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Postglacial uplift, neotectonics and seismicity in Fennoscandia

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Abstract

Fennoscandia has experienced major uplift in postglacial time, which is assumed to reflect a glacial isostatic process connected to the melting of the last ice sheets. Extensive modelling of the isostatic movements show that the applied deglaciation and uplift model fit the observations well. There are, however, areas with significant deviations between uplift measurements and regional model predictions. The misfit between observations and the isostatic uplift modelling is interpreted here to reflect a tectonic component of the uplift. The objective of the present investigation is to isolate this tectonic uplift component. Interestingly enough, the areas found partly correspond to areas with pronounced seismic activity, and the assumption that the postglacial rebound is responsible for much of the observed onshore seismicity is substantiated.

We conclude that there seems to be present-day deformation along the shoreline of mid-Norway, southern Norway (shoreline and mountain areas), and along the Swedish east coast with the centre northeast of the Gulf of Bothnia that cannot be explained by glacial isostasy. Not all of the deformations in these areas are necessarily co-seismic. The study suggests that such vertical deformations are small in magnitude and overprint the glacial rebound. The deformations may be a consequence of the Plio-Pleistocene erosional pattern, which is of glacial origin.

1. Introduction

In historic time, the rate of uplift along the coasts of Fennoscandia has been so high that its effects were easily observed within one generation. Since the 18th century, the cause and the rate of displacement has been intensively discussed. At first, the phenomenon was variously explained in terms of global changes in sea level, changes in the earth's rotation or elevation of the crust. It was not until the middle of the 19th century that the theory of an 'Ice Age' was presented, and Jamieson (1865) was the first to see the Fennoscandian uplift as an evidence for a deformation of a non-rigid earth by an ice cap — 'glacial isostasy'.

The seismicity in Fennoscandia is remarkably high for an interior plate region, with high seismicity concentrated in regional areas. The mechanism for the seismic activity has been debated for many years. Kolderup (1930) presumed that the seismicity, to a large extent, was due to the postglacial uplift, Kvale (1960) on the other hand, argued against this explanation. Muir-Wood (2000) found that the observed seismicity favours a model with alternating quadrants of seismicity and aseismicity around the former forebulge and rebound dome. Gudmundsson (1999) has modelled the doming to improve our understanding of the associated stress field, with relation to Fennoscandia in particular. He found that one might expect strike slip or reverse faulting in the marginal parts, as a consequence of the postglacial uplift. Rohr-Torp (1994) substantiated the dome uplift and the predicted stresses of Fennoscandia with groundwater-flow measurements. Wu et al. (1999) find that the postglacial rebound is probably the cause of the large postglacial thrust faults observed in Fennoscandia, and that the ice-load history has large effects on the onset time of earthquakes and the magnitude of fault instability.

The aim of this paper is to identify a possible neotectonic component in the postglacial uplift and to quantify it by means of movement direction.

2. Earthquake activity

The earliest historical records of large ground shaking were written in documents intended for other purposes

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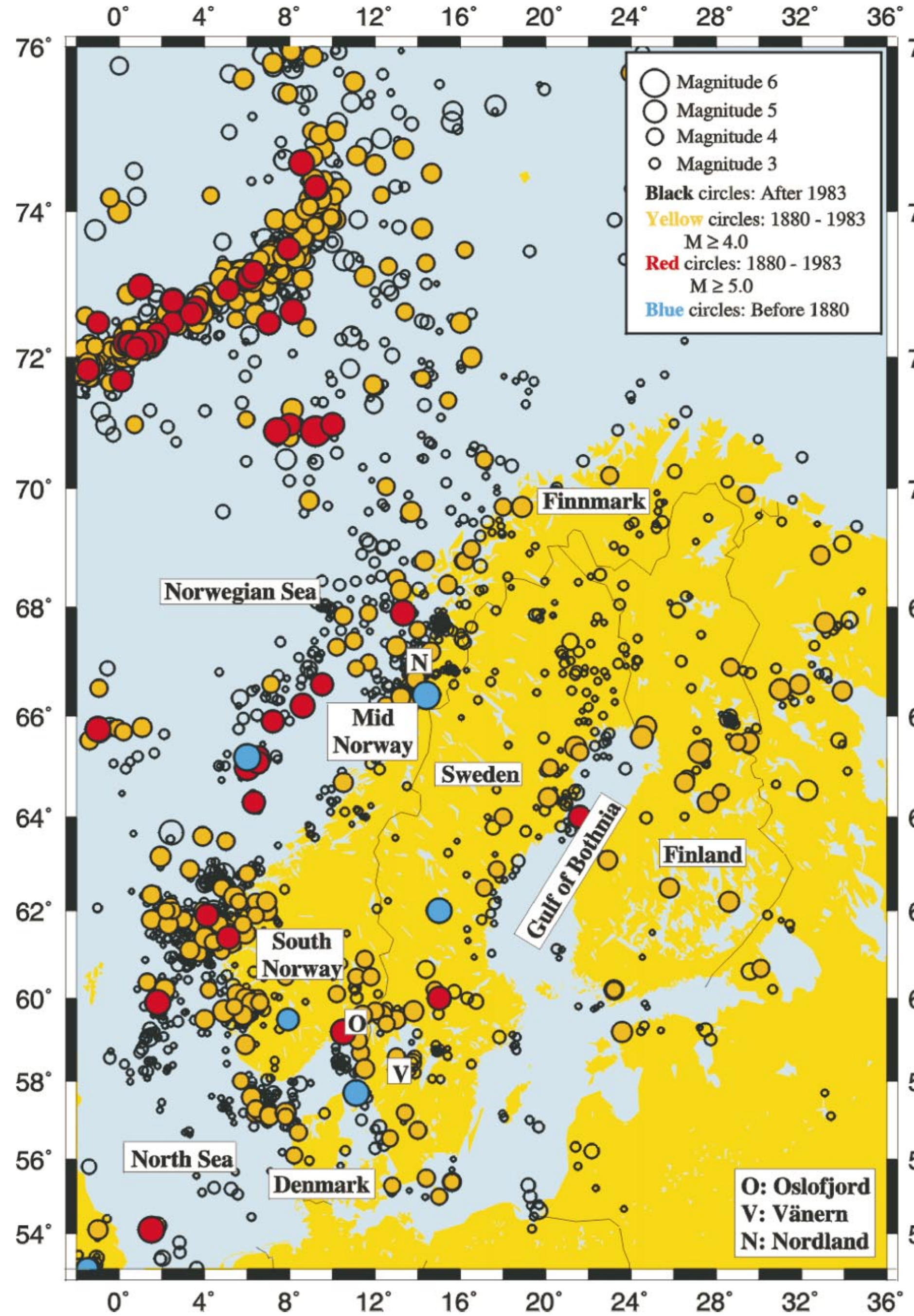

