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# Seismotectonics and Lithospheric Stresses in the Northern Fennoscandian Shield

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## *Abstract*

*The seismicity, fault distribution and stress pattern of northern Fennoscandia are investigated. Some active fault zones are suggested, e.g., several faults exposed to large displacement at the late-glacial phase about 9,000 years ago. Stress orientations, derived from crack distribution and a few earthquake focal-mechanism solutions, are different in different areas. In some cases there is a good agreement with expectations from ridge-push generated and propagated compressive stress. However, the inhomogeneity in the stress field of the region as a whole indicates contribution from local factors.*

*Key words: seismotectonics, lithospheric stress, Fennoscandian Shield*

## *1. Introduction*

Typical for an intraplate region, earthquakes of the Fennoscandian Shield are sparse, small and spatially scattered, although areas of enhanced activity can be observed. The generating mechanism is poorly understood. The present undertaking is an attempt to increase the seismotectonic understanding of the northern part of the shield by correlating data of seismicity, focal mechanisms, faults and stresses.

## *2. Geology*

The seismicity of the area of investigation is shown in Figures 1-3. The problem of discriminating the earthquakes from the frequent mine explosions is addressed in *Wahlström and Assinovskaya* (1996).

The Fennoscandian Shield is an old structural unit that has kept its main non-sedimentary character for the last billion years or more. Within the northern part of the shield, there are two main geological provinces of different age, the mainly Archaen Lapland-Kola-Karelia and the Proterozoic Svecofennia (Figure 3). A regional tectonic classification is suggested by *Berthelsen and Marker* (1986). The Precambrian crust was subject to several orogenies and has rotated significantly, the average rotation rate being 0.3 degrees per million years (*Kakkuri*, 1992). During the orogenies and rotation the crust was destroyed (upper part) and broken into many blocks surrounded by fracture zones, faults, cracks, ductile shear zones, etc. The largest faults form the border between the two main provinces mentioned above. In Figure 3, the distribution of faults, after *Kozlov* (1979) and *Korsakova et al.* (1988), is superimposed on the seismicity in 1963-1993, a period of fair instrumental coverage except for the Kola Peninsula.

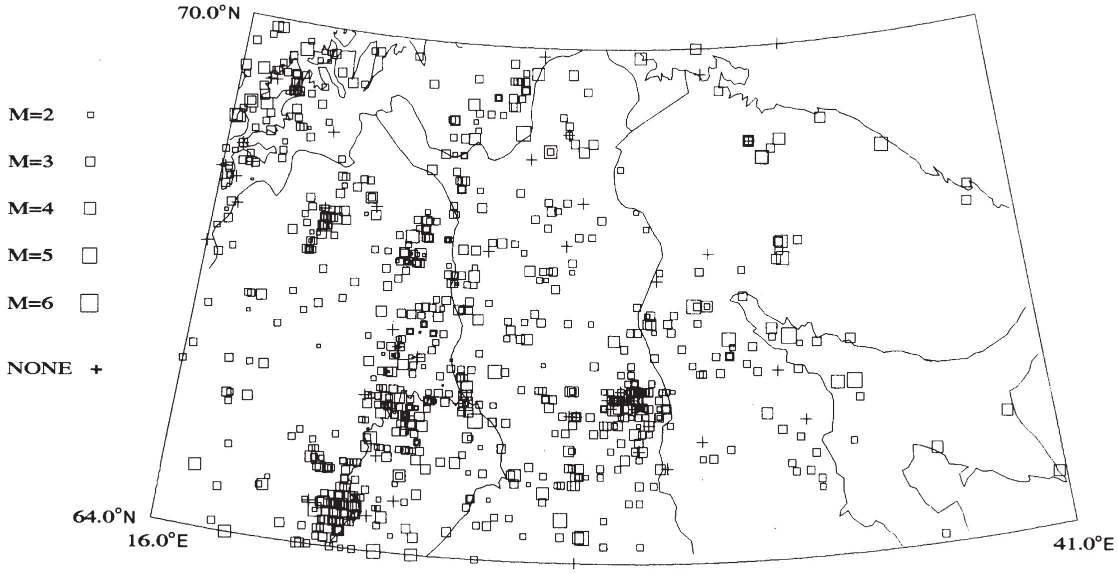


Fig. 1. Seismicity of northern Fennoscandia and Kola, 16ºE-41ºE, 64ºN-70ºN, time period 1375-1993; from *An earthquake catalogue for Northern Europe*.

