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Intraplate earthquakes in Scandinavia and Greenland Neotectonics or postglacial uplift

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ABSTRACT
Even if the intraplate areas of Scandinavia and Greenland have only experienced small earthquakes within the time of human tale, we can learn 4 lessons from these regions.

In a small part of Scandinavia, where the present earthquake activity is not significantly different from its surroundings, large faults have been discovered. And these are interpreted to show the occurrence of large earthquakes about 10,000 years ago. Signs of this are coincident landslides as well as liquefaction in loose sediments, which are well dated through varve-counting. Many Scandinavian scientists interpret the cause to be the deglaciation after the last Ice Age. And since the present dominating stress field in the area follows the pattern of the World Stress Map Project, namely compression within the plate, oriented in the direction of the absolute plate motion, the glacier off-loading is a significantly different cause, 10,000 years ago. Stress reorientation clearly indicates that present-day earthquake activity is caused by neotectonics - plate motion.

Into this argument goes the observation from Greenland and Antarctica, that no earthquakes occur under the ice caps. For Scandinavia the argument is that no earthquakes occurred under the ice sheet of the Ice Age, and that the stored stresses were released, when the ice sheet melted 10,000 years ago. A third lesson comes from Greenland. Here we find that the compressional regime in the intraplate region is not reached until several hundreds of kilometers from the mid-ocean ridge. The few existing focal mechanisms show spreading and strike slip motion. This is supported by data from Iceland far out from the spreading zone. When a map became available a few years back of deep-reaching faults in the Denmark a comparison was attempted. The question asked was, whether we can now point to some of these faults and call them active? Can the regional earthquake distribution be well correlated with the mapped deep faults? And the answer was for part of the region YES; while for another it was NO. The earthquake activity adds its own component to the fault map of Denmark.

The region is full of faults. Can we feel rather safe, because the stress seems to have diminished since the end of the Ice Age 9,000 years ago? Or can we expect large earthquakes as observed 10,000 years ago?

INTRODUCTION

Intraplate earthquake regime in Scandinavia and Greenland has been taken up in the present paper. Ice cap loads and the resulting lithospheric stresses are or have been important for both areas. And for both areas it is presently discussed what the causes of the small earthquakes are, plate tectonics motions or changes or disappearance of ice cap load. For Greenland the shrinking of the ice cap, and the ensuing uplift ended about 5-6,000 years ago. For Scandinavia the ice cap of the Ice Age left the area about 9,000 years ago. The latest several years phenomenon of shrinking ice cap in Greenland does not yet have any influence on the lithosphere.

DISCUSSION ON SCANDINAVIAN STRESSES FROM PLATE TECTONICS VERSUS POSTGLACIAL UPLIFT

The earthquake distribution in Scandinavia is shown in Figure 1. The general pattern of seismicity is the same for any time window, while smaller details can be different. The figure shows that the earthquake activity is scattered along the Norwegian coast and continental margin, along the Swedish east coast. It is well established in the Denmark area, that the earthquake activity is the southern limitation of the Scandinavian seismicity. It is probably also established that the earthquake activity is lesser in northern Germany, in Poland and in the Baltic states. In the

