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Neotectonics in Fennoscandia and eastern Canada

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Sammendrag:

Litteraturen om neotektonikk i Fennoskandia og østlige Canada er undersøkt. Sen- eller post-glaciale forkastninger i Fennoskandia opptrer som veldefinerte, ofte lineære trinn i et ellers jevnt morenedekke eller berggrunnsoverflate. Den maksimale vertikale spranghøyde er 25 m. Den vestlige blokka er vanligvis senket. I Canada opptrer de fleste påviste forkastningene på glatteroderte berggrunnsblotninger. Disse forkastningene er vanligvis mindre enn tilsvarende i Fennoskandia. I begge områder er de reversforkastninger. De er i stor grad styrt av eldre svakhetssoner.

Det er en geografisk sammenheng mellom de neotektoniske strukturene og jordskjelvaktivitet i Fennoskandia. Dette antyder at de kreftene som forårsaket forkastningen fremdeles er aktive. Retningen på forkastningene er hovedsakelig parallell de Midt-Atlantiske og Arktiske spredningsryggene. In situ spenningsmålinger og forkastningsplanberegninger fra jordskjelvregistreringer viser i de fleste tilfeller at den maksimale horisontale spenningen er vinkelrett disse spredningsryggene og at Fennoskandia og det østlige Canada er under kompresjon. Det er derfor sannsynlig at spenningen som oppstår ved havbunnspredning, er et viktig bidrag til dannelsesmekanismen for forkastningene. Utløsningen av disse spenningene kan imidlertid skyldes den postglaciale landhevingen.

Emneord		
	Tektonikk	Holocen
Geofysikk	Forkastning	
Kvartærgeologi	Seismologi	Fagrapport

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Neotectonics in Fennoscandia and eastern Canada

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Several fault-lines, of late- or post-glacial age, occur in eastern Canada and in Fennoscandia. The faults appear as well defined, often linear, steps in the otherwise smooth till cover. The maximum observed displacement in Fennoscandia is 25m. Generally the western block is depressed. Most of the evidence for late quaternary faulting in eastern Canada is based on sharp steps in the smoothed and striated bedrock. These faults are usually smaller than the Fennoscandian equivalents. The faults are reverse in Fennoscandia as well as in eastern Canada. The faults are largely influenced by the older fault-zones, but late quaternary fracturing outside these zones also occurs.

The regional connection between the neotectonic structures and the recent seismic pattern within Fennoscandia is obvious. This indicates that the forces which produced the faulting are possibly still active. The direction of the faults are mainly parallel to the Mid-Atlantic Spreading-Ridge. In-situ stress measurements as well as earthquake fault plane solutions indicate that maximum horizontal stress is NE-SW to E-W and compressive. It is therefore concluded that stress associated with the spreading of the Mid-Atlantic Ridge is an important contributor to the mechanism generating faults. The release of these stresses could however be related to the postglacial rebound.

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Introduction

A smooth postglacial emergence pattern has been assumed to totally dominate the quaternary tectonics in eastern Canada and Fennoscandia (Walcott 1972). As the earth's crust within the Canadian and Baltic shields is fairly stable, earthquakes are few in most of the area and of relatively low intensity (see Ahjos & Korhonen 1984, Basham et al. 1979). For this reason fault scarps that occur in many places, have always been considered to be of prequaternary age.

But, during the last twenty years, the late quaternary faults shown in Fig. 1 have been documented in Finland (Kujansuu 1964) and in Sweden (Lundqvist & Lagerbäck 1976). Tanner (1930) had previously discussed evidence for Holocene faulting in the Fiskerhalvøya peninsula in the USSR close to the Norwegian border. Lundqvist & Lagerbäck (1976) and Lagerbäck (1979) have given a short summary of previous works dealing with neotectonic phenomena in Scandinavia. Oliver et al. (1970) gave a review of previously published postglacial faults in addition to description of new occurrences in New York, Ontario and Quebec. Grant (1980) reported late quaternary faulting in Nova Scotia.

In connection with the debate on nuclear-waste storage, further geological and geophysical investigations have been carried out in Sweden (Lagerbäck & Witschard 1983, Henkel et al. 1983, Wahlström & Kulhánek 1983) and in Finland (Kuivamäki & Vuorela 1985, Kukkonen & Kuivamäki 1985). For the same reasons, Adams (1981, 1984) described postglacial faults in Canada.

