# An isostatic test of the hypothesis of ice-free mountain areas during the last glaciation

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There has long been a discussion on whether parts of the highest mountains of Norway were totally ice-covered, or if ice-free areas existed during the Late Weichselian glacial maximum. In this study the hypothesis of a very thin ice sheet was tested by modelling the isostatic response, using an Earth model with layered mantle viscosity overlain by an elastic lithosphere. The theoretical pattern of the present rate of uplift and the tilting history for the western coast of Norway based on a thin ice model show significant deviations from the observations, which seems to rule out the thin ice model as a viable option. However, this is based on the assumption that the present Fennoscandian uplift is caused by glacial isostasy alone. If there really existed large ice-free areas in the highest mountains of Norway in the last glacial maximum, the present Fennoscandian uplift must be ascribed to another mechanism in addition to glacial isostasy.

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## Introduction

The ice age theory was first presented by Agassiz (1837). From the time it became apparent that the northern countries had been glaciated, there has been a discussion of the extent and thickness of the ice sheet. Analogies with data from the Greenland and Antarctic ice sheets, which first became available 50 years ago (cf., e.g. Paterson 1994), indicated much thicker ice sheets than previously believed.

For many years there has been a discussion among botanists and geologists on whether parts of the highest mountains of Norway had been ice-covered, or if ice-free areas existed during the Late Weichselian glacial maximum (e.g. Blytt 1876; Dahl 1949; Mangerud 1973; Nesje et al. 1988; Birks 1994). Nesje & Dahl (1990) found that the geographical and altitudinal distribution of autochtonous block fields and trimlines in southern Norway indicates a low-gradient, multicentred, asymmetric Scandinavian ice sheet. According to their model, the highest mountain areas in Norway were ice free and the maximum ice thicknesses were around 1500 m, with the highest ice-sheet culmination about 2000 m above the present sea level (in Jotunheimen).

Important understanding of the ice sheet has also been achieved through modelling of the glaciological processes. The deformation of ice can be described in terms of conservation laws and mechanical principles (e.g. Nye 1952). Recent modelling (Ehlers 1990; Holmlund & Fastook 1993) has shown that the Fennoscandian ice sheet must have been thick (more than 2500 m).

This aim of this study is to test isostatically whether the hypothesis of a thin ice model (with ice-free mountains) is a viable option.

## Model approach

The Earth is modelled by a half-space with constant gravitation and adiabatic density gradients in a Newtonian mantle in which the viscosity may vary with depth. The viscous fluid is overlain by an elastic lithosphere of constant thickness. With this flat Earth model, we are able to treat the isostatic problem analytically, by the Fourier transform technique. The method used here is described in detail in Fjeldskaar & Cathles (1991a).

## Hydroisostasy

The movement of the ocean bottom caused by the variation in sea level is calculated separately using the same viscosity structure as for the glacial isostasy. The land–ocean distribution during the deglaciation is assumed to be

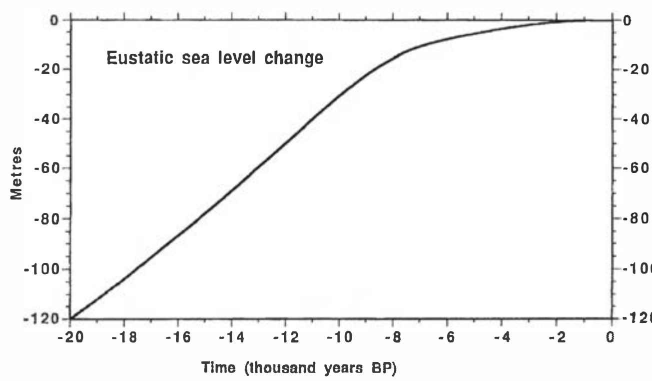


*Fig. 1.* Eustatic sea level curve used to calculate the hydroisostatic effect. The curve mimics the eustatic sea level change according to Shepard (1963).