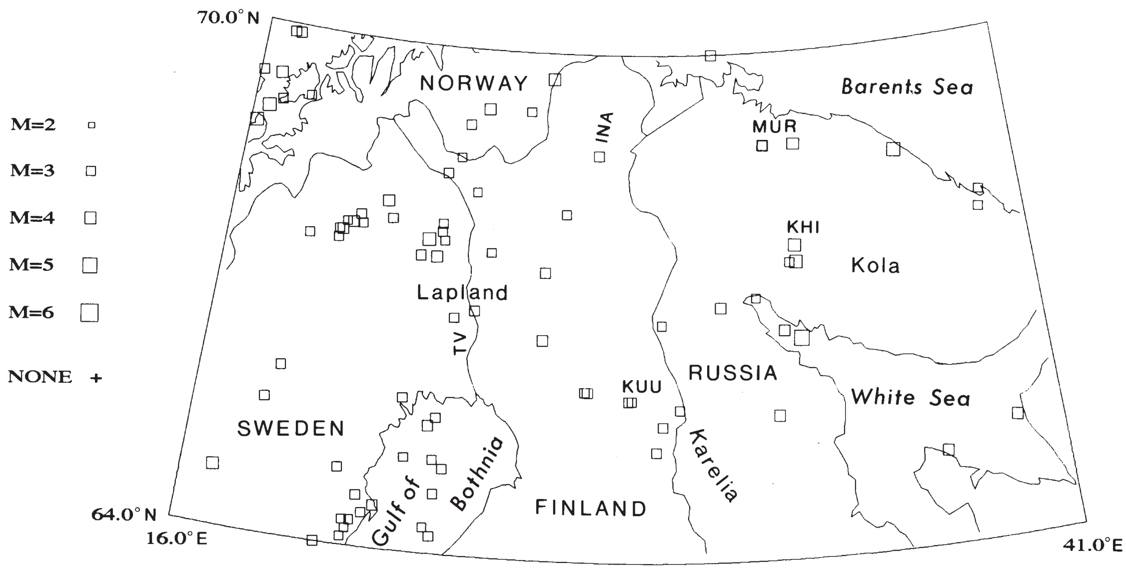


Fig. 2. Subset of seismicity of Figure 1 for the time period 1963-1993 and magnitude, $M_L$, of 3 and larger. Except for Kola, where only one station was operated until the mid 1980s, there has been a fair instrumental coverage of the area since 1963.
Abbreviated names: INA Inari line, KHI Khibiny massif, KUU Kuusamo region, MUR Murmansk region, TV Torne Valley.

