Earthquakes and change of stress since the ice age in Scandinavia

SØREN GREGERSEN

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In a small, northern part of Scandinavia, where the present earthquake activity is not significantly different from its surroundings, large surface faults have been interpreted to show the occurrence of large earthquakes about 9,000 years ago. Signs of this are coincident landslides as well as liquefaction in loose sediments, which are very well dated through varv-counting. The interpretation is that the cause is stress release related to the final deglaciation after the last Ice Age. In contrast, the present dominating stress field in Scandinavia as a whole follows the pattern of the World Stress Map Project, namely compression along the absolute plate motion. This compression, NW-SE in Scandinavia, shows little influence of the deglaciation rebound, which is delineated by the area of the present-day lithospheric uplift. Through these observations change of dominating stress is clearly indicated during the last 9,000 years. And the modern earthquake activity of Scandinavia is not concentrated near the old, large earthquake faults. All these arguments influence the modern evaluation of earthquake hazard. This must be based on the present stress field, and not on that of 9000 years ago. The expectation of a large "10,000-year-earthquake" one of these days is zero, with the small uncertainty that such an earthquake could occur unexpected anywhere in a stable continental region.

Key words: Stress in Scandinavia, earthquakes in Scandinavia, seismicity in Scandinavia, earthquake hazard, stress from deglaciation, stress from plate motion.

Søren Gregersen [*srg@kms.dk*], *National Survey and Cadastre, Denmark, Rentemestervej 8, DK-2400 Copenhagen NV, Denmark. 17 December 2001.*

Physically there is no doubt that there is an intimate connection between earthquakes and faults. And still it is not always possible to find in geological/geophysical studies the faults responsible for the present earthquake activity (Gregersen et al. 1996), even if the geological studies emphasize postglacial geology. Reactivation of old or recent faults depends on the relations of stress orientation and fault orientation.

For the postglacial uplift area of Scandinavia many geological and geodetic authors have emphasized the importance of the uplift for the geodynamics (e.g. Lagerbäck 1990 and 1991; Kakkuri 1993; Ekman 1985, 1993; Arvidsson 1996; Lambeck et al. 1998). Lagerbäck (1990) has argued, that many large geological faults in northern Scandinavia are indicators of earthquakes released right after the Ice Age. This view was supported by a compilation of evidence in Norway by Olesen (1991). Recent stress modelling of realistic crust-mantle structures subjected to deglaciation support that a "pulse" of ice-caused earthquake activity is possible 9,000 years ago (e.g. Johnston et al. 1998). It is shown that the stresses in this connection will diminish with time.

On the other hand recent stress measurements align on an average dominating orientation along the present plate motion (e.g. Slunga 1989; Gregersen et al. 1991; Gregersen 1992; Mueller et al. 1992). Already while the stress indicators were being collected and interpreted the discussion on the relative importance for earthquake generation of the postglacial uplift versus plate motion was taken up in an international workshop in Denmark (Gregersen & Basham 1989). The present paper takes up this discussion in the light of new knowledge.

Geological stress and earthquake indicators in Scandinavia

Arguments were presented by Lagerbäck (1990) that very large faults can be recognized as signs of large earthquakes in many locations in northern Scandinavia. A picture of a very large example is reproduced on Figure 1. These faults are seen in connection with large

Fig. 1. One of the most spectacular postglacial faults, the 10 m high Karhuvaara fault near Lansjärv in Sweden. From Lagerbäck (1990).

coincident land slides and liquefaction phenomena in water-filled sediments (Fig. 2) in the same areas. Through this connection they are interpreted as signs of large earthquakes in areas, which are now only moderately active. These phenomena can well be seen as periglacial, but it is judged that they only developed by severe shaking. The age of the faults is close to 9,000 years, which is right after the end of the latest Ice Age. Many authors agree with Lagerbäck's interpretation (e.g. Muir Wood 1989; Arvidsson 1996; Lambeck et al. 1998; and a compilation of expert opinions in Stanfors & Ericsson (editors) 1993). The area extends into Norway (Olesen 1991) and into Karelia (Zhuravlev & Ekman 1989; Lukashov 1995).

The about 2 km thick ice cap left the northern part of Scandinavia finally 9,000–8,500 years ago. Then the lithosphere is interpreted to have had a fast adjustment phase, releasing plate tectonics stress, which has been accumulated over the long duration of the Ice Age, and developing stress by isostatic adjustment (e.g. Johnston 1989). At this time around 9,000 years ago the stress field from the off-loading was dominating over the stress from the plate tectonics (e.g. Muir Wood 1989; and similarly for Scotland: Davenport et al. 1989). The near coincidence of the areas of maximum uplift and of paleoearthquake occurrence is illustrated in Figure 3.