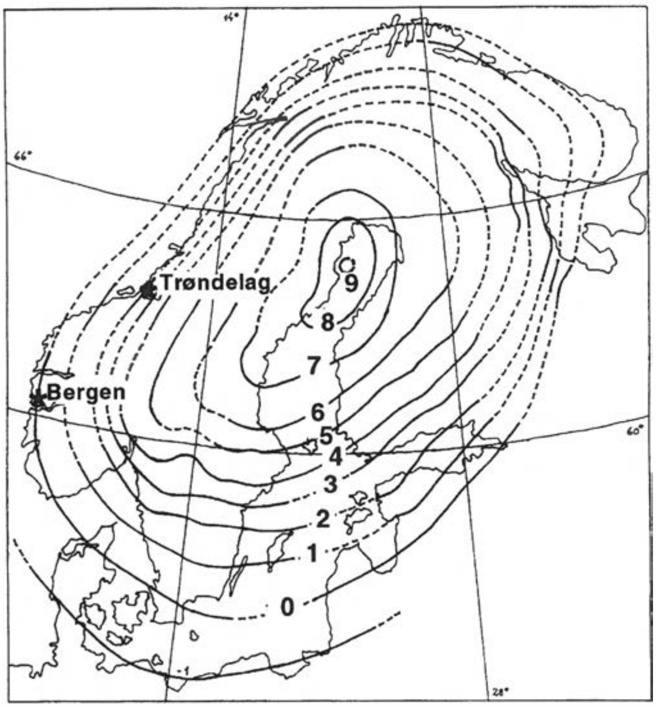


*Fig. 2.* Observed apparent present rate of uplift in mm/year. After Ekman (1996).

as at present. The late-glacial and postglacial change in sea level, assumed to take place outside the present land area (Fig. 1), is in accordance with published eustatic curves for late-glacial and postglacial time (e.g. Shepard 1963).

## Observed uplift

The observed present rate of uplift in Scandinavia relative to mean sea level shows an increase from 0 mm/yr at the western coast of Norway to 9 mm/yr in the Baltic Sea (Fig. 2). The standard errors are typically around 0.2 mm/yr (Ekman 1993). To obtain the uplift of the crust relative to the Earth's centre rather than relative to mean sea level, the uplift rate has to be corrected for eustatic changes. This involves (1) a correction for the gravitational effect of the uplift and (2) a correction for the uniform eustatic sea level change. The uniform eustatic component would, probably, add approximately 1 mm (cf. Nakiboglu & Lambeck 1991) to the numbers given in Fig. 2. The theoretical gravimetric effect of the present rate of uplift gave a maximum geoidal rise of 0.47 mm/yr in the central Baltic Sea (Fjeldskaar & Cathles 1991b). The uplift of the crust relative to the Earth's centre is thus the sum of present rate of uplift, the uniform eustatic component and the gravimetric effect, amounting to 10.5 mm/year in central Fennoscandia.

The late- and post-glacial uplift is mapped by shore-level displacement or shoreline diagrams. The shoreline diagrams give the observed shoreline tilting versus time. In this study we have used curves from two locations, from Bergen and Trøndelag, on the western coast of Norway (for location, see Fig. 2). The uncertainty in the determination of the gradients is probably less than 0.15 m/km (Fjeldskaar 1994). The reason for using curves of shoreline tilt, and not shoreline displacement curves, is that the shoreline tilts are not (or at least insignificantly) influenced by movements of the ocean surface. Hydroisostasy will not be of significance for the palaeo-shoreline tilt, compared to the glacial isostasy.

## Best fitting Earth rheology

Modelling of palaeo shorelines and pattern of present rate of uplift has been reported by this author in several publications (e.g. Fjeldskaar & Cathles 1991a, b; Fjeldskaar 1994; Fjeldskaar 1997). The modelling has been done based, to a large extent, on the Denton & Hughes (1981) deglaciation model (Fig. 3). In Fjeldskaar (1997), however, five ice thickness models were run: our preferred and most likely model (Fig. 3), two thinner ice models (75% and 85% of the ice thicknesses of model of Fig. 3), and two thicker ice models (25% and 50% thicker ice than model of Fig. 3).

With the assumption of a present-day rate of uplift in the central Baltic Sea of approximately 10 mm/yr, the asthenospheric viscosity will be different for the five ice models. For example, our preferred model gives a fit with the observed maximum present rate of uplift (Fig. 4a) and observed tilts of palaeo shorelines in Norway (Fig. 4b, c) using a mantle viscosity of $10^{21}$ Pa s overlain by a 75 km asthenosphere of viscosity $1.3 \times 10^{19}$ Pa s. The lithosphere rigidity is close to $10^{23}$ Nm (elastic thickness $t_e = 20$ km).