Fig. 1. Earthquakes in Fennoscandia during different periods of observation.

(parish records, etc.) and are of limited scientific value. The felt earthquakes were first recorded in a more systematic way at the end of the 19th century, and in the 1980s Norway installed the first sensitive electromagnetic seismographs capable of detecting microearthquakes (i.e. earthquakes not felt by people); around the same time, Sweden, Finland and Denmark made similar installations. With the low seismic activity of Scandinavia, our understanding of the Fennoscandian earthquake activity is largely based on 20 yr of microseismic data. Nevertheless, Fig. 1 shows how the Fennoscandian earthquake activity is clearly concentrated in certain regions, particularly in the offshore Norway sector of Western Fennoscandia. The highest activity in offshore Norway is found in a belt offshore mid Norway; and in the northern end of the North Sea. These areas regularly exhibits larger earthquakes ($M = 4$–5). The largest historical earthquakes (Rana, Nordland 1819 and Oslo 1904) occurred

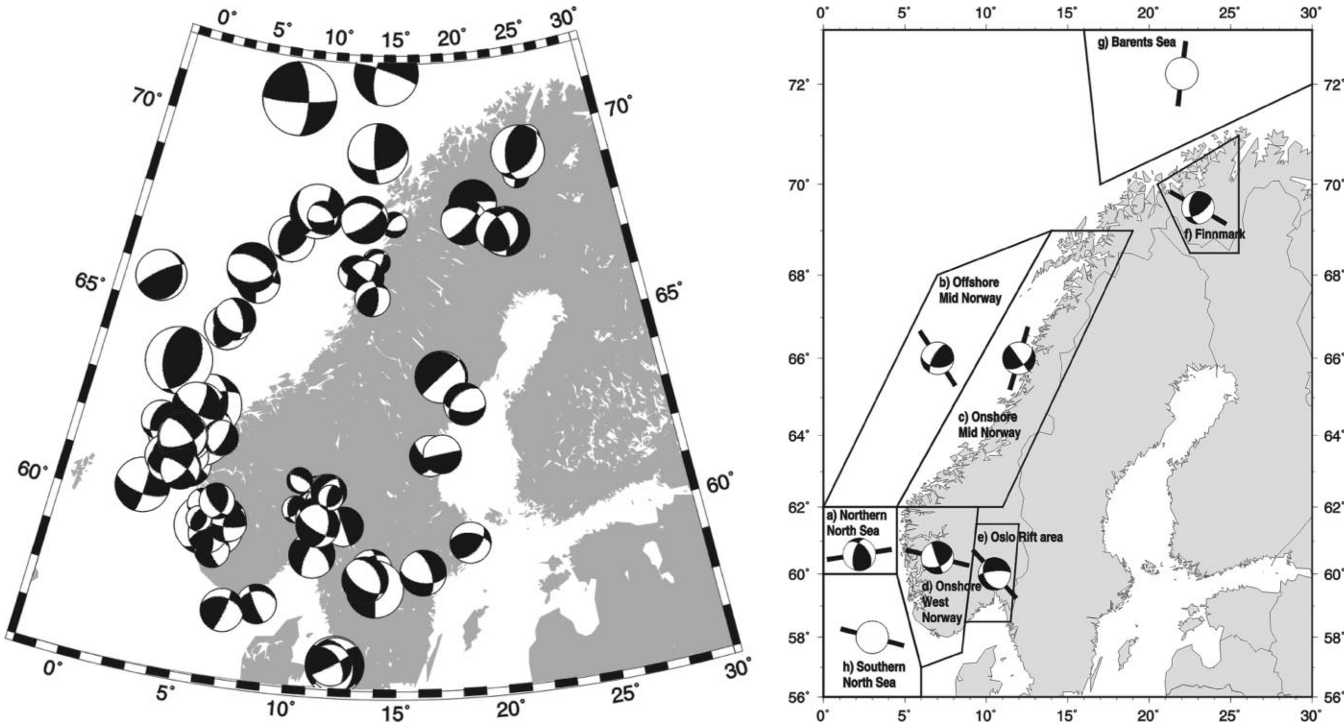

Fig. 2. (a) Earthquake focal mechanisms in Fennoscandia. Complete for Norwegian regions only, only selected from Sweden; (b) Directions of horizontal compression synthesized for selected Norwegian areas.

in areas that have been relatively quiet the past 20 yr. Onshore activity is characterized by lower activity and smaller magnitudes. These areas are the Nordland coast, western Norway coast, Oslofjord area, Vänern area, the Swedish coast of the Gulf of Bothnia and northwards towards Finnmark, and the zone in mid Finland.