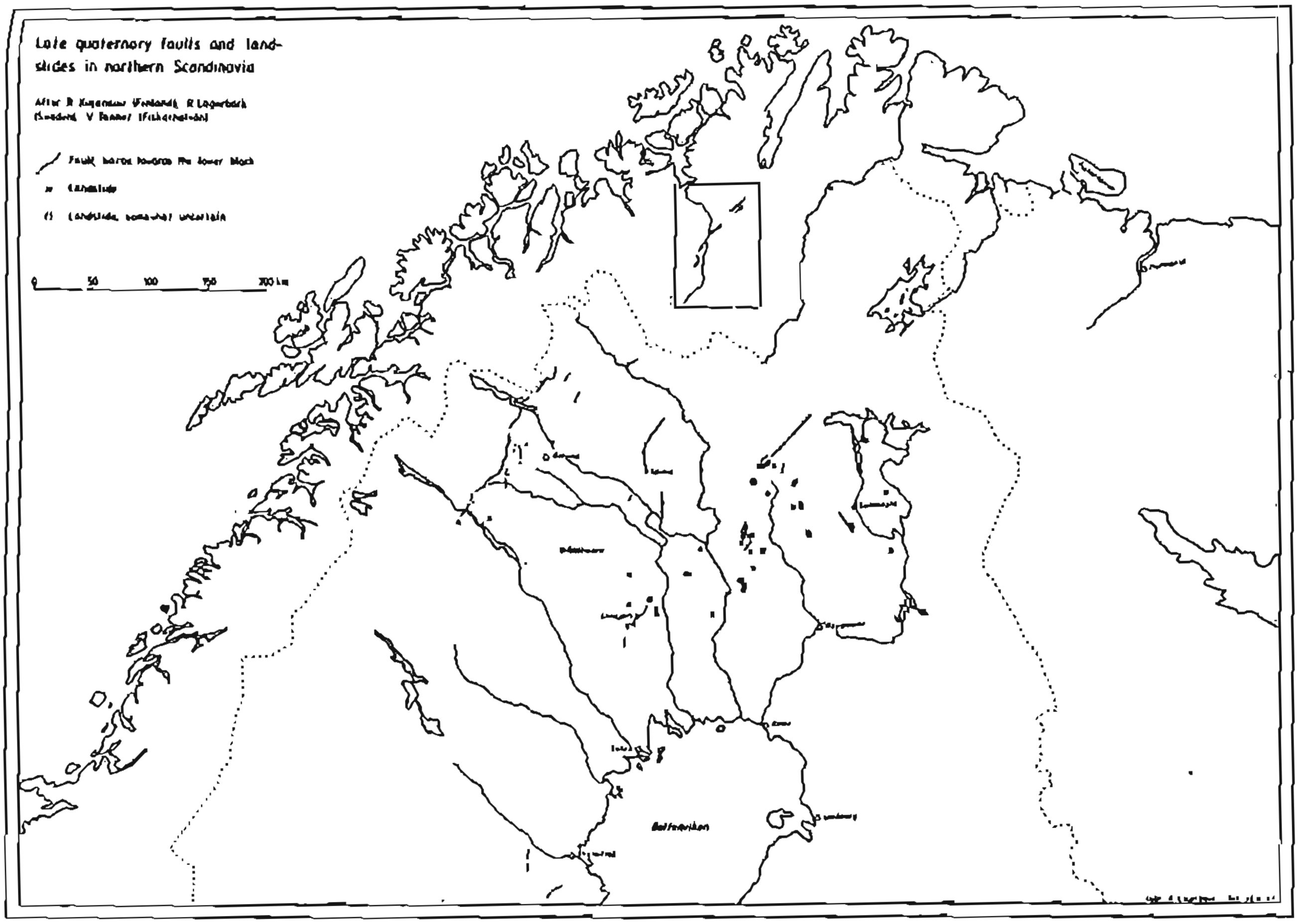

Fig. 1. Late quaternary faults and landslides in northern Fennoscandia from Lagerbäck and Witschard (1983). The Masi fault (Olesen 1985) is added to the map and an area covering this fault is framed.

Recently an active fault in Scandinavia has been detected. Bakkelid & Skjøthaug (1985) found that a part of the town of Egersund in southern Norway has been upthrown approximately 4cm during the last 34 years. This displacement rate, ≈ 1mm/year, is of the same order of magnitude as if the approximately 5m of displacement often observed in late quaternary faults, was distributed over a period of 10.000 years. The detection of the young fault in Egersund throws new light on the previously mapped late quaternary faults.

Description of the postglacial faults

The faults in northern Fennoscandia (Fig. 1) occur as marked, linear and sharp steps in the generally smoothed till cover (Fig. 2). Along most of the faults, the downthrown side is to the north-west. The maximum observed vertical displacement is 25m (Lagerbäck 1979). The drainage is often influenced by these faults; the scarps seem to govern streams and swamps. The faults are some places split into two faults. The northernmost of these two minor faults is downthrown northwards and some places the southernmost fault is downthrown southwards, and the bedrock is consequently forming low horsts.

Fig. 2 Oblique aerial photograph of the Masi fault (UTM 604500 - 7709000) approximately 2km north of Masi. The fault crosscuts an elevation in the terrain. To the right is the maximum observed offset along the fault, 7 m (Olesen 1985).

The young faults are partly governed by older fracture zones (Henkel et al. 1983, Kukkonen & Kuivamäki 1985, Olesen 1985), and they are mainly situated within quartzites and granitoid rocks and terminate often towards mafic rocks (Lagerbäck 1979, Olesen 1985) or older fault zones (Henkel et al. 1983). This phenomenon can be explained, as quartzite and granitoid rocks are more brittle rocks, and consequently the stress only produces faults in these rocks.

No strike-slip displacement has occurred along the late quaternary faults in Scandinavia. This is indicated by the irregular course of the fault and by cross-cut upheavals in the terrain not being displaced, as seen in the middle of Fig. 2. Where the till cover is thin, outcrops with brecciated rocks often occur.

The terrain in northern Fennoscandia was smoothed extensively during the glaciation. It seems unlikely that these marked structures could exist for a long time beneath an active inland ice. The faults are therefore formed at a late stage during the Ice age or afterwards. The faults often crosscut glaciofluvial deposits. Thus, sections of the zone must have been formed after the deglaciation.