During the 9,000 years since then the northern part of Scandinavia around the Bothnian Bay has been uplifted by approx. 300 m following an uplift of approx. 500 m in the period 13,000 to 9,000 years ago (e.g. Mörner 1980). A thousand km away from the center of the uplift (Fig. 3) the northern part of Denmark has risen approx. 60 m (Mertz, 1924), since the ice left that area 13,000 years ago. Here in the northern part of Denmark the island of Laesoe has been especially investigated. Large fault movements, which could have released earthquakes, have been postulated here as late as 4,000–5,000 years ago (Hansen 1980, 1986 and 1994). Also large discrepancies from the regional pattern of postglacial uplift in northern Jylland are claimed

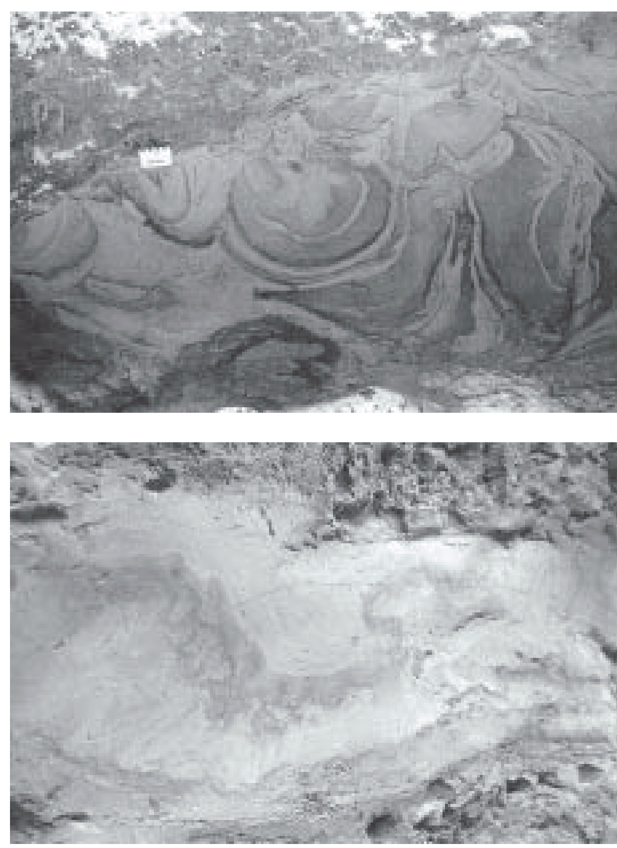

Fig. 2. Two cross sections of disturbed sediments indicating liquefaction of the waterfilled sediments, which were laid down 9,000 years ago. Scales similar in the two pictures, shown via centimeter marking or 2.5 centimeter coin. From Lagerbäck (1991).