3. Earthquake focal mechanisms: stresses and mode of faulting

The earthquake focal mechanism resolves the main stress directions and mode of deformation. An earthquake is generated through stress build-up and subsequent release, and if regional stress generating mechanisms dominate, this should be visible in the focal mechanisms. However, there are a range of local features (crustal strength, local stress deviation, etc.) that may influence the individual earthquake rupture. By grouping many focal mechanisms we attempt to reduce the impact of local features and, thereby, enhance the regional stress imprint and the regional tectonism. Over the last few years, increased deployment of seismic stations have allowed improved resolution and more detailed analysis. One of the major advances through this deployment is the increasing number of focal mechanisms that could be compiled, and as of 1999 more than 120 mechanisms have been computed for Norway and Sweden. Fig. 2 provides a synthesis of the compressional stress directions obtained from this focal-mechanism dataset. Fig. 2 shows that the regional stress consistency is generally good, and regionally consistent stresses are the only viable explanation for these data. This consistency is also reflected in the in situ data (Fejerskov and Lindholm, 2000).

4. Stress-generating mechanisms and observed horizontal stress

The forces acting on the crust cause the observed stresses, and these stresses may be differentiated with respect to origin and lateral extent (Sykes and Sbar, 1974; Engelder, 1994). According to Zoback (1992) the general situation is that the observed stress is composed of plate-wide continental stress overprinted by regional and local effects. For Scandinavia, there may be a number of stress-generating mechanisms that act together which can be grouped into classes reflecting their lateral extension (following Fejerskov and Lindholm, 2000). The first-order stresses in Fennoscandia are generally attributed to forces at the plate margins under the assumption of an elastic lithosphere in which stresses can propagate. The nearest plate margin is the mid-Atlantic ridge, and the dominance of NW–SE compression subnormal to the mid Atlantic ridge is found throughout Scandinavia (e.g. Stephansson, 1988). The second-order

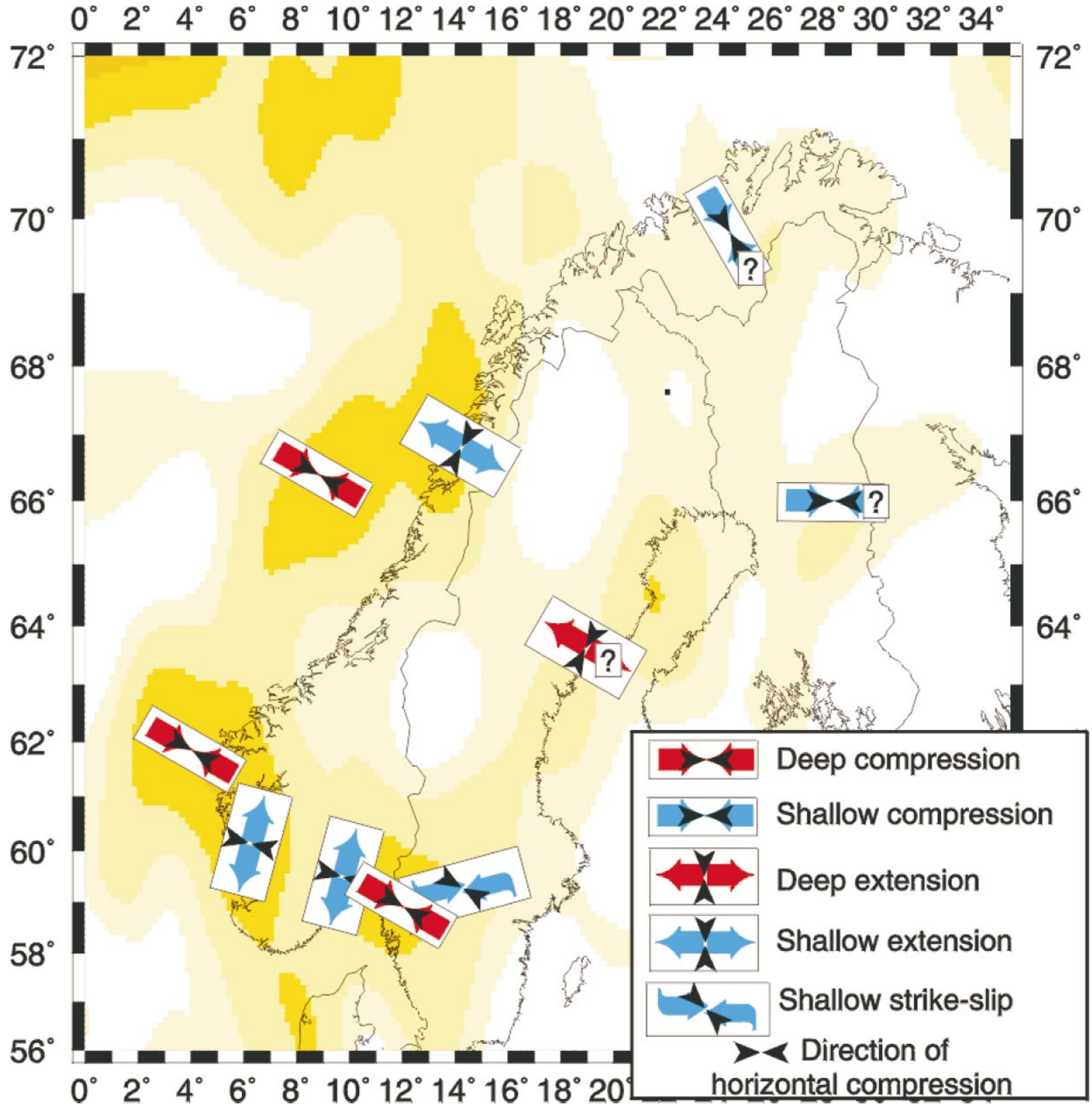

Fig. 3. Stress directions, type of faulting and focal depths synthesized from earthquake focal mechanisms and in situ stress measurements. Areas of less data are indicated with questionmarks. Intensity of yellow indicates intensity of seismicity (from Hicks et al., 2000).

stresses are more limited in extent (covering up to Scandinavia as a whole), whereas the third-order stresses relate to local features and rarely extend beyond ~ 100 km (Table 1).

