alternatives are given for each event, but only one of these is real, the other has no physical meaning. Only the best fitting fault plane orientations are given. Other orientations are normally possible, because the observations seldom allow a perfect inversion. A perfect inversion gives a unique acceptable fault mechanism. The fault mechanism of event 2 is, however, very well determined due to the closeness of this event to the array stations KEF, SUF and KAF.

In Fig. 4, the circles are centered at the earthquake epicenters and the possible faults are shown as lines where the fault plane should cut the earth surface if it were extended. The dip of each fault is in the direction of the center of the circle of the event. If the possible fault passes close to the circle center, the fault is almost vertical.

In southern Sweden, good agreement has been found between surface faults and the faults obtained by the earthquake analysis, in the few cases where geological fault data are available (SLUNGA *et al.*, 1984a). It seems that the earthquakes are primarily associated with major faults having lengths of tens of kilometers. For a conclusive study of this association, accurate earthquake data (epicenter, focal depth and focal plane orientation) and accurate fault data (position, strike, length and dip) should be available for the same area. In this case the uncertainties in both epicenter locations, focal depths and fault orientations are

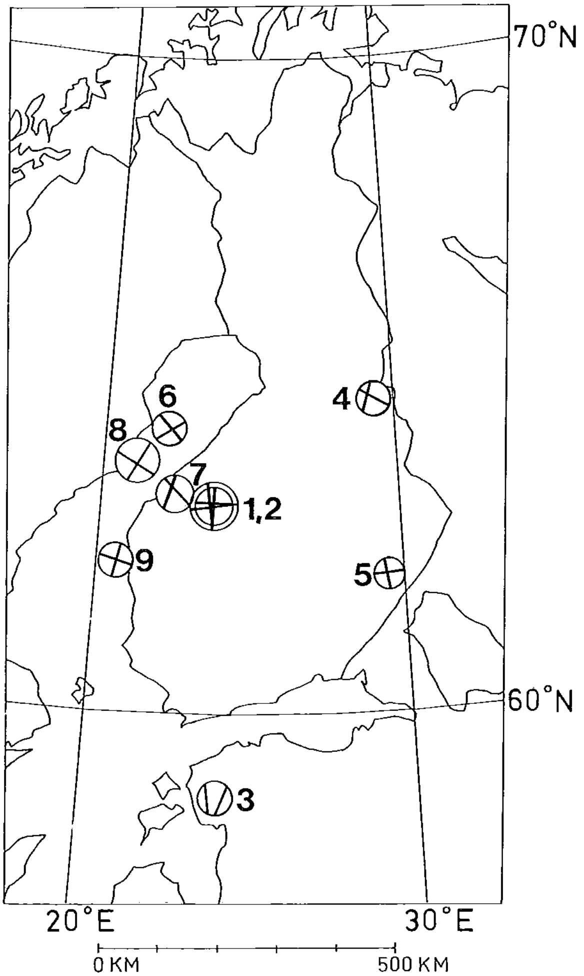

Fig. 4. The best fitting fault plane solutions for the earthquakes included in the study. From the epicentre (circle), from the focal depth and from the estimated fault orientation, the possible surface faults have been estimated by extending the fault planes up to the surface. A vertical plane passes the center of the circle. Fault lines not passing the center dip in the direction of the circle center.

The different faults for event 1 and its aftershock, event 2, are probably due to the lack of complete information about the amplitudes of the main shock. The mechanism of event 2 is more reliable and should be taken as the best solution for both events 1 and 2.

The discrimination between the two fault planes given here must be made either by use of other geological and geophysical information as in Table 2 or by a more detailed seismic analysis requiring a denser seismic network.

Table 2. Qualitative discussion of the possible relations between the estimated earthquake faults and lineaments found at the surface.