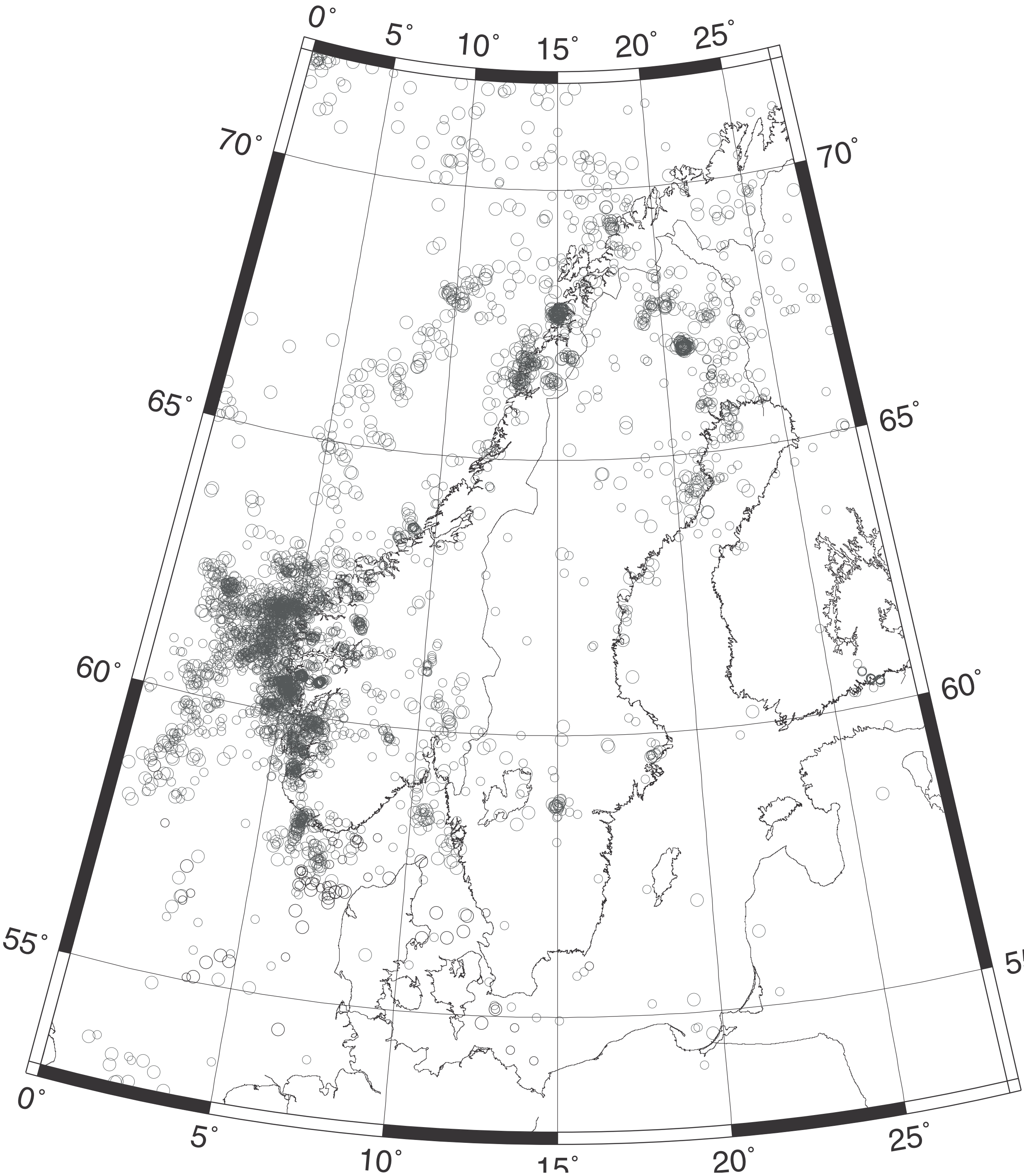

Fig. 3. Map of earthquake geography in Scandinavia, based on the Scandinavian bulletin from Helsinki University, 1987–1997, and results from the European Union project Rapid Transfrontier Seismic Data Exchange Network (Transfrontier Group) 1990–1994 as well as locations from the Danish seismograph network 1987–1997. Large circles are earthquakes of magnitude 2½ and above, small circles below 2½. Hatching shows the area, where the present postglacial uplift is 7 mm/year or larger (Kakkuri, 1993). Very thick lines show the positions of the large postglacial faults of age close to 9000 years.

by Petersen (1985). In Karelia, in another direction from the central uplift area, the timing of large faulting has been postulated to occur over a long time interval from 10,000 to 2,000 years ago (Zhuravlev & Ekman 1989; Lukashov 1995).

All of the geological stress and earthquake indicators are at least several thousand years old, showing a "pulse" of activity right after the Ice age, and diminishing activity since then.

The present geophysically determined stress field

Many modern stress investigations have been performed in Scandinavia (Slunga 1989; Gregersen 1992; Mueller et al. 1992; Ask et al., 1996). Already in 1988 it was concluded in a workshop in Vordingborg, Denmark (Gregersen & Basham 1989) that the present dominating stress field in Scandinavia is that of plate tectonics and not the off-loading after the Ice Age. And this was concluded valid for Scandinavia as well as for North America, where postglacial uplift is also active since the latest Ice Age. Supplemented with more recent Norwegian investigations (Bungum & Lindholm 1996; Fejerskov & Lindholm 2000; Lindholm et al. 2000) the input to the World Stress Map Project (Gregersen 1992) shows that the dominating horizontal compressional stress is oriented NW-SE, but also that the scatter is tremendous, so that each single focal mechanism or a limited region can show significantly deviating orientation. The impression is that the stress release in earthquakes is influenced by the local faults. In Denmark the edge of the Fennoscandian Shield, i.e. the fault system of the Fennoscandian Border Zone, does not influence the stress field; the only slight deviation from the dominating orientation is in the North Sea, in the Central Graben, where some orientations are approx. E-W. An updated Scandinavia version of the World Stress Map can be found on the internet under the addresses www.world-stress-map.org and www-wsm.physik.uni-karlsruhe.de. Press the button: enter the WSM project. Choose from the menu: stress data. Choose from the menu: stress maps. And finally one can choose between many existing maps and the possibility of specifying a geographic area of interest.

The structural trends expressed in the rocky coast lines of Norway and of northern Sweden influence the location of earthquakes, as is shown in Fig. 3. Since earthquake location capability is improved over the years a display of the earthquake geography of a recent 10 year period has been chosen as documentation. The data sources are the Scandinavian bulletins from the Institute of Seismology in Helsinki University and the locations made through a European Economic Community project in the 1990s called Rapid Transfrontier Seismic Data Exchange Network (Transfrontier Group). The major earthquake zones are not in the area of the postglacial faults (Fig. 3), they rather follow the major geological lines like the rocky coasts, the continental margin and the grabens in the North Sea, although some zones are not easily interpreted in terms of known geological inhomogeneities (e.g. in Denmark, Gregersen et al. 1996).