Fejerskov and Lindholm (2000) modelled the ridge-push force based on elevation of the ridge and age of the crust, and compared stress magnitudes from this source with stress magnitudes originating from glacial rebound, crustal flexures and topographic effects. The results indicated the first-order plate margin stresses (ridge push) to be of major importance. However, sediment loading (offshore) and topography may also be important secondary stresses. The modelling did not indicate high stress magnitudes from deglaciation flexures. However, the lateral extent of this mechanism combined with the Zatsepin and Crampin (1997) model, which allow deformations at very small deviatoric stress levels, may again increase the recognition of this stress source.

Fig. 3 synthesises the main trends of Figs. 1 and 2 in terms of seismic activity, type of faulting and direction of horizontal compression. Where the amount of data is large, as in offshore western Norway, the synthesis in Fig. 3 is quite reliable. However, in areas of lower seismic activity or offshore far from the seismic stations, the synthesis drawn in Fig. 3 is more tentative. From Fig. 3, two remarkable trends can be seen. Firstly, deep earth-

Table 1
Stress-generating mechanisms

Stress field	Lateral endurance	Stress-generating mechanism
First order (continental)	1000 km	Plate tectonic forces Ridge push Slab pull Basal drag
Second order (regional)	100–1000 km	Large-scale density Inhomogeneities COB Flexural stresses Deglaciation Sediment loading Major topographic loads
Third order (local)	< 100 km	Topography Fjords Mountain ranges Geological features Faults Rock inclusions

quakes occur mainly offshore. They are dominated by reverse faulting and reflect stress directions that can be attributed to the mid-Atlantic ridge push (NW – SE). Secondly, shallow earthquakes occur predominantly onshore. Normal faulting (extentional deformation) is dominant and the direction of horizontal tension is largely coast perpendicular (for Norway).

5. Postglacial uplift and model parameters

Data on postglacial uplift can be considered in two ways: (1) present rate of uplift; and (2) shoreline tilts versus time. These observations are mainly results of the movements of the solid Earth, they are scarcely affected by movements of the sea level. The movements of the solid Earth are assumed here to have a glacial isostatic origin connected to the melting of the last ice sheets. It is, however, not unreasonable to assume that there is a neotectonic component in the uplift rate and the palaeo-shoreline gradients. The general pattern of the uplift is believed to be a result of glacial isostasy, but there may be local disturbances to this general pattern caused by tectonic processes.

The dome-like present rate of uplift in Fennoscandia is now generally explained in terms of glacial isostasy. Previously, Fjeldskaar (1994, 1997) modelled the isostatic response to deglaciation in Fennoscandia using an Earth model with a layered mantle viscosity overlain by an elastic lithosphere. The modelling is based on the mapped deglaciation. The melting history used previously, is compiled by B.G. Andersen and presented in Denton and Hughes (1981). The modelling was further based on a spatial resolution of approximately 50×50 km.

The modelled tilting of palaeo-shorelines at particular locations peripheral to the former ice load and the pattern of present rate of uplift are consistent and suggest a low-viscosity asthenosphere. It is suggested that the asthenosphere has a thickness less than 150 km and viscosity less than 7.0×10^{19} Pa s beneath the lithosphere. The mantle viscosity below the asthenosphere has been set to 10^{21} Pa s.

The most likely glacier thickness model gives a flexural rigidity of 10^{23} N m ($t_e \approx 20$ km) at the Norwegian coast, increasing to above 10^{24} N m ($t_e \approx 50$ km) in central parts of Fennoscandia.

6. Present rate of uplift

The present rate of uplift in Fennoscandia was calculated using data from tide-gauges, precise levelling, and GPS and gravity measurements. Uplift rates calculated from repeated precise levelling along roads throughout Norway, Sweden and Finland make up the bulk of the data. Levelling results from the northern part of Finland have been used, together with the 1, the 2, and a few lines from the 3rd precision levelling of Sweden. Data from all available Norwegian precision levelling lines were used, including the lines measured by surveyors from the Norwegian Railways (Danielsen, pers. comm.). The levelling lines are tied to tide-gauges along the coast. Additional tide gauge records from around the Baltic Sea (Ekman, 1998) helped constrain the regional uplift pattern. Between 1966 and 1984, repeated precise gravity

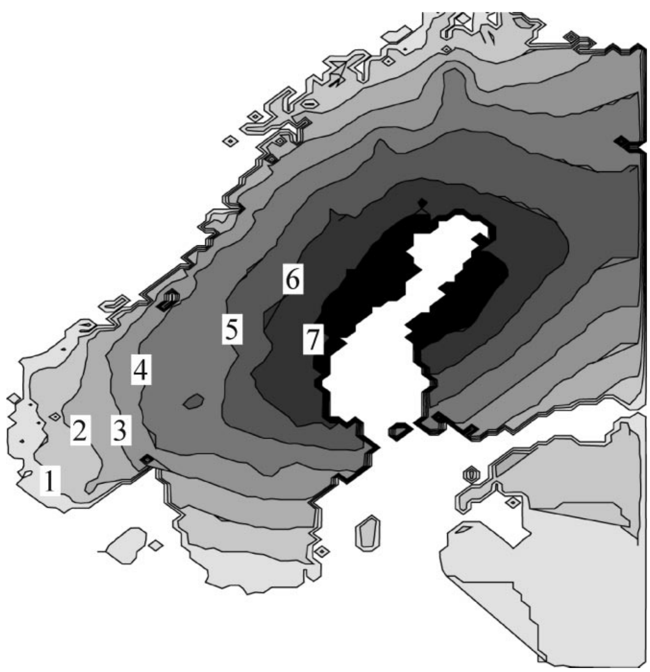

Fig. 4. Observed present rate of uplift. Contour interval is 1 mm/yr.

measurements were performed on three lines across Norway, Sweden and Finland to determine the rate of uplift (Mäkinen et al., 1986). Permanent GPS stations located in Sweden and Finland have also provided measurements of uplift rate (Ekman, 1998).