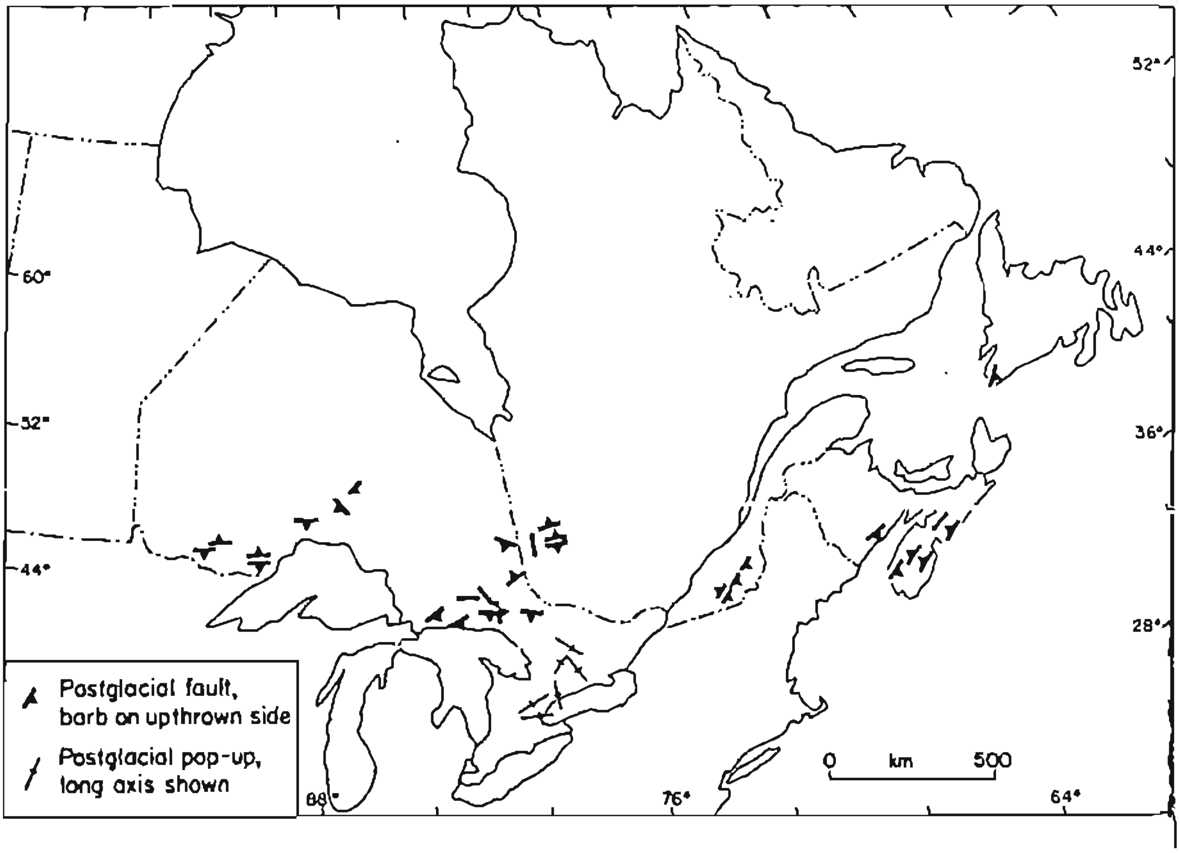

Fig. 3. Postglacial faults and pop-ups in eastern Canada (Adams 1984).

In eastern Canada most of the evidence for postglacial faulting is based on sharp steps in the smoothed and striated bedrock. The faults occur in a broad arc from western Ontario to southern Newfoundland (Fig. 3). The faults have minute throws (commonly a few tens of mm), and are only detected because the surfaces they displace are so smooth (Adams 1984). This throw is much smaller that the observed throws in Fennoscandia and this can explain why scarps in the till cover are not observed in eastern Canada. But although the individual throws are small, they are systematic and can accumulate to a significant displacement, approx. 2 m across a 50 m outcrop (Adams 1981). However, a few postglacial faults of large (several meters) displacement occur on Newfoundland (Adams 1981). The faults occur on bedding planes, cleavages or joints, or other high-angle planes of weakness. Where the dip of the plane can be observed, the faulting is always reverse (thrust) and so the postglacial faults appear to represent compression normal to the fault. They seem to have little or no strike-slip displacement.

'Pop-ups' are postglacial surficial folds (Adams 1984) that occur within the Paleozoic sedimentary cover of southern Ontario (Fig. 3). They resemble the buckles that occur on quarry floors when overburden is removed, and for similar reasons are inferred to indicate the orientation of maximum horizontal stress in the area (Lo 1978). A typical pop-up is an anticlinal ridge of broken rock 5 to 10 m wide and 50 to 500 m long, with flank dips of about 20°, that may rise 1 to 2 m above the level of the surrounding ground. Pop-ups probably form because the bedded nature of the flat-lying sedimentary rocks in which they occur allows the decoupling of the topmost 1 to 2 m along some bedding plane or shale layer, and because the horizontal stresses of 5 to 10MPa found in the region then exceed the bending strength of the rock beam (Adams 1984).