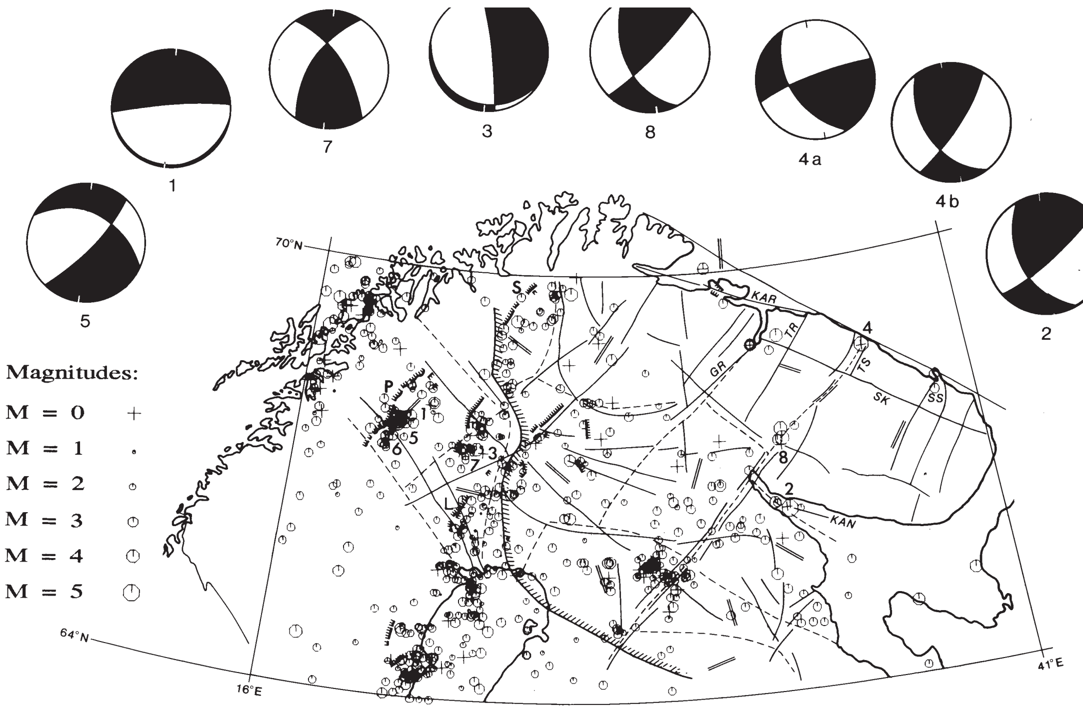


Fig. 3. Subset of seismicity of Figure 1 for the time period 1963-1993.
Tectonic and stress elements of the northern Fennoscandian Shield:
Faults, marked by full lines, are after *Kozlov* (1979) and *Korsakova et al.* (1988). The most important faults on the Kola Peninsula are: Granitni (GR), Kandalaksha (KAN), Karpinski (KAR), Severo-Kejvski (SK), Strelninsko-Svjatonoski (SS), Teriberka (TR) and Tsaginski (TS).
Late-glacial fault scarps, marked by thicker, barbed lines (barbs towards lower block), are after *Lagerbäck* (1990): Lansjärv (L), Pärvie (P) and Stuoragurra (S) faults are denoted.
Focal mechanisms (lower-hemisphere projections) are from this study (No 2, 4 and 8), *Arvidsson and Kulhánek* (1994; No 5 and 7), and *Kim et al.* (1988; No 1 and 3). Event enumeration according to Table 1 (No 4 has two different solutions - a and b; there is no determinate solution for No 6).
Maximum compressional stress directions, marked by double lines, are derived from the crack formation method of *Nikolaev* (1992); based on these directions, subareas of consistent stress regime, separated by dashed lines, can be distinguished.
The border between the Lapland-Kola-Karelia (to the north and east) and Svecofennian (to the south and west) provinces is marked by the hatched line.

## *3. Stress map*

The method to map the stress field follows *Nikolaev* (1992). It is based on a statistical analysis of the distribution of cracks. Under homogeneous stress field conditions conjugate cracks develop and are scattered around two predominant directions, each in a plane tilted about 45º from the direction of maximum compressive stress. The geological medium is thus broken into blocks at varying scales. Mapping lineaments in the topography identifies the boundaries and stress pattern of each block. The interaction between the stress fields of the different blocks causes tectonic movement and deformation, to some extent manifested as earthquake activity. A statistical analysis of the distribution of cracks is, in lieu of the aforementioned scatter of their orientation, a useful method to indicate the stress field in a region.

In our investigated area, the base for the tectonophysical analysis is made up by maps of lineaments of relief, showing mainly the network of rivers formed in the Tertiary before the beginning of the Antropogene (*Nikonov*, 1964). This is thus the age of the stress field we are trying to reconstruct for the upper crust. Following *Nikolaev* (1988), we consider that linear morphological elements reflect fault structures. Old fault systems are consolidated or activated due to the geodynamical situation, as shown in studies of different regions of the earth by the agreement of geophysical, geological, geomorphological and deep drilling data.

We make two assumptions in applying *Nikolaev's* (1992) method:

(1) For any selected reasonably morphologically homogeneous region (sub-area), lineaments of the length 10 km - 20 km observed from topographical maps are, taken together, indicative of tectonic processes. Not all lineaments are earthquake prone today.

(2) Strike-slip deformation is predominant in the region. This implies principal horizontal stress orientations. This assumption is supported from various types of stress data (focal mechanisms, deep drilling). *Muir Wood* (1993) found strike-slip faulting predominant for most of northern and western Europe.