Uplift data from all sources were combined and gridded using a minimum curvature method. The resulting high-resolution grid shows areas of local disturbances (Fig. 4). The rate of uplift is close to zero along the Norwegian coast, increasing up to 8 mm/yr in central parts of the Baltic Sea. It is, however, not unreasonable to assume that there is a neotectonic (i.e. non-glacial-isostatic) component in the uplift rate and the palaeo-shoreline gradients. The general pattern of the uplift is here believed to be a result of glacial isostasy, but there may be local disturbances to this general pattern caused by tectonic processes.

The model that best fits with the observations is expected to give a good regional image of the glacial isostatic process. There will, however, be local areas with significant differences between the observations and the calculated uplift. One of the basic assumptions in this study is that these anomalous areas are today subject to vertical deformations of non-glacial-isostatic origin.

7. Neotectonics

A new modelling based on the above concepts was constructed, but with higher spatial resolution, approximately 20×20 km. A modified ice model for 20,000 BP was developed (Fig. 5), partly based on data from Svendsen et al. (1999), and the present topography in Scandinavia was also taken into account in the modelling (Fig. 6).

The net glacier thicknesses for various glacial times were the ice models of Fig. 5 minus the palaeo-topography. The palaeo-topography is calculated as the present topography modified by the glacial isostasy at the various time steps, calculated by the Earth rheology parameters mentioned above. The calculated uplift history for different times is shown in Fig. 7. Note the development of the forebulge offshore mid Norway. The resulting palaeo-topography is shown in Fig. 8. The calculated

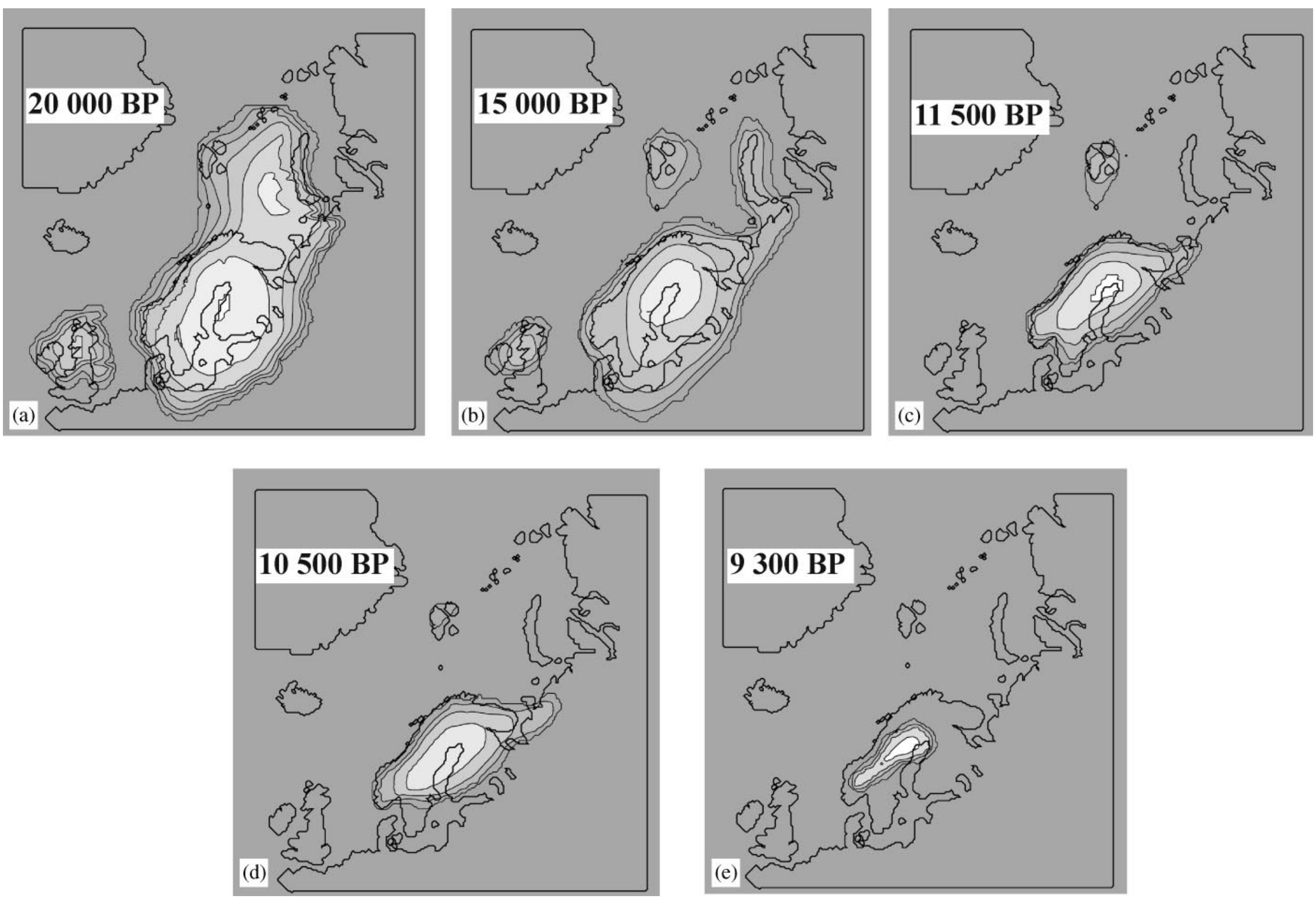

Fig. 5. The extent and thickness of the ice sheet during the deglaciation in Northern Europe partly based on Denton and Hughes (1981): (a) 20,000 yr BP, (b) 15,000 yr BP, (c) 11,500 yr BP, (d) 10,500 yr BP, and (e) 9300 yr BP Contour interval is 500 m, except for (e), where the contour interval is 200 m.