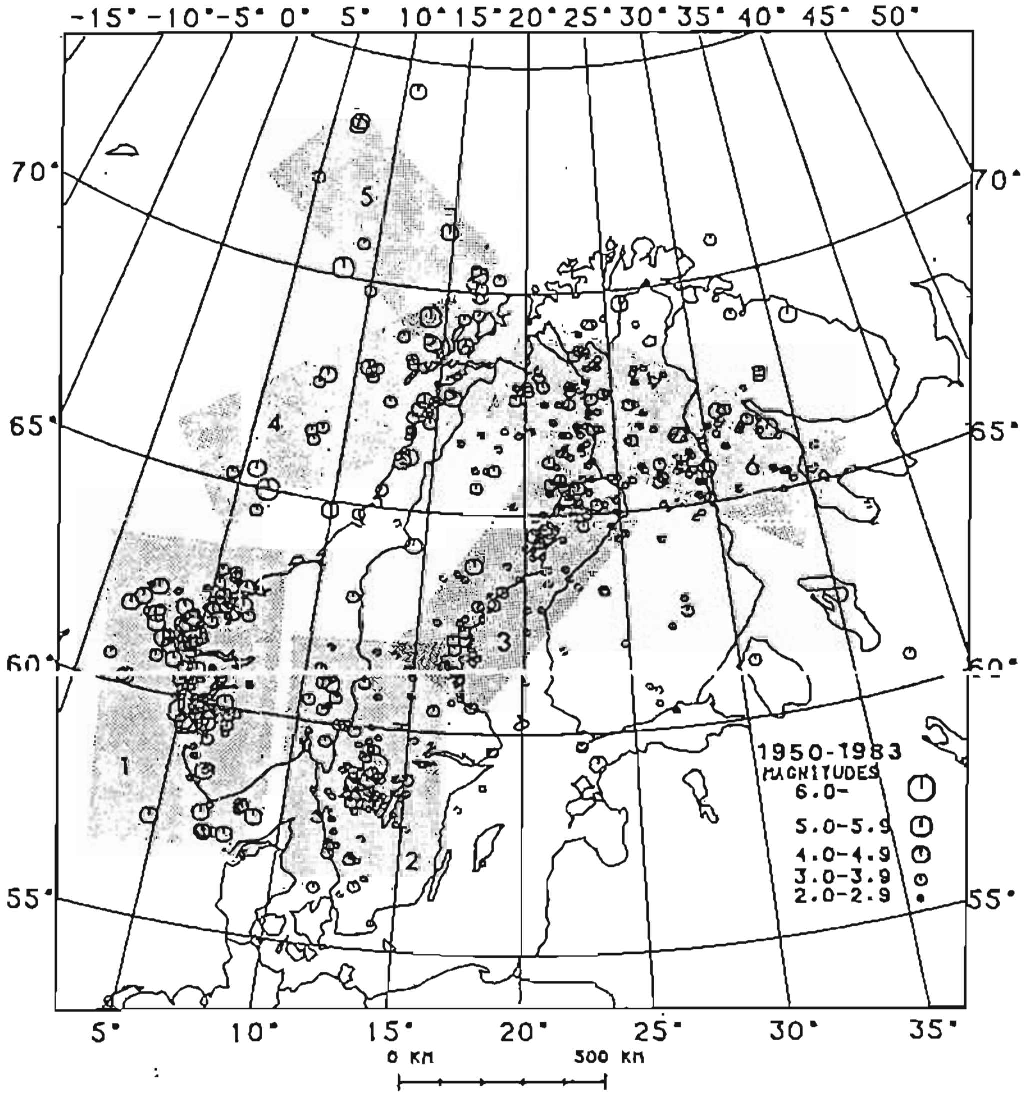

Fig. 4. Epicentral map of Fennoscandian earthquakes in the period 1950-1983. The main seismic zones are shaded, 1: Western Norway zone, 2: Telemark-Vänern zone, 3: Bothnian zone, 4: Norwegian Shelf zone, 5: Norwegian Sea zone and 6: Lapland zone (Ahjos & Korhonen 1984).

Seismicity in Fennoscandia and eastern Canada

In terms of the world-wide pattern of tectonic activity, eastern Canada and Fennoscandia are stable areas. But some active zones occur: the Helgeland coast in northern Norway, Telemark-Vänern, western Norway and the Bothnian area (Fig. 4). Earthquakes in eastern Canada also tend to occur in clusters or zones (Fig. 5), the most prominent zones being the western Quebec (WQ), Charlevoix(CQ), Lower St. Lawrence (LSLQ), and the Miramichi, New Brunswick (MNB) zones. A diffuse zone is apparent along the Northern Appalachians (NA), and lesser activity occurs in northwestern Ontario (NWO) (Basham et al. 1979). Earthquake fault plane solutions shown in Fig. 6 indicate a predominantly thrust fault regime in the upper crust in eastern Canada. The majority of the fault plane solutions indicate uniformity in stress orientation. The confinement of deviatoric compression stress orientation within or close to the ENE octant implies the presence of a uniform stress component overprinting localized stresses in the upper crust of eastern Canada.