The strikes of more than 1,000 lineaments in 25 tentative subareas were measured and analysed. The selection of subareas was made from criteria of geomorphological homogeneity. Where stress orientations of neighbouring subareas are similar, areas are lumped together. As a result, stress orientations for 12 areas are obtained and are introduced in Figure 3. The figure shows that different stress regimes prevail in different parts of northern Fennoscandia and the Kola Peninsula. Approximately NE-SW oriented compressive stress dominates the northern part of the Lapland-Kola-Karelia province. Further south the direction is mainly NW-SE. The northern part of the Svecofennian province shows NE-SW and E-W oriented compressive stress.

Obtained compressive-stress orientations coincide only partly with those expected from ridge push (North Atlantic Ridge), e.g., see *Solomon et al.* (1980). However, the stress pattern is in accordance with the known fact that the direction of stress often changes near faults (see Figure 3). The stress field in Finland north of the Gulf of Bothnia coincides with geodetic measurements of horizontal crustal strain presented by *Kakkuri* (1992).

## *4. Focal mechanisms*

Besides the limitation to strike-slip type movement, the use of crack formation patterns as indicators of stress orientation is uncertain for larger crustal depths. Earthquake focal mechanisms provide the most valuable type of information here. Typically, the earthquakes in our region occur in the focal depth range 10 km - 30 km. Since there is a paucity of seismological stations, mechanism solutions can only be derived for the largest earthquakes and even then the precision in estimated focal depths is low.

For the Swedish part of the area of study, four reliable mechanism solutions (according to criteria specified in *Muir Wood*, 1993) already exist. The events are listed in Table 1 and the mechanisms are shown in Figure 3. The dip-slip mechanism solutions for events No 1 and 3 (from *Kim et al.*, 1988) were derived from synthetic seismogram modelling and are perhaps dubious. The solutions for events No 5 and 7 are based on P-polarities (*Arvidsson and Kulhánek*, 1994).

Table 1. Earthquakes with magnitude, $M_L$, of 3.4 and larger in the northern part of the Fennoscandian Shield for which focal-mechanism solutions have been derived, in this and/or previous studies (see Figure 3).

| No | Date | | | Time GMT | | Location | | Magnitude | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | (y) | (m) | (d) | (h) | (m) | lat. (ºN) | lon. (ºE) | ($M_L$) | |
| 1 | 1967 | 04 | 13 | 08 | 46 | 68.1 | 20.8 | 3.7 | KIM |
| 2 | 1967 | 05 | 20 | 23 | 18 | 66.6 | 33.7 | 5.2 | PRES, ASS |
| 3 | 1975 | 08 | 11 | 18 | 28 | 67.5 | 22.8 | 3.9 | KIM |
| 4 | 1981 | 04 | 10 | 19 | 43 | 68.7 | 37.2 | 4.5 | (PRES,) ASS |
| 5 | 1987 | 04 | 19 | 12 | 39 | 67.8 | 19.8 | 3.6 | ARV |
| 6 | 1987 | 12 | 26 | 08 | 29 | 67.7 | 19.5 | 3.6 | (PRES) |
| 7 | 1988 | 05 | 16 | 23 | 50 | 67.5 | 22.0 | 3.4 | ARV |
| 8 | 1989 | 04 | 16 | 06 | 34 | 67.5 | 33.7 | 4.3 | PRES |

Source parameters are from *An earthquake catalogue for Northern Europe*.
References: ARV *Arvidsson and Kulhánek* (1994), ASS *Assinovskaya* (1986), KIM *Kim et al.* (1988), PRES present study (indeterminate solution in parentheses).

In order to obtain more focal mechanisms, P-polarities were read from Russian, Finnish, Swedish and Norwegian station records of more than 20 earthquakes with regional magnitude, $M_L$, of 3.4 or larger. Each reading (compression or dilatation) was assigned full or half weight depending on its quality. No data from distances 130 km - 170 km were used to avoid confusion of Pg- and Pn-waves.

A modified version of the computer program FOCMEC (*Snoke et al.*, 1984, *Wahlström*, 1987) provided families of focal-mechanism solutions for four events, No 2, 4, 6 and 8 (see Table 1). There were too few data for the other events. In a previous study, *Assinovskaya* (1986) obtained manual polarity-based solutions for events No 2 and 4. Our solutions for the two events are based on revised and partly new data.

Determinate solutions were obtained for events No 2 and 8, two different solutions for event No 4, and no determinate solution (wide scatter of possible solutions) for event No 6. Figure 3 shows the obtained mechanisms, including both possibilities for event No 4. The tectonic context of the mechanisms is discussed in the next section.