Modern geodetic strain measurements have long been on the verge to show significant horizontal deformations in the Fennoscandian Shield. Kakkuri (1993) reported on comparisons between older triangulation measurements and modern GPS measurements as well as repeated GPS measurements. The latter has been a project in Norway, Sweden and Finland for about 10 years, and recently deformations which are significant have been reported for the Scandinavian shield area as a whole (Milne et al. 2001). Maximum vertical motion, of up to 10 mm/year, is centered in the classically known uplift area (Fig. 3), and the radial, outward motion is between 1 and 3 mm/year. Less certain deformations have been obtained for the border zone of the Fennoscandian Shield in southern Sweden (Talbot et al. 1998; Pan et al. 1999). The claim has even been put forward by Veriö (1992) that a small local earthquake can be correlated with a geodetic deformation, in time and space. Very soon it will be possible to determine also the pattern of deformations from seismological focal mechanisms as seismograph observations and computation methods improve.

Discussion

The two end points in stress dominance, mentioned above are presently well established. Johnston (1989) argued that present-day seismicity under the existing ice sheets in Greenland and Antarctica is extremely low, and that this can be understood physically through the loading of the crust, which locks crustal fractures from breaking, because they are dominantly under compression from plate tectonic forces. But around 9,000 years ago a "pulse" of many large earthquakes shook Scandinavia as a consequence of the release of stored plate motion compression as well as lithospheric adjustment to the loss of the ice load. This has been argued physically. And the physical arguments were supported in numerical model computations on lithospheric adjustment by Wu & Hasegawa (1996), and by Johnston et al. (1998) in analytical model computations. Both show that significant earthquake generating stresses will occur in realistic lithosphere models in the deglaciation stage. And the fault instability has a maximum at a time around the retreat of the last ice. The arguments are similar for the Laurentide ice sheet in North America (Wu & Hasegawa 1996), and in Scandinavia (Johnston et al. 1998), but they do show larger fault instability in Scandinavia than in North America.

The time history of the stress development from uplift dominance to plate motion dominance, which we get from the modeling, is unfortunately rather uncertain. Besides showing that the fault instability has a maximum shortly after the retreat of the ice sheet, at the time of fast postglacial rebound, Wu & Hasegawa (1996) find that the subsequent stress field caused by the deglaciation is too small to generate earthquakes, but may be large enough to trigger earthquakes that are caused by plate motion stresses. In Canada their claim is that an earthquake 7–8,000 years ago was triggered by the postglacial rebound (Wu & Hasegawa 1996). In Denmark it has been claimed that an earthquake could have been triggered by the deglaciation stresses in Laesoe island as late as 4-5,000 years ago (Hansen, 1994). And in southern Sweden Mörner and Trøften (e.g. 1993) have claimed evidence for paleoseismotectonics far away from the large faults in northern Scandinavia, but at a coincident time.

The change in earthquake generating stress is well documented experimentally and theoretically, but the transition from one stage of stress to the other needs further study of old and present earthquake mechanisms and times of occurrence. With the present state of knowledge we are limited to evaluating that the probability now, in the plate motion stress field, of a large "10,000-year-earthquake" is zero, but it is a zero with uncertainty.

Dansk sammendrag

I et lille område i det nordligste Skandinavien, hvor den nuværende jordskælvsaktivitet ikke adskiller sig meget fra omgivelserne, er der konstateret store forkastninger i overfladen, som bliver taget som tegn på store jordskælv for omkring 9000 år siden. At det var jordskælv understøttes af samtidige klippeskred i området samt af "liquefaction" i løse sedimenter, som er veldaterede ved varv-tælling. Interpretationen er, at jordskælvene skyldes spændingsudløsning i forbindelse med isens endelige afsmeltning efter Istiden. Som kontrast hertil følger det nuværende dominerende spændingsfelt i Skandinavien generelt tendensen fra World Stress Map Project, der siger kompression langs med pladetektonikkens absolutte bevægelsesretning. Denne kompression, NV-SØ i Skandinavien, ser ikke ud til at have sammenhæng med den hævning af lithosfæren, der skyldes isens forsvinden. Så den klare konklusion er, at der er sket et skift af de dominerende spændinger inden for de sidste 9000 år. Og den moderne jordskælvsaktivitet er ikke koncentreret nær de gamle, store jordskælvs forkastninger. Disse argumenter har betydning for den moderne bedømmelse af jordskælvsrisiko. Denne må baseres på det nuværende spændingsfelt, og ikke det for 9000 år siden. Forventningen om et stort "ti-tusind-års"-jordskælv i nutiden er nul, med den lille usikkerhed, at sådan et jordskælv kan ske uventet hvor som helst i et stabilt kontinentalt område.

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