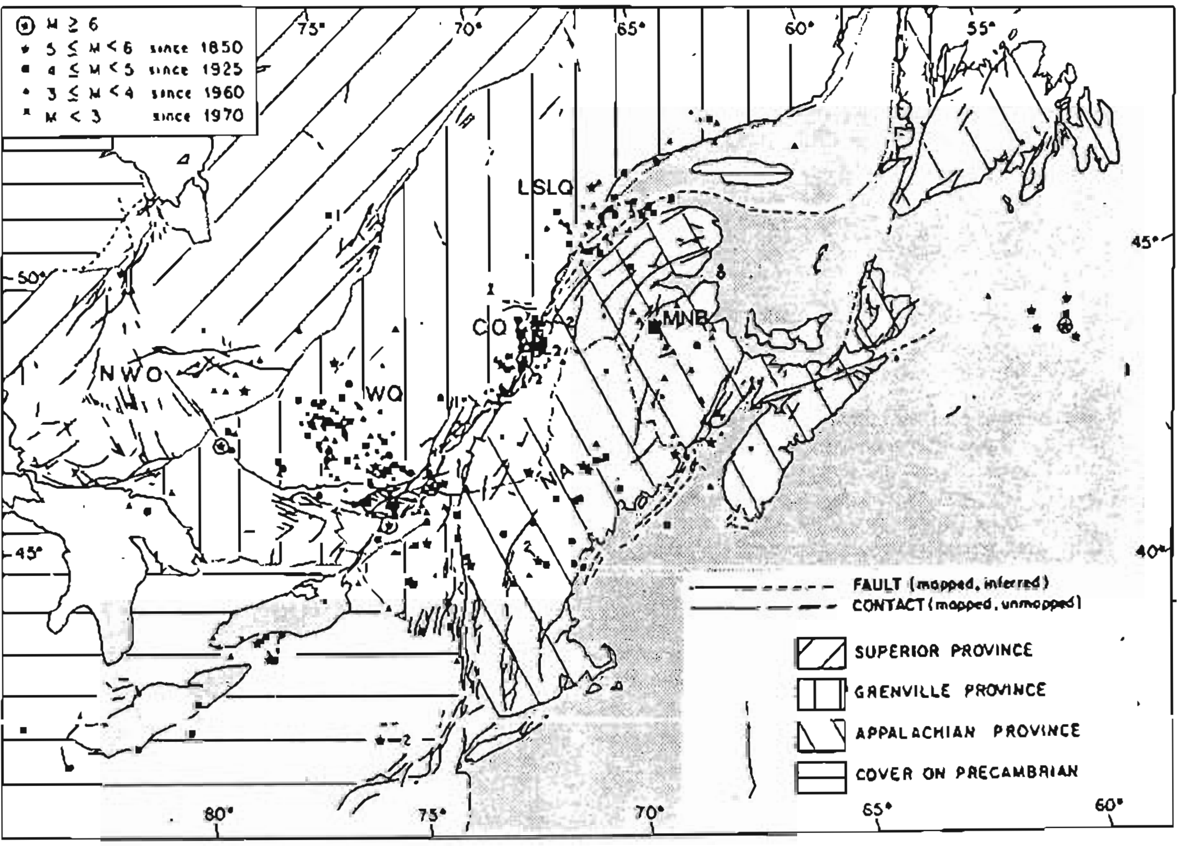

Fig. 5. Eastern Canada seismicity to 1975 superimposed on tectonic provinces and geological structures (Hasegawa et al. 1985). Acronyms denoting seismic regions are defined in the text (after Basham et al. 1979).

Based on the correlation between regional and global seismic activity, Båth(1984) suggested that regional seismic activity in Sweden is linked to the global activity by plate tectonics, rather than land uplift after the glaciation. Forsyth (1981) suggested that seismicity in eastern Canada is occurring along ancient (e.g.

Paleozoic and older) structural trends or boundaries that are being reactivated by the neotectonic stress regime.