Earthquake data		Comparison with the lineament data by		
		Härme (1961)	Korhonen et al. (1974)	Mikkola & Vuorela (1974)
No	Fault strikes			
1,2	A 91 B 181	no good fit but there are short N-S segments	the N-S fault fits well to N-S parts north and south of the epicenter	both faults fit line segments on both sides of the epicenter
4	A 25 B 125	NW-SE fault fits well with two fairly long segment	NW-SE fault fits well but also the other fault is close to a lineament	NW-SE fault fits the lineament data well
5	A 86 B 171	NNW-SSE fault fits into a scattered line of short segments along eastern Finland	NNW-SSE fault fits fairly well but also the other fault fits to lineaments in the map	both faults fit the long lines shown in the map by segments
6	A 139 B 234	possible fit to NW-SE lines extended under the sea	NW-SE fault fits line extended under the sea	NW-SE fault fits lines extended under the sea
7	A 138 B 201	NW-SE fault fits well two lineaments	both faults may fit, the NNW-SSW possibly better	NW-SE fault fits fairly well
8	A 122 B 210	possible fit to NW-SE lines extended under the sea	no fit	NE-SW fault is parallel to several long lineaments in Finland
9	A 108 B 193	no fit	no fit	no fit but there are NW-SE lines both to the north and to the south

fairly large due to the small number of seismological stations. This, together with the lack of available geological and geophysical fault data, prevents a detailed quantitative analysis of the possible relation between our resulting earthquake fault planes and the observed surface faults.

We have, however, made a qualitative judgement of our data in relation to a few published studies on the fault pattern in Finland. These judgements are given in Table 2. The following lineament studies have been used: HÄRME (1961), KORHONEN *et al.* (1974) and MIKKOLA and VUORELA (1974). It is not possible to make any firm conclusions from Table 2, but the fairly good fit in several cases indicates that we may have a very close relation between surface lineaments and

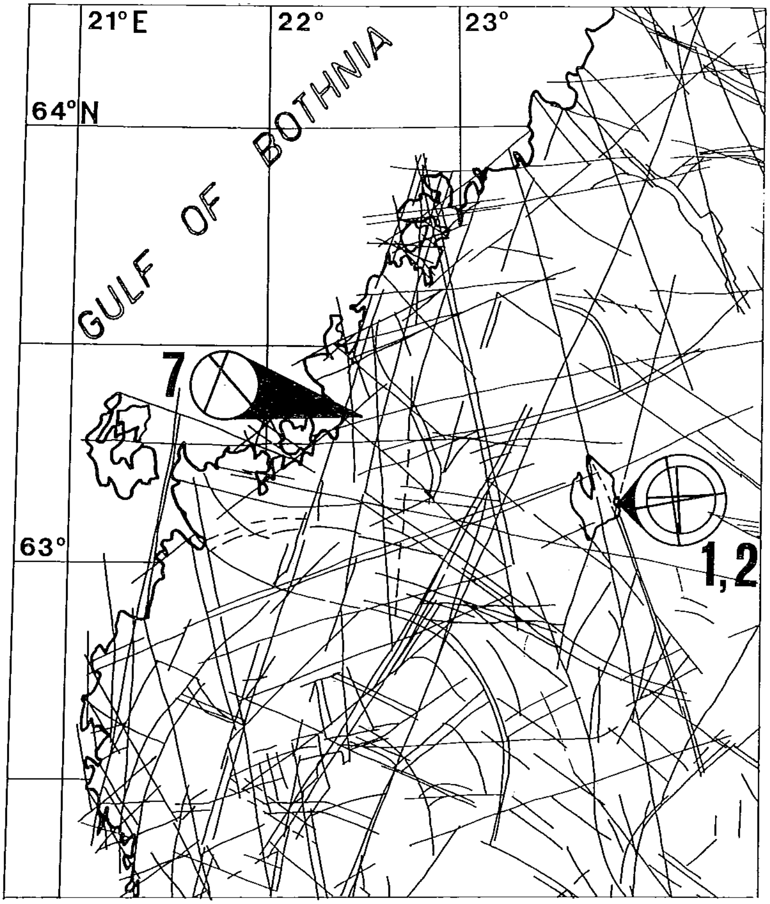

Fig. 5. Comparison of the fault plane orientations of events 1, 2 and 7 with lineaments from mosaics of Landsat-1 summer imageries. Interpretation of Landsat lineaments is made by Aimo Kuivamäki from the Geological Survey of Finland (personal communication).