Besides the mechanism solutions classified as reliable (see above), solutions for 71 microearthquakes in northern Sweden by *Slunga* (1991) show a great variety of orientations of compressive stress. Focal mechanisms have also been derived for many microearthquakes along the Stuoragurra, Norway (*Lindholm et al.*, 1995) and Lansjärv, Sweden (*Wahlström et al.*, 1987, 1989) late-glacial faults. The Stuoragurra solutions show reverse faulting, whereas the Lansjärv solutions are more ambiguous. However, the solutions for the microearthquakes along both faults are poorly constrained. The mechanisms from *Slunga* (1991), *Lindholm et al.* (1995) and *Wahlström et al.* (1987, 1989) are not included in Table 1 or Figure 3.

## *5. Seismotectonic correlation*

The stress field obtained from focal mechanism data and from lineament maps relate to different times, contemporary vs Tertiary, and different crustal depths. This should be kept in mind when we discuss differences and possible changes in the stress field with time and depth, and their seismotectonic implications.

Seismicity maps show that the distribution of epicentres is not random, but often form linear zones. In this section, based on Figure 3, we propose that some zones and faults are seismically active today. Geographical names in the text are given in Figure 2 and names of major faults in Russia are given in Figure 3.

It is generally difficult to identify which of the nodal planes obtained in a focal-mechanism solution is the fault plane by correlating with geologically mapped faults. The maximum deviatoric compressive stress is often found to be oriented similarly to the corresponding stress derived in the crack distribution analysis. This may indicate some invariability of stresses with time and for different crustal depths.

A number of spectacular fault scarps and marks of landslides in northern Fennoscandia are related to large earthquakes (estimated magnitudes up to 8+) occurring at the latest phase of glaciation about 9,000 years ago (e.g., see *Lagerbäck*, 1990). The earthquakes are likely manifestations of release of plate tectonic generated stress, accumulated during tens of thousands of years under the load of the ice cap. The seismicity maps and microearthquake studies of some of the faults (*Wahlström et al.*, 1987, 1989, *Olesen*, 1988) indicate that they are still active, on a small scale, and extend to depths of at least some 10 km.

Events No 5 and 6 are located close to the NNE-SSW oriented Pärvie late-glacial fault and to a NW-SE extended fault. No 5 has a strike-slip, oblique mechanism with one of the nodal planes approximately aligned with Pärvie. Unfortunately, no unambiguous mechanism solution could be obtained for event No 6. Event No 7 is located at another late-glacial fault. The mechanism solution shows one nodal plane aligned with the fault and the maximum compressive stress axis is oriented E-W, i.e., in agreement with the crack distribution analysis for this block.

Events No 1 and 3 have dip-slip solutions with a predominantly vertical deviatoric compressive stress axis. These solutions, perhaps dubious (see previous section), are in conflict with available data on near-surface regional fault patterns and may reflect local deformation at depth.

At the border zone between the Lapland-Kola-Karelia and Svecofennian provinces, the segment from the northern part of the Gulf of Bothnia, through the Torne Valley and northward, has enhanced seismicity.

The concentration of seismicity in the Kuusamo region (central Finland and eastward into Russia) could be the effect of an intersection of NE-SW and NW-SE oriented faults.

Several historical earthquakes, up to magnitude 5, have been reported from the steep-slope border zone between the shield and the Barents Sea platform (*Assinovskaya*, 1994). The seismic activity in this zone along the Karpinski fault tends to increase where the fault is intersected by other faults, i.e., Teriberka, Tsaginski and Strelninsko-Svjatonoski.

Event No 4 took place near the intersection of the Karpinski and Tsaginski faults. The latter structure is manifested both onshore and in the sea bottom relief. Our solution is ambiguous, the two possible solutions representing near-horizontal P-axes in the NNE-SSW (No 4a) and ESE-WNW (No 4b) directions, respectively. The location is near the border of two tectonic blocks, and each stress orientation is in fair agreement with the orientation derived in our crack distribution analysis for the areas to the east (4a) and west (4b), respectively. None of the possible nodal planes agree with the Karpinski fault, which makes the Tsaginski fault a candidate host for the rupture (aligned with one of the planes of solution 4b).

The NNE-SSW oriented Inari line and the Murmansk region, where the Severo-Kejvski fault zone is intersected by the NE-SW aligned Granitni fault and where significant earthquakes occurred in historical time, in 1968 and in 1990, are other areas of enhanced seismicity in the north.