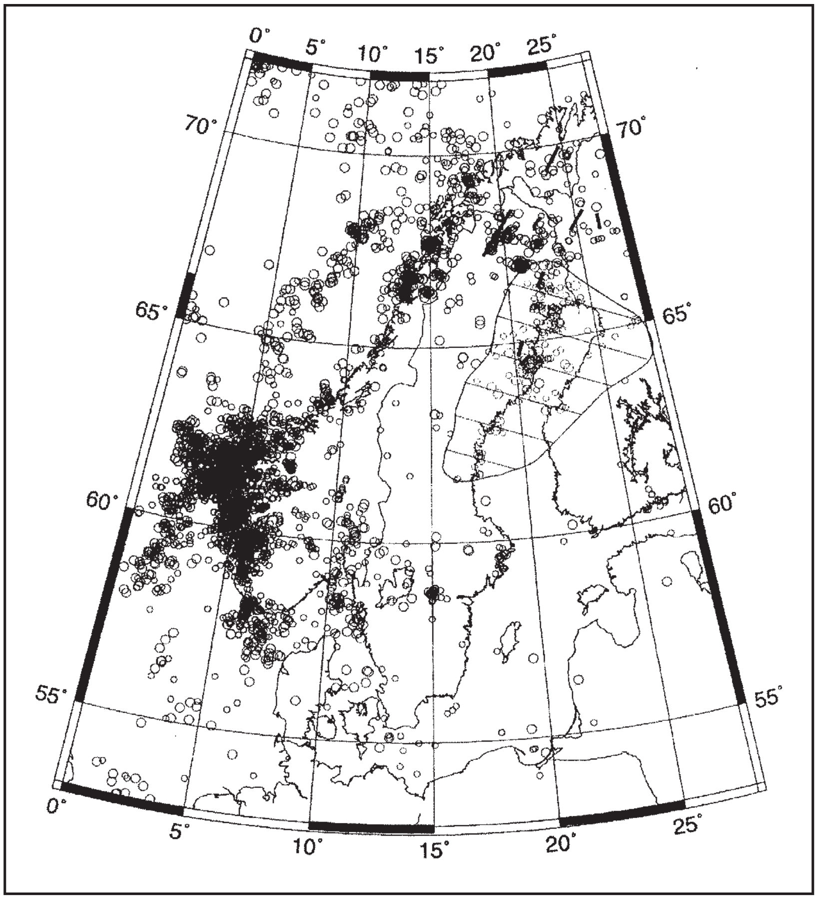

Figure 1. Map of the earthquake distribution in Scandinavia, based on the Scandinavian bulletin from Helsinki University, 1987-1997, and results from the European Union project Rapid Transfrontier Seismic Data Exchange Network (Transfrontier Group) 1990-1994 as well as locations from the Danish seismograph 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).

Thick lines show positions of the large postglacial faults of age close to 9,000 years. Updated earthquake files for Denmark are available in home page www.geus.dk under seismology.

latter areas the seismograph coverage has until recently been significantly poorer, so the information in the map is influenced by less sensitivity to small earthquakes.

Also shown in Fig.1 are short heavy lines in northern Norway, Sweden and Finland. These show the locations of large postglacial faults (Lagerbäck, 1991), which probably were developed in large earthquakes. The dating of these earthquakes is through disturbances of sediments in liquefaction, and counting of varve layers. Coincident with the liquefaction phenomena are large landslides, support for the interpretation of these large faults as signs of earthquakes 9,000 years ago.

Fig. 1 also shows a broad-striped area, where the present uplift since the ice age is most significant, above 7 mm/year. Neither the specific area of largest uplift, nor some zone around it of the shape of the uplift area stands out with special earthquake activity. This has been recently elaborated in a paper by Gregersen (2002). The argument which emerges from the significant differences in earthquake activity 9,000 years ago and now is that the stress pattern has changed dramatically. 9,000 years ago, when the last ice cap disappeared the stresses were dominated by disappearance of the ice load. So the stress concentrations and the stress orientations were determined by the latest ice locations in the area of the large postglacial faults of Fig.1. The pattern of earthquakes was besides influenced by another phenomenon which is seen in present-day ice cap

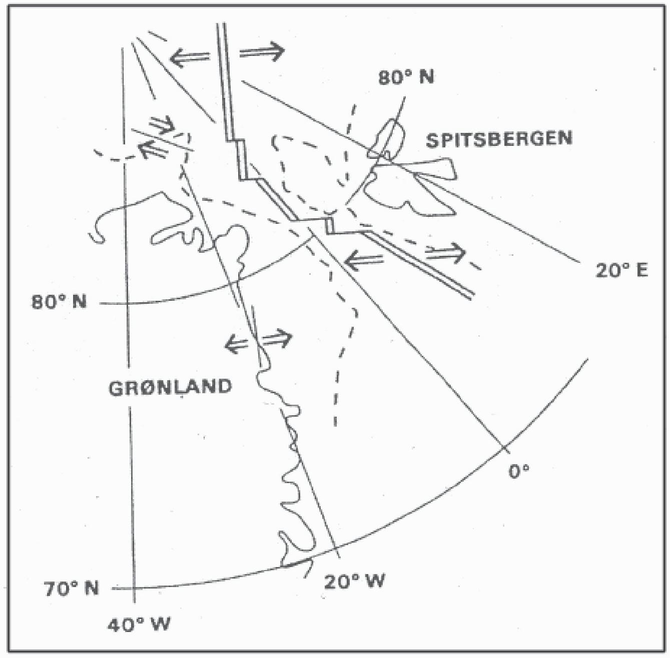

Figure 2. Stress map of the World Stress Map Project, Heidelberg Academy of Sciences and Humanities. Orientations of maximum horizontal compressional stress via many different geophysical /geological measurement methods.

regions, Greenland and Antarctica. Here no earthquakes occur under the ice caps. Just one exception, confirming the rule, has occurred in Antarctica (Adams, 1985).