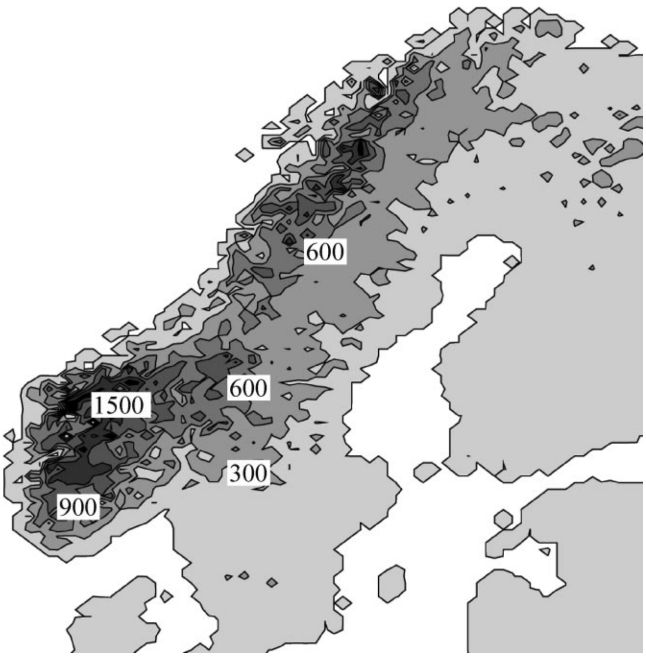

Fig. 6. Present-day topography in Scandinavia (spatial resolution 20 × 20 km).

present rate of uplift in Fennoscandia is shown in Fig. 9, which is the model that best fits the observations.

The uplift residuals are calculated only for land areas, and for Norway and Sweden, only. The areas with significant positive deviations (> 1.0 mm/yr) between the observations and the calculated uplift are shown in Fig. 10, where it is seen that almost the entire Norwegian land area has abnormal uplift rates. The most significant residuals (> 1.5 mm/yr), however, are located in the mountainous areas onshore mid-Norway and northern part of western Norway. These areas correspond largely with the areas of high Plio-Pleistocene (last 2.5 million yr) erosion (Riis and Fjeldskaar, 1992). The Plio-Pleistocene erosion is assumed to be of glacial origin. Even though the estimated erosion is expected to have been largest in the early part of the Plio-Pleistocene (because the earliest ice ages were the biggest), a significant part of the subsequent uplift may seem to take place up to present. If this is correct, the mountain building process in Norway is a slow process, possibly connected to phase boundary migration (Riis and Fjeldskaar, 1992).

Fig. 11 shows that there is an area of significant negative (> 0.5 mm/yr) residuals onshore northern part of the Baltic Sea, and, less pronounced, southwards on the eastern coast of Sweden. This area corresponds to area of no Plio-Pleistocene erosion (Riis and Fjeldskaar, 1992). The Baltic Sea area constitutes a bulge area during the uplift of the surrounding land areas, because of the concentric erosional pattern of a central depression, marginal highs and huge sedimentary wedges made by continental ice sheets, as first pointed out by White (1972).

There are three areas of significant anomalies in Scandinavia, relative to regionally predicted glacial rebound: (1) onshore mid Norway; (2) onshore western Norway, including the zone from western to southeastern Norway; and (3) the onshore area around the Gulf of Bothnia.

8. Discussion

The neotectonic movements resulting from the above calculations are based on several factors. Firstly, it is assumed that the observed present rate of uplift is mainly a postglacial phenomenon caused by isostatic adjustments following the melting of the Late Weichselian ice sheet. This is the most critical assumption, and not necessarily a correct one. Mörner (1979) proposed that the observed postglacial uplift consists of two different components, one linear and one exponential. The linear component is assumed to have a tectonic origin and the exponential is assumed to be of glacial isostatic origin. He argues that the present rate of uplift is not a glacial isostatic phenomenon, but rather a tectonic process, with linear uplift rate. The arguments are based on an inferred change from exponential to linear uplift with time. However, the time resolution and precision of these curves are relatively low, and the arguments of Mörner are hence disputed.

The basis for this study is that present rate of uplift is mainly of glacial isostatic origin. The reason for this assumption is the consistent picture given by the observations of the deglaciation, palaeo-shoreline tilts and present rate of uplift. It is highly unlikely that a tectonic process would give a maximum present rate of uplift in the same geographical location as predicted from the observations of the deglaciation. It has been shown previously (e.g. Fjeldskaar, 1997) that the best-fitting parameters for palaeo-shoreline tilts also is the best-fitting parameters for the present rate of uplift.

Fig. 9 shows the uplift over the wider Fennoscandian domain, including the forebulge of offshore western Norway. The modelling predicts the transition zone between uplift and subsidence to be located just offshore, and in this zone the bending (stress) of the crust will be at its maximum. The high seismic activity offshore mid Norway may reflect this maximum bending with horizontal compression in a NW–SE direction. Additionally the horizontal compression originating at the mid-Atlantic ridge gives rise to similar stress directions. Finally the observation of shallow normal faulting earthquakes along the coast in the onshore areas are also in accord with expectations from the isostatic rebound model.