It was also concluded, based on the present rate of uplift and palaeo shoreline tilts, that the minimum ice thickness model (75% of the most likely model; Fig. 3) was on the lower range of what is reasonable for the maximum Late Weichselian ice thickness.

## Ice-sheet model with ice-free mountains

The ice-sheet model with ice-free mountains used here (see Fig. 5) is based on Nesje & Dahl (1990). Their published ice model, significantly thinner than other ice-sheet models, is used for maximum Late Weichselian glaciation in Fennoscandia. For modelling purposes it is assumed that this ice sheet was unchanged up to 12,000 yr BP, followed by a linear melting to 9300 BP (see Fig. 3e). The area was supposedly ice free at 8500 yr BP. The density of the glacier ice is 917 kg $m^{-3}$.

## Present rate of uplift

In the modelling with the thin ice sheet, we assume that the mantle viscosity is $10^{21}$ Pa s, overlain by a low viscosity asthenosphere. In the modelling the maximum present uplift rate in the Baltic Sea is kept close to 10 mm/yr (matching the observations). This is done by adjusting the

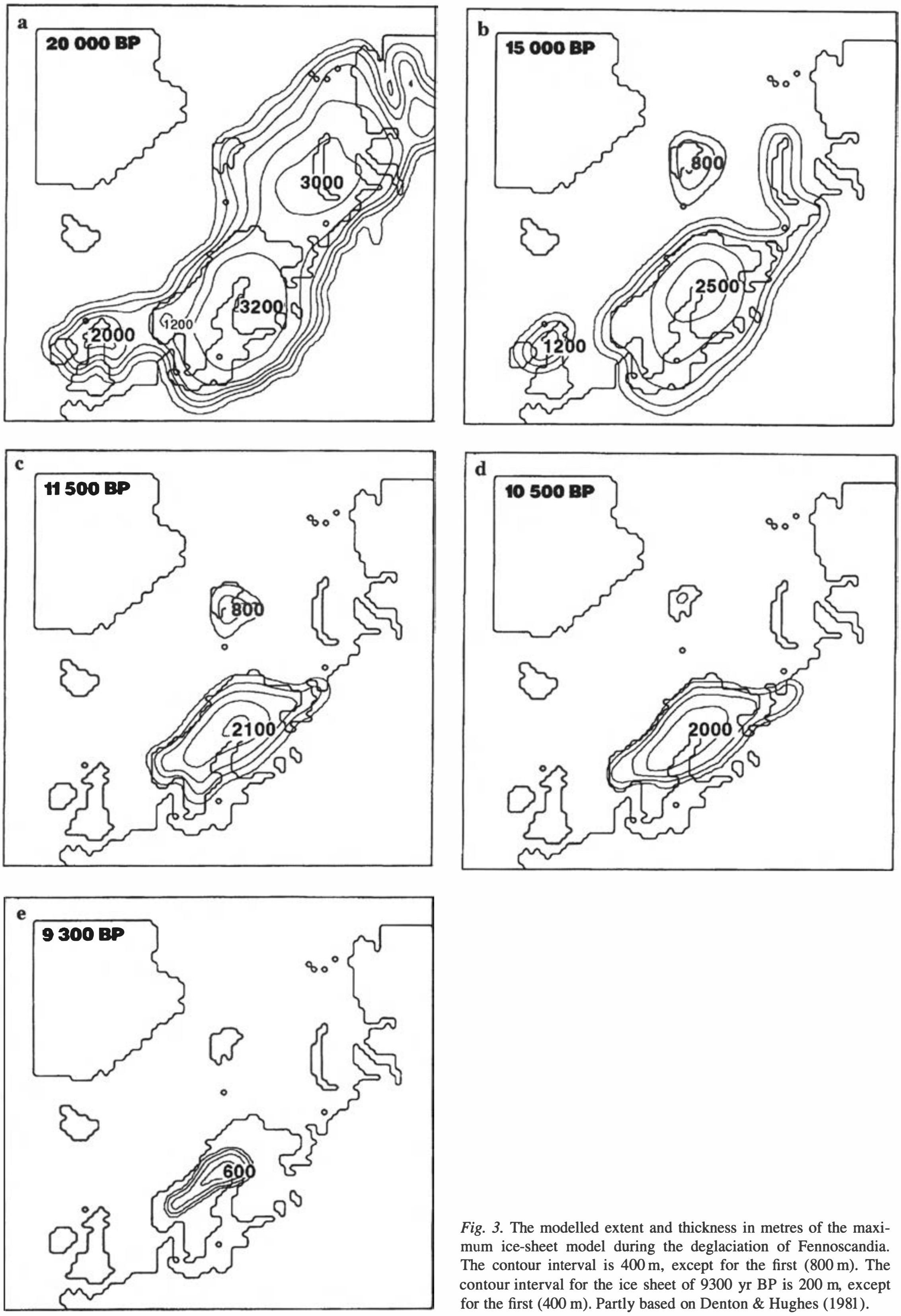


*Fig. 3.* The modelled extent and thickness in metres of the maximum ice-sheet model during the deglaciation of Fennoscandia. The contour interval is 400 m, except for the first (800 m). The contour interval for the ice sheet of 9300 yr BP is 200 m, except for the first (400 m). Partly based on Denton & Hughes (1981).

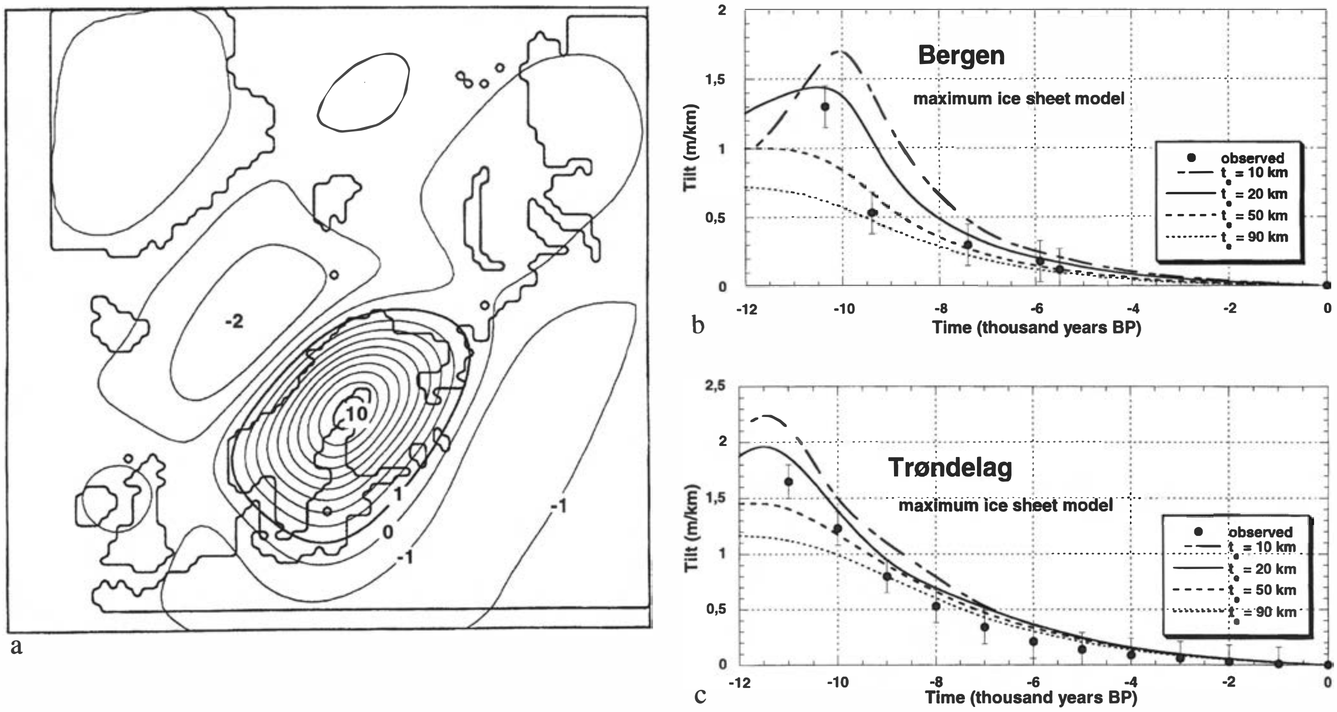


*Fig. 4.* (a) Theoretical present rate of uplift (mm/yr). $10^{21}$ Pa s mantle with a 75 km thick asthenosphere. Note that the 1mm/yr-contour (the solid thick line) is to be compared with the observed apparent 0-contour uplift (Fig. 2). (b) Theoretical versus observed (Kaland 1984) shoreline tilting for Bergen. (c) Theoretical versus observed (Kjemperud 1986) shoreline tilting for Trøndelag.