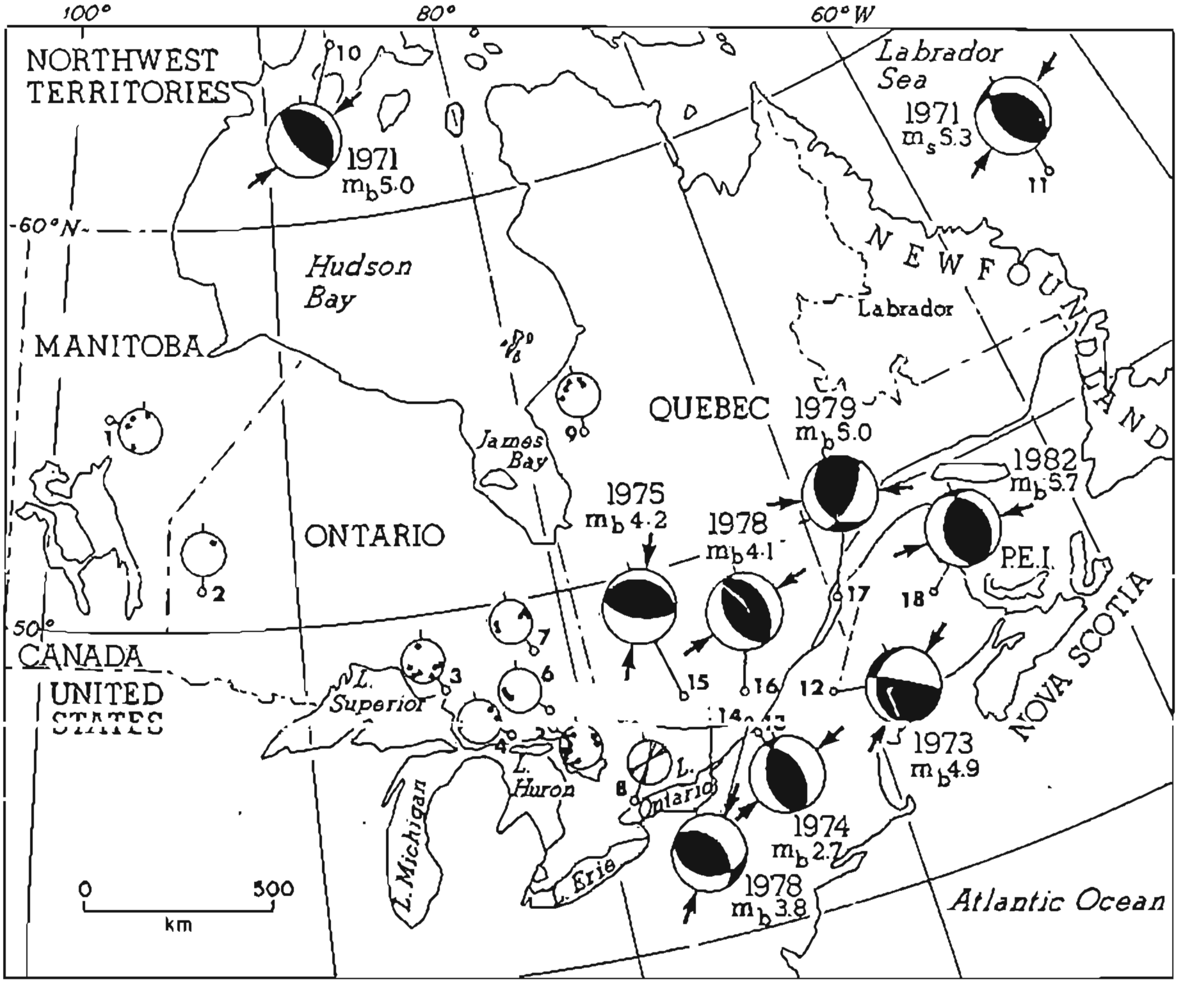

Fig. 6. Orientation of maximum stress component in eastern Canada (Hasegawa et al. 1985). Dots in circle are lower hemisphere stereographic projections of maximum principal stress from in situ (overcoring) stress measurements; depth of overcores vary from 200 to 2200 m. Fault projections in circle are equal-area projections onto lower hemisphere of earthquake plane solutions, with associated pair of arrows denoting azimuth of deviatoric compression component.

Fig. 7, which is a part of the seismicity map of Fennoscandia compiled by Ahjos & Korhonen (1984), shows the location of earthquakes in the area in relation to the Masi and Pärvi faults. The earthquakes seem to make up lines parallel to the faults. The lines are displaced approximately 30 km to the southeast of the faults, consistent with the observation that the faults are reverse. The mean focal depth of Fennoscandian earthquakes is 9 km (Ahjos & Korhonen 1984). Many are concentrated at depths of 7-10 km, 20 km and 27 km. The earthquakes can consequently be generated at a fault plane dipping gently to the southeast from the faults. This indicates that the forces which produced the late quaternary faulting in Finnmark may still be active. This possibility has also been proposed by Lagerbäck(1979) for the late quaternary faults in northern Sweden.

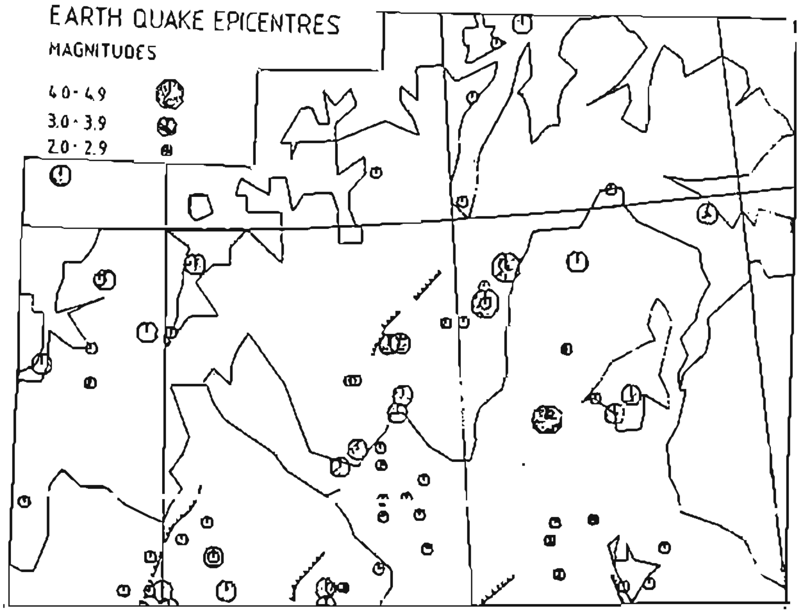

Fig. 7. Enlarged part of Fig. 4 with the Masi fault and late Quaternary faults in Finland and Sweden (Olesen 1985).

A microearthquake survey by Wahlström & Kulhánek (1983) has been performed along the late quaternary Lansjärv fault. Several recorded events could be classified as being located near the fault and possibly associated with it.

Possible stress generation mechanisms

Factors believed to contribute to the stress field in eastern Canada and Fennoscandia, have been discussed by Adams (1984), Hasegawa et al. (1985), Lagerbäck(1979) and Henkel et al. (1983). They suggest that two possible mechanisms, postglacial rebound and plate tectonics, may be responsible for the development of the faulting. The dominating type of late quaternary faults in eastern Canada, as well as in northern Fennoscandia (Adams 1981, Lagerbäck & Witschard 1983, Kukkonen & Kuivamäki 1985; Olesen 1985) is reverse with dip to the southeast, indicating that compressional forces have been dominating in the process. The present vertical motion of Fennoscandia as well as eastern Canada is glacial-induced (Peltier 1986). Compressional stress in Fennoscandia and eastern Canada can be formed either by plate tectonics (Richardson et al. 1979), by a subsiding ice sheet due to its load (Walcott 1970) or by membrane stress (Turcotte 1974).

Plate tectonic stress

Two aspects of plate tectonic stress as illustrated in Fig. 8, can account for this fairly uniform azimuth direction in the upper crust of eastern Canada and Fennoscandia. These are due to ridge push associated with spreading at the Mid-Atlantic Ridge and continental drag force (Cox & Hart 1986). A ridge is an enormous mass of rock rising several kilometers above the abyssal ocean floor. The force exerted on an obstruction at the base of such a flowing body is substantial. The Eurasian plate has the highest portion of continental area of all plates (Cox and Hart 1986). Mantle drag force is a resistive force that is weak beneath oceans and strong beneath the continents.