It was shown by Slunga (1989) for the Baltic Shield, and emphasized by Gregersen (1992) for Scandinavia, that the dominant stress field is compression along NW – SE. This is in agreement with the results of global seismic stress (Zoback, et al, 1989) showing a worldwide pattern of compressional stress in the interiors of the lithospheric plates along the direction of the absolute plate motion which is the NW – SE direction for Scandinavia. This same pattern is shown in Fig.2, which is a recent printout of the file of the continuously updated World Stress Map (World Stress Map reference). Shown are orientations of various geological/geophysical stress indicators. For Scandinavia the main sources of stress information are the small earthquakes of Fig.1. The picture is not indisputable. Even if the dominant NW – SE compression is distinguished there is much scatter. So for many specific areas the conclusion must be that specific local causes exist. Discussions of data displays like Figs. 1 and 2 have led Arvidsson (1996) to the opposite conclusion, namely that the uplift since the Ice Age is the dominant cause of earthquakes in the intraplate region of Scandinavia.

It has been known that Scandinavia is one of the regions on the globe, where uplift is documented at the centimetre level in the central areas of the latest Ice Age. This has been believed by scientists over the years (e.g. Arvidsson, 1996) as the possible cause of the small earthquakes. The observations as included in Fig. 1 were determined by levelling (Kakkuri, 1993). Geodetic measurements of vertical as well as horizontal motion in the shield of Scandinavia have recently been made through GPS measurements on permanent stations. The horizontal motions, which could be responsible for the earthquake stresses are about 2 mm/year (Milne et al. 2001) in outward directions from the center of the uplift shown as hatched area in Fig.1.

When a map of deep basement faults in the area of Denmark was published (Vejbæk, 1997) it was possible to correlate the earthquake activity with specific faults. This correlation was only partly successful (Gregersen et al., 1996). Some earthquakes are located in zones/lines, which can not be seen in the fault map. Since a conclusion that the earthquakes do not happen at faults is not sensible we must conclude the fourth lesson that the earthquake activity adds to the fault map in its own right.