viscosity of the asthenosphere until an uplift rate close to 10 mm/yr is achieved. For the thin ice model the resulting asthenosphere viscosity turns out to be close to $7 \times 10^{19}$ Pa s. The theoretical present rate of uplift has a pattern in the peripheral areas that is quite different from what is observed (Fig. 6). The spacing of the uplift isolines is extremely uneven, which is contrary to the observations. Tuning of the elastic parameters or the viscosity structure, within the acceptable limits (as mentioned above, the maximum present rate of uplift is kept at 10 mm/yr), will not change the pattern of the present rate of uplift.

## Tilting of palaeo shorelines

The theoretical tilting of palaeo shorelines based on the above Earth rheology is calculated for the Trøndelag and Bergen areas. The tilts caused by the thin ice-sheet model are less than 50% of what is observed in late-glacial time in these two areas (Fig. 7a, b). It is also demonstrated that changing the elastic thickness of the lithosphere does not give a significant better fit to the observations.

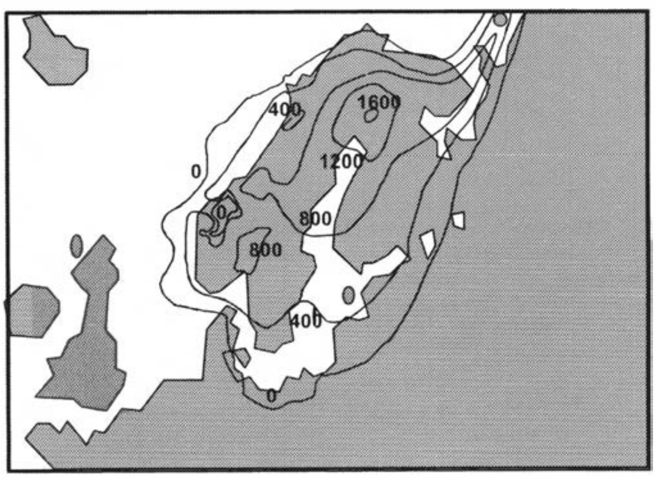


*Fig. 5.* The extent and thickness in metres of the ice sheet of maximum glaciation in Fennoscandia, partly based on Nesje & Dahl (1990).

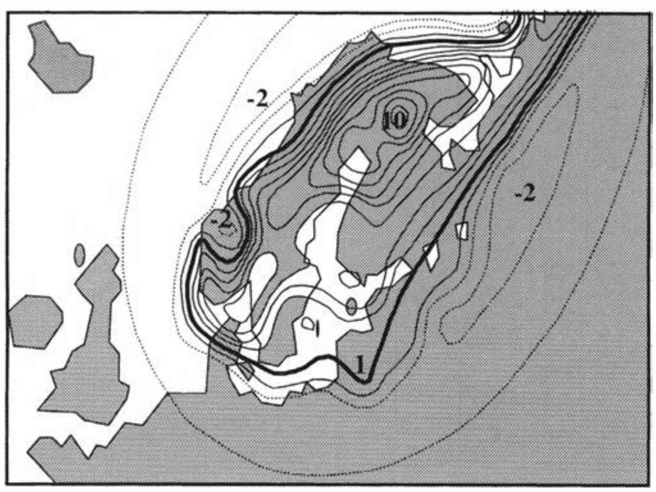


*Fig. 6.* Theoretical present rate of uplift based on the best-fit Earth model: a mantle viscosity of $1.0 \times 10^{21}$ Pa s, a 75 km thick asthenosphere of viscosity $7 \times 10^{19}$ Pa s and a lithosphere of flexural rigidity $10^{23}$ Nm. Please note that the 1 mm/yr-contour is to be compared with the observed apparent 0-contour uplift (Fig. 2).