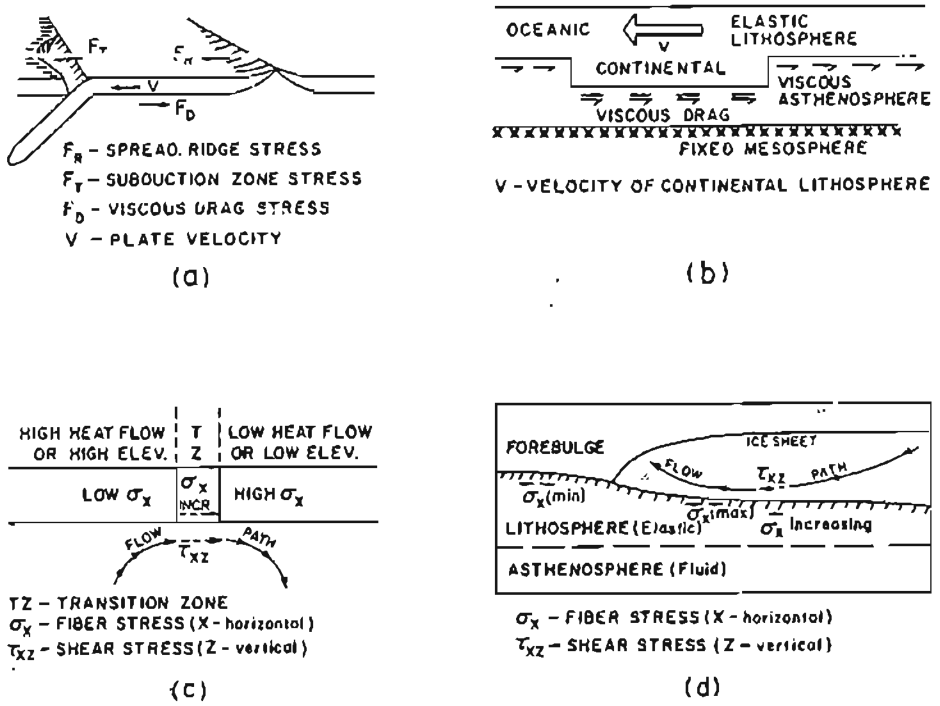

Fig. 8. Phenomenological models of four potential contributors to stress field in upper crust of eastern Canada (Hasegawa et al. 1985). (a) Three main types of plate tectonic stresses. (b) Viscous drag across North American craton. (c) Viscous drag mechanism that can generate deviatoric horizontal stress (σ_x) that increases linearly with depth in low heat flow province due to basal shear stress τ_{xz} in transition region. (d) Two mechanisms by which moving glacier can impart stress into underlying crust, by loading σ_x (min) and σ_x (max), and by quasi-viscous drag τ_{xy}, which induces σ_x.

Finite element calculations by Hasegawa et al. (1985) showed that an initial stress of 10MPa (Richardson et al. 1979) at the Mid-Atlantic spreading ridge could even be enhanced to 40-50MPa in the central part of the Canadian Shield due to viscoelastic relaxation in the upper crust.

Glaciation - Deglaciation

A glacier can impart stresses into the underlying lithosphere in different ways (Walcott 1970, Hasegawa et al. 1985). The weight of the glacier will generate flexure in the lithosphere, causing uplift (forebulge) in front of the ice load and subsidence under the load. The pattern of the horizontal stress component σ_x is as shown schematically in Fig. 8d. During the glaciation this stress would be compressional under the ice sheet. The maximum thickness of the ice sheet in Canada as well as in Fennoscandia is estimated to be 3km

(Clark 1980, Mörner 1980). For this case, maximum values of σ_x during the glaciation in Canada are of the order of 30MPa using the formulation of Walcott (1970). However, faults formed under the ice would most probably be smoothed during the glaciation. The movement of the ice can induce a horizontal stress (σ_x) in the ground of magnitude 0.1-0.2 MPa (Patterson 1972, Prest 1983) which is small compared with stresses due to the ice load.

On the basis of the gravity field, Balling (1980) calculated a remaining uplift of 100-150 m for the Scandinavian shield. Other estimates vary from 200m (Niskanen 1939) to 30 m (Cathles 1975). Based on both the evidence of geoidal subsidence, estimated from satellite data (Bjerhammar 1980), as well as the analysis of free air anomalies Sharma (1984) shows that estimates of the remaining isostatic uplift is of the order of 100m. Estimates of remaining uplift in the Hudson Bay region vary also and range from 300 m (Walcott 1970) to 200 m (Turcotte & Schubert 1982) to 150 m (Andrews 1970). Assuming 300 m of uplift remains in the Canadian shield, Weertman (1978) estimated residual stress of 3-5MPa. The stress induced by the deglaciation is consequently at least an order of magnitude smaller than ridge spreading stress.

Membrane stress

Membrane stress due to latitudinal drift of plates is also suggested as being a potential contributor to the horizontal stress component by Hasegawa et al. (1985). The generation mechanism here is related to changes in the principal radii of curvature when the assumed rigid plates move over the surface of the imperfectly spherical earth (Turcotte 1974). Estimates of membrane stress for a viscoelastic plate are of the order of 10MPa (Dickman & Williams 1981). Within the inner portion of an elastic plate that is under horizontal compression, σ_{hmax} is N-S and σ_{hmin} is E-W (Turcotte 1974); toward the center of the plate σ_{hmin} approaches σ_{hmax}.