We have in this paper assumed that 100% of the regional part of the uplift is of glacial isostatic origin. This may be wrong. However, a sensitivity test shows

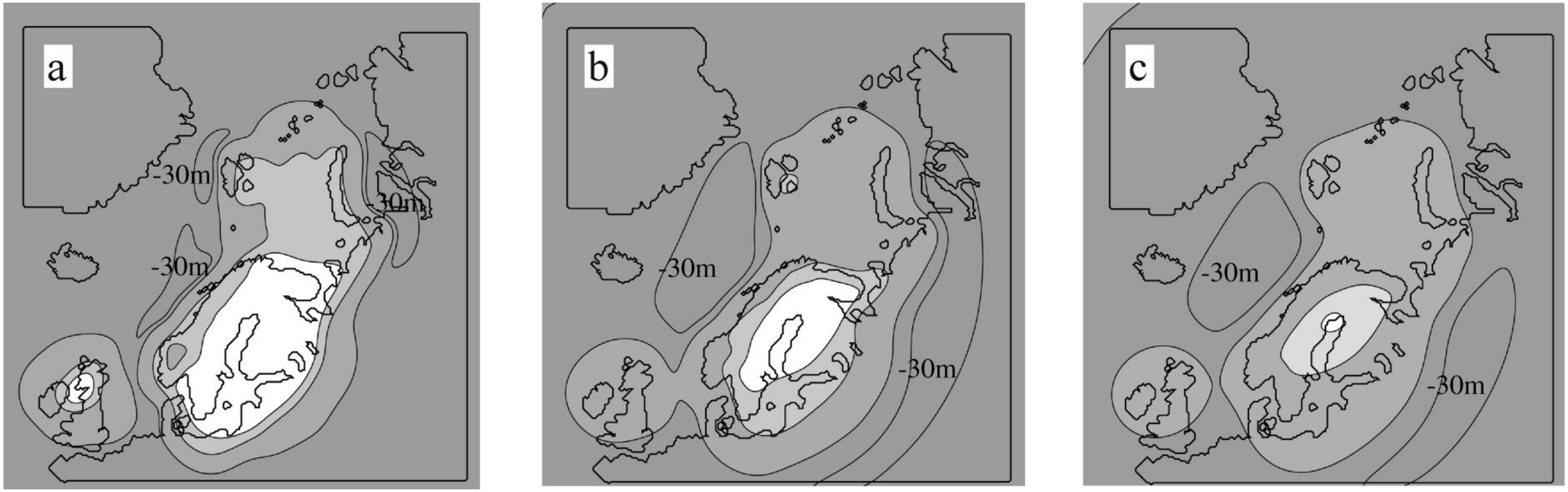

Fig. 7. Theoretical uplift response in meters for glacial and post-glacial time: a) 15000 BP, b) 12000 BP and c) 9000 BP. Contours are given for — 30 m (forebulges), 0 m, 300 m, 500 m and 1000 m.

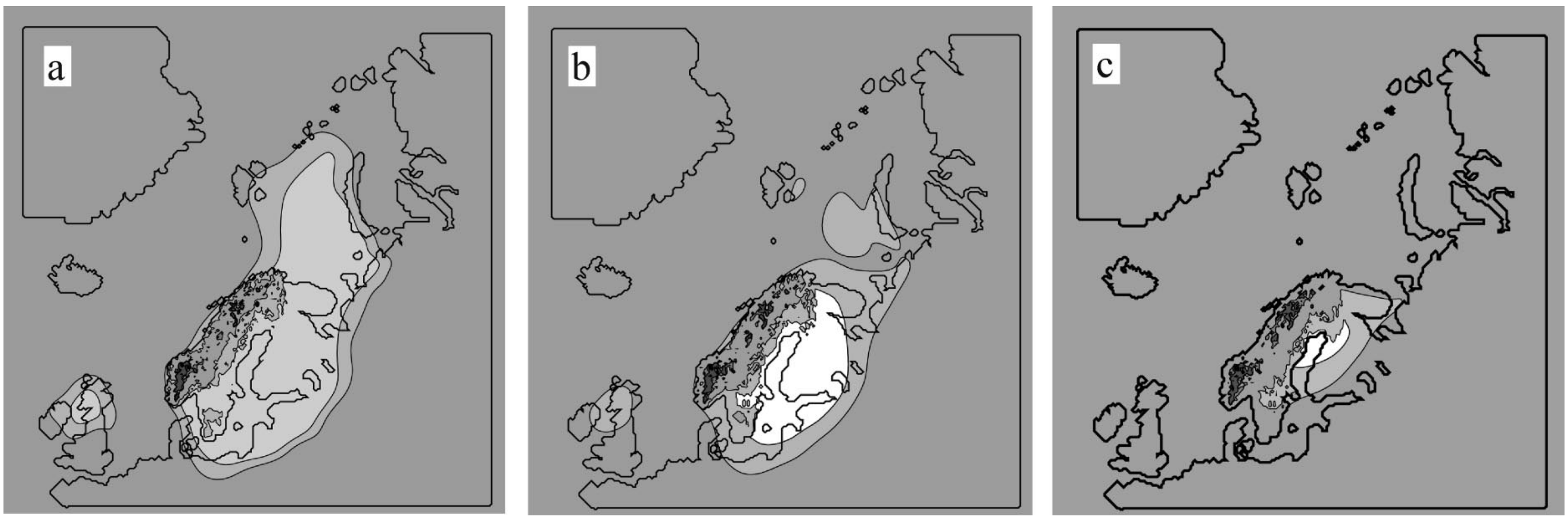

Fig. 8. Calculated palaeo-topography is assumed to be the present topography modified by glacial isostasy for the various time step: a) 15000 BP, b) 12000 BP and c) 9000 BP. The glacial isostasy is calculated with the earth parameters mentioned above. Light areas indicate areas from 0 to 300 m below present sea level, dark areas more than 300 m above the present sea level.