fault planes of earthquakes. Fig. 5 illustrates, how the fault planes of events 1, 2 and 7 coincide with the lineaments derived from mosaics of Landsat summer imageries. The NNW-SSE fault orientation of events 1 and 2 is in good agreement with long lineaments in the same direction. For event 7 both the NW-SE and NNE-SSW fault plane orientations coincide with the orientation of surface lineaments.

We have also compared our earthquake faults of events 4 and 5 with the diabase dike orientations given by LAITAKARI (1969). The NW-SE fault orientation of event 4 coincides with the many diabase dikes of the epicenter area. Laitakari describes no diabase dikes close to event 5 epicenter, but the dikes east, and especially west, of the epicenter coincide with the NNW-SSE fault of this earthquake. SLUNGA *et al.* (1984a) found that the earthquakes in Scania had fault orientations, which also coincided with the diabase dike orientations. These observations also indicate that the earthquakes occur along old well-established and reactivated fracture zones in the crust. Diabase dikes are often parallel to the faults of the area. More earthquake data is needed for a detailed study of these associations.

6. *The seismic moments*

The seismic moment is defined as the product of the shear modulus of the crust at the source region, the fault area and the mean slip along the fault. It is thus a physically well-defined parameter that can be used directly in studies of the crustal movements and deformations. Table 1 gives the seismic moments of these nine earthquakes, together with the seismic moment of the major Estonian earthquake in 1976 (SLUNGA, 1979).

7. *Fault radius and static stress drop*

The fault radius, *i.e.* the radius of the area of the fault plane over which slip occurs during the seismic faulting, can be estimated from the corner frequency of the frequency spectrum of the elastic waves generated by the faulting. The experience from the Swedish seismic network indicates that observations from stations which are near the source (less than 130 km) should preferably be used (SLUNGA *et al.*, 1984a). In this case we cannot rely on such observations, which means that our estimates of fault radii can be too large and our estimates of the static stress drops too small. However, they are given in Table 1 as they can be used at least as upper and lower limits respectively. Note that the fault radii are typically not larger than 100–200 m. This is very small compared to the focal depths of the earthquakes, typically several kilometers. The static stress drop is the size of the drop in shear stress on the fault plane due to the earthquake slip. Typical values for earthquakes in southern Sweden were 1–10 MPa. This quantity is generally one of the least well estimated quantities, as it depends on the cube of the corner frequency (often uncertain). For a detailed analysis closer recordings are needed than available in this study.

8. *Conclusions and discussion*

The main conclusion is that the regional NW-SE compression of the crust is consistent in all parts of Fennoscandia this far studied. It seems reasonable, therefore, that Fennoscandian seismicity is related to global tectonic processes. These earthquake measurements refer to the deep crust where direct stress measurements cannot be made.

The earthquake data now available indicate that close relations may exist between surface faults and the earthquake fault planes. It should be noted, however, that the earthquake fault areas of most of these earthquakes are rather small compared to the focal depths, which means that the earthquake rupture seldom or never reaches the surface. Therefore, it is not possible to study the earthquake slip directly. If earthquakes occur in structures visible at the surface, then aseismic slip dominates in the uppermost part of the crust. This is also true for the lower crust. The seismicity is mainly restricted to 5–20 km depth (AHJOS and KORHONEN, 1984; SLUNGA *et al.*, 1984a).

We think that these results illustrate the value of earthquakes in the study of the geophysical and geodynamical processes in the crust. Each earthquake represents an »in situ» measurement. These measurements cannot be obtained without using high quality seismic recordings.

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