Discussion

The fact that the late quaternary Fennoscandian faults terminate at mafic rocks at both ends does not necessarily mean that the stresses which caused the faulting are limited to the length of the fault zone. The deformation of the mafic rocks is probably ductile and consequently does not involve faulting. The stresses may consequently be of a more regional scale. The faults are mostly parallel and are often extensions of each other.

In eastern Canada the stress associated with postglacial rebound does not generate its own earthquakes, but triggers earthquakes in prestressed regions. In doing so the postglacial stress is rarely capable of dictating the focal mechanism of the earthquakes (Quinlan 1984). One of the important contributors to this earthquake generating stress field in eastern Canada is considered to be spreading (Mid-Atlantic) ridge stress (Hasegawa et al. 1985). It is also reasonable to think that the late quaternary faults were mainly generated by the ridge spreading stress. This is supported by the fact that most of the late quaternary faults in northern Fennoscandia are reverse indicating compressional stress. Most in situ stress measurements in Fennoscandia (Myrvang pers. comm.) and eastern Canada (Herget 1980) show that the maximum principal stress is essentially horizontal and the azimuth directions of σ_{hmax} is E-W and NE-SW respectively. Estimates of stress caused by plate tectonics, subsiding ice sheet and latitudinal drift of the plates (see previous chapter) show that ridge push is the dominating stress generation mechanism.

The reason why the late quaternary faults are most frequently triggered in northern Fennoscandia compared with southern Fennoscandia, may be that the uplift-gradient is larger here (Fig. 9). Several factors however, make the discovery of moderately high faults more difficult in southern Fennoscandia. These limiting factors are as follows (Lagerbäck 1979): (1) Denser afforestation (2) An often very rough relief (3) Human activity in the landscape, like agricultural pattern, timber fellings and roads (4) Abrasion and sedimentation below the highest shoreline.

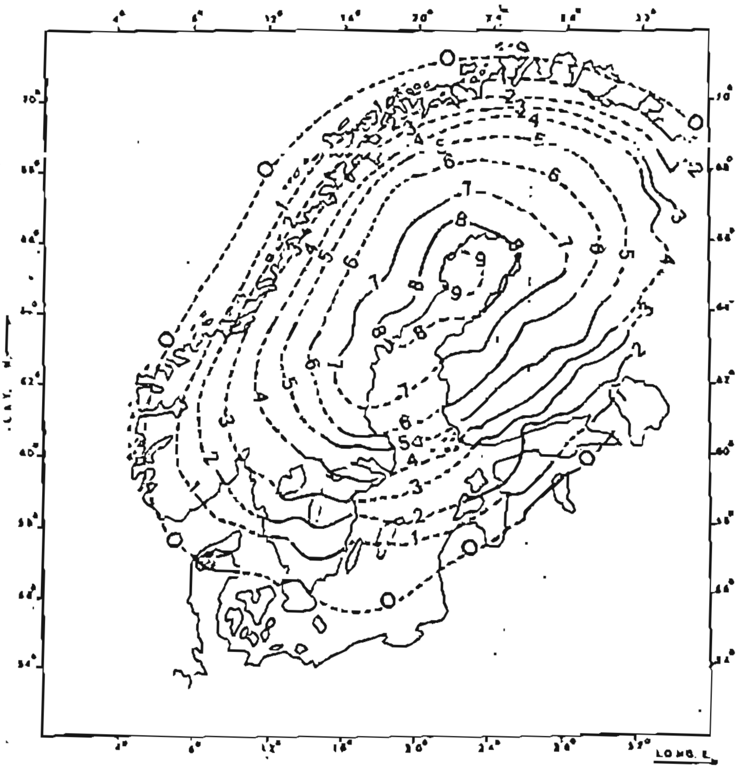

Fig. 9. Present rate of land uplift (mm/yr) in Fennoscandia (Bjerhammar 1980). Broken curves indicate isoline interpretations in areas with no precise levelling and/or insufficient tide gauge data.

The Masi fault and the Pärvi fault in Sweden coincide with a topographic border. The mountainous area to the northwest has an average higher elevation than the area to the southeast. The ice was consequently thickest in the southeastern area. This would involve more depression during the glacial age and consequently a greater contribution to the following postglacial stress regime. The differential loading of ice across a prestressed fault line might consequently be sufficient to cause fracturing and reactivation of the fault, and so produce a fault scarp.

Conclusions

The occurrence of several late- or post-glacial faultlines in Fennoscandia and eastern Canada suggests that fault movements plays a part in the post-glacial regional uplift. The recent discovery of an active fault in Fennoscandia supports this hypothesis.

The regional connection between the neotectonic structures and the recent seismic pattern within Fennoscandia is obvious. This also indicates that the forces which produced the faulting are possibly still active. The fracturing in Fennoscandia has mostly occurred along old fracture zones, but occasionally also in unfaulted rocks. The stresses which caused this faulting most likely have a regional distribution. The limited length of some of the faults is most certainly due to termination of the faults towards mafic rocks where the deformation is less brittle. Both in situ stress measurements and earthquake plane solutions in the upper crust indicate that the maximum horizontal stress is NE-SW and E-W in eastern Canada and Fennoscandia respectively. The stress regime is compressional. This is consistent with the late quaternary faults mainly being parallel to the Mid-Atlantic Spreading-Ridge and reverse.

The main contributor to the fault generating mechanism is therefore believed to be stress associated with spreading of the Mid-Atlantic Ridge and viscous drag underneath the lithosphere. The release of these stresses can however be related to the postglacial rebound.

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