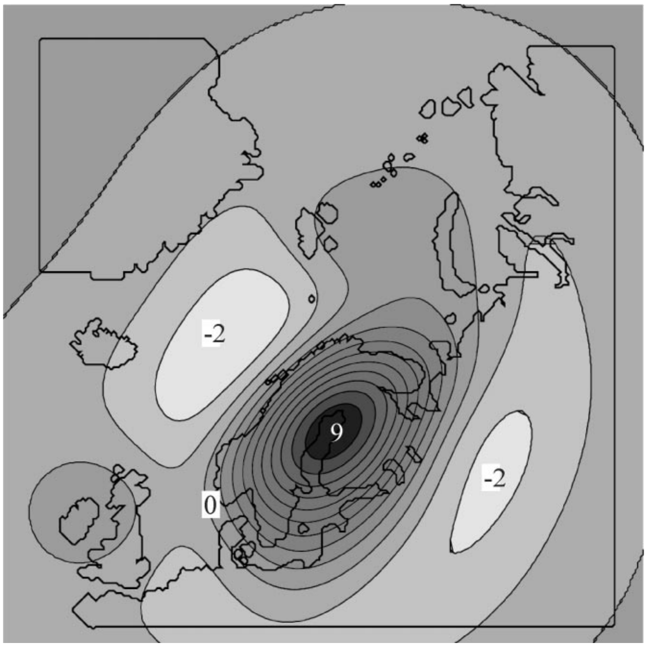

Fig. 9. Theoretical present rate of uplift in Fennoscandia.

Fig. 11. Areas with significant negative deviations (> 1.0 mm/yr) between the observations and the calculated glacial isostatic uplift.

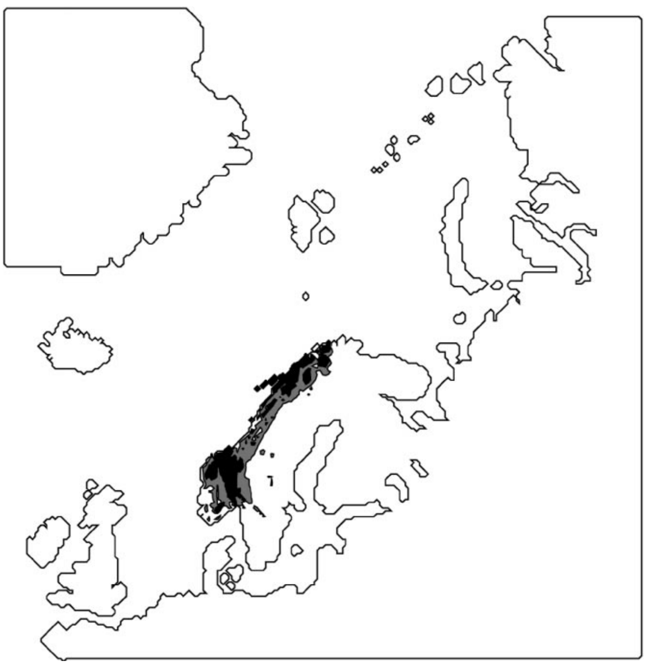

Fig. 10. Areas with significant positive deviations (> 1.0 mm/yr) between the observations and the calculated glacial isostatic uplift.

that if only 80% of the regional uplift dome has a glacial isostatic origin, we would still have the same anomalies (i.e. neotectonic movements) in the regions.

The quality and density of empirical data is crucial in any investigation: The uplift data, from which the uplift curves are constructed, are unevenly distributed, stemming from different methods and varying (and sometimes large) uncertainties. The possible incorrectness of these data or the synthesised uplift curves inevitably will affect the modelling results. The overall fit indicates that the data are reliable on the Fennoscandian scale, but it is presently not possible to resolve whether some of the deviations between model and observation reflect poor data.

9. Conclusions

We have demonstrated that the Earth's response to the deglaciation in Fennoscandia can be modelled using a layered viscous model overlain by an elastic lithosphere, and that the model response to the ice load is able to explain the regional uplift pattern to a considerable degree. The modelling has depicted certain areas with anomalous uplift rates in the order of 1.0 mm/yr (southern Norway, along the coast of northern Norway and in the Bothnian Bay). One interpretation is that the glacial isostatic uplift in these areas is overprinted by a weak tectonic uplift component.

The seismicity in Scandinavia, which is the highest in northwestern Europe, is largely concentrated in a few zones. In particular, the offshore seismicity zones west of Norway correspond to zones where the uplift model predicts forebulges (compression), and this NW–SE compression would act constructively with ridge-push-generated compression. Furthermore, the shallow onshore (but coastal) normal faulting closely follows the Younger Dryas ice margin (10 500 BP), thereby indicating the importance of the deglaciation for present-day seismicity, and in full accord with the glacial isostatic rebound model. In conclusion, the findings support the idea that the stresses in western Scandinavia have two important components that interact constructively: postglacial uplift and ridge push.

One idea supported by this investigation is that the Scandinavian peninsula is subject to a tilting with uplift to the west and subsidence to the east. The model anomalies reveal a zone of relative subsidence along the eastern Swedish coast and northwards which geographically coincide with the weak seismicity zones in Fig. 3. However, the quality of the horizontal compression with depth (both magnitude and direction) in these areas is too uncertain to allow sound conclusions. Nevertheless, the apparent tilting may be a consequence of the Plio-Pleistocene erosional pattern, which is of glacial origin. The erosion has supposedly a maximum (marginal highs) in the mountainous areas of Norway (southern and northern Norway), and there will be a pronounced central depression in the Gulf of Bothnia. This is supported by the present investigation, both in terms of seismicity and calculated uplift residuals.

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