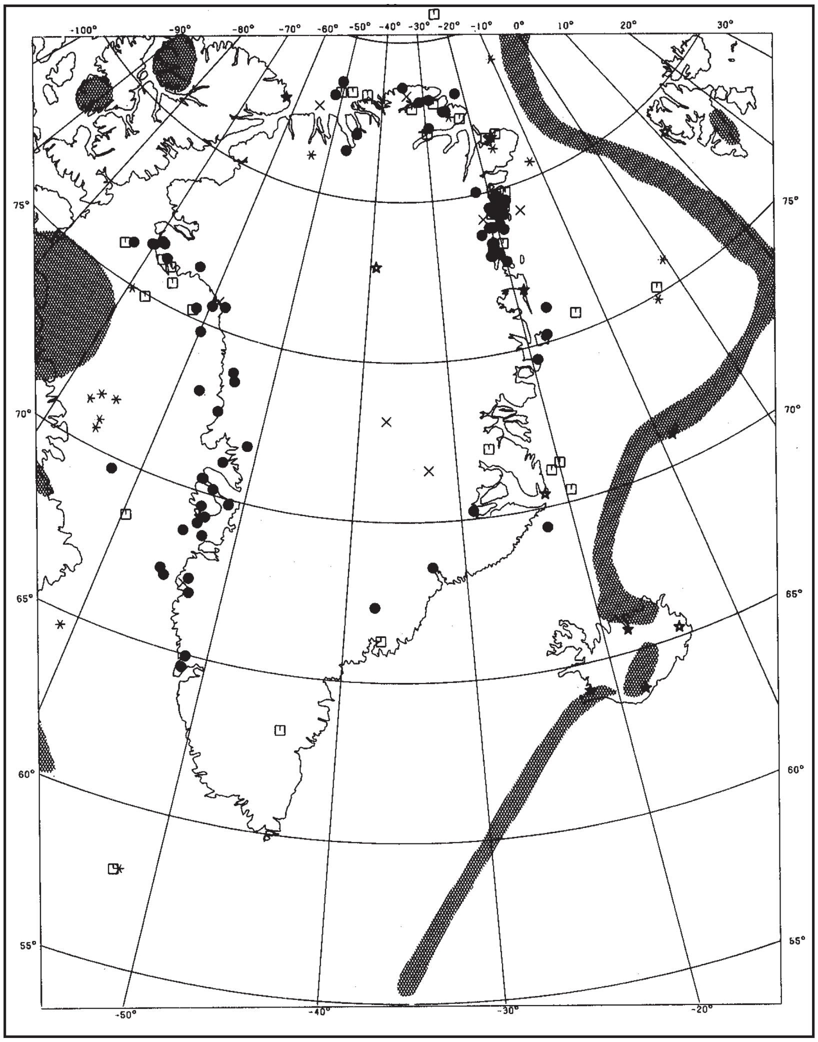

Figure 3. Sketch of the mechanisms of earthquakes in relation to spreading of the mid-ocean ridge and shearing in transform forms close to north-east corner of Greenland.

Discussion on Greenlandic stresses from plate tectonics versus postglacial uplift

The earthquake activity of Greenland has been described in a paper by Gregersen (1989). Here the second lesson of this paper is emphasized by the distribution of all the known earthquake activity, from historical reports (Gregersen, 1989). The map of the earthquake activity shows without any doubt, that earthquakes only occur in the coastal regions, and not under the Inland Ice. The same observation has been put forward for Antarctica. And then one earthquake has happened with a magnitude of a little over 5 (Adams, 1985). We apparently have an observational rule with an exception emphasizing the rule. This rule has been used by Johnston (1989) in arguments for the appearance of the special suite of Scandinavian earthquakes 9,000 years ago. Part of the cause, Johnston (1989) argues is that the ice load disappeared. But another part of the earthquake activity pulse is that the stresses under the ice cap, while it existed in Scandinavia, were not released, because the ice cap prohibited the stress release in earthquakes just like the present-day situation in Greenland and Antarctica.

From the only two available focal mechanisms in Greenland, Gregersen (1989) put forward an argument, which can be expressed as the third lesson of this paper. The earthquake mechanisms can be illustrated by their horizontal projections in picture in Fig. 3. None of these are of the type, which is generally dominating in the interior of continents, namely thrust mechanisms (Zoback et al., 1989). It was interpreted, that the spreading and shearing of the mid-ocean ridge with its transform faults is causing spreading and shearing in the plate at distances of several hundred kilometers. This conclusion was similarly observed in Iceland by Einarsson (1989) looking at quakes some hundreds of kilometers from the spreading axis.

Chung and Gao (1997) have argued differently based on two new earthquake mechanism determinations by those authors, both normal faulting. One is located near the NE corner of Greenland and the other earthquake is close to the southern tip showing a normal mechanism with strike approximately SW – NE. This is far from the mid-ocean ridge, so the above argument can not be made. Chung and Gao (1997) interpret their two mechanisms to show that uplift is the cause of the earthquakes in Greenland. The present author does not have an alternative explanation.

This paper makes a present-day combination of the information on the two sides of the north Atlantic Ocean deriving the 4 lessons of (1) stress change, (2) no earthquake activity under an ice cap, (3) the extended width of the spreading region around a mid-ocean ridge, and (4) the addition of deep faults through seismicity to the structural knowledge of an area. These conclusions have been developed over a long time, one important step being a NATO symposium in Denmark in 1988 (Gregersen and Basham, 1989). Not all of the discussions taken up in the present paper were touched, but the main conclusion that the dominant cause of earthquakes in the intraplate regions around the north Atlantic Ocean, which experience postglacial uplift, is plate tectonics and not postglacial uplift is already emphasized in many papers of that symposium (Gregersen and Basham, 1989). Taking into account the arguments by Arvidsson (1996) it is convincing to the author that the evidence of the year 1989 and the following years of the World Stress Map is still the valid interpretation of the existing data. The dominant stress field in these intraplate regions on the two sides of the North Atlantic Ocean is caused by the plate motion, not the postglacial uplift.

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