A clear concentration of events is found in the Khibiny massif. Historical earthquakes have been reported from the area, but the current seismic activity is mostly induced from extensive mining activity in the apatite deposits, the shallow depth indicated by recorded Rg-waves. Event No 8 is a rockburst released by a simultaneous mine explosion (*Sirnikov and Tryapitsyn*, 1990). The predominantly horizontal P-axis is oriented ESE-WNW, which is in excellent agreement with the direction found in many stress measurements in the Khibiny area (*Markov*, 1977) and with the stress orientation calculated from topographical data for the area just north of the epicentre. A complex local stress pattern has been created by the mining operations.

The NW-SE oriented Kandalaksha fault, a graben structure in the western White Sea, is the site of several historical earthquakes (*Nikonov*, 1991). The earthquake of May 20, 1967 - event No 2 - is the largest event in the northern part of the shield in modern time. One of the nodal planes of our mechanism solution agrees roughly with the extension of the fault. The maximum deviatoric compressive stress has a predominant horizontal component oriented ESE-WNW, i.e., in fair agreement with the stress orientation obtained from topographical data for the subarea to the south. Currently, no deep structure data are available in this area, but to the west seismic profile data show a Moho depth of about 50 km in the Kandalaksha region, greater than in surrounding areas (*Sharov*, 1993). The Moho gradient could indicate tectonic instability.

It is worth noting the similarity of all investigated Russian earthquake mechanisms (i.e., No 2, 4b and 8), indicating a homogeneous stress field in the eastern part of the Kola Peninsula.

## *6. Discussion*

Spatial correlation between the seismicity, focal mechanisms, mapped faults and stress orientations is made with some success in areas where we have good data. There are several possible reasons for the lack of correlation, e.g., different geological hypotheses give different characteristics and interpretations of fault zones, possible distribution of seismicity over broad zones of weakness rather than along individual faults, few and poorly constrained focal-mechanism solutions, ambiguous stress data.

Figure 3 shows that stresses are homogeneous over large areas in northern Fennoscandia, cutting across diverse geomorphological provinces. However, the topographical data also suggest separation into tectonic blocks with their own stress fields. Support for the imhomogeneity of the large-scale stress field is given from various sources. In situ measurements in Lapland show considerable scatter, the reasons for which, in terms of contacts between blocks, relief, lithology, cracks, intrusion, etc., are discussed by *Muir Wood* (1993). Geodetic data divide the area into several blocks with different stress orientations (*Kakkuri*, 1992). *Sim* (1991) demonstrates several geological indicators of a varying stress field in the eastern part of the shield.

A recent study by *Garbar and Trofimov* (1993) suggests the existence of several old rift zones of different age in the northern part of the Fennoscandian Shield. There is a high spatial correlaton of these zones with the seismicity (Figure 4). Rift zones could thus provide a supplementary explanation of the current seismic activity in the area.

Two seismogenic hypotheses prevail for Fennoscandia: (1) Isostatic land uplift and (2) ridge push with propagation of compressive horizontal stress. (2) seems to be favoured by most investigators based on crustal stress characteristics and orientations, e.g., see *Olesen et al.* (1992) and *Saari* (1992) for different parts of northern Fennoscandia. (1) has a strong advocate in *Muir Wood* (1993), based on tensional vs compressional horizontal strain relationship. However, the largest earthquakes in the shield occur on the Kola Peninsula where the uplift is minor. There is some support for the ridge push theory in our data, but the lack of established seismotectonic relationships, and especially of more and better focal-mechanism solutions, make it impossible to underrate the role of isostasy. Inhomogeneity of the stress field suggests the existence of superimposed local sources of stress. The ridge push hypothesis would imply a complex stress field for the northern part of the shield, since the shape and orientation of the relevant segments of the North Atlantic Ridge vary. For a more thorough discussion on seismogenic processes in Fennoscandia, see *Wahlström* (1993).


Fig. 4. Old rift zones, after *Garbar and Trofimov* (1993), and seismicity from Figure 3.
Borders of old rift zones are marked by barbed lines (barbs towards lower block).
Dashed lines denote presumed rift zones.
Solid line marks an old transform fault.
The spatial correlation between geological structures and seismicity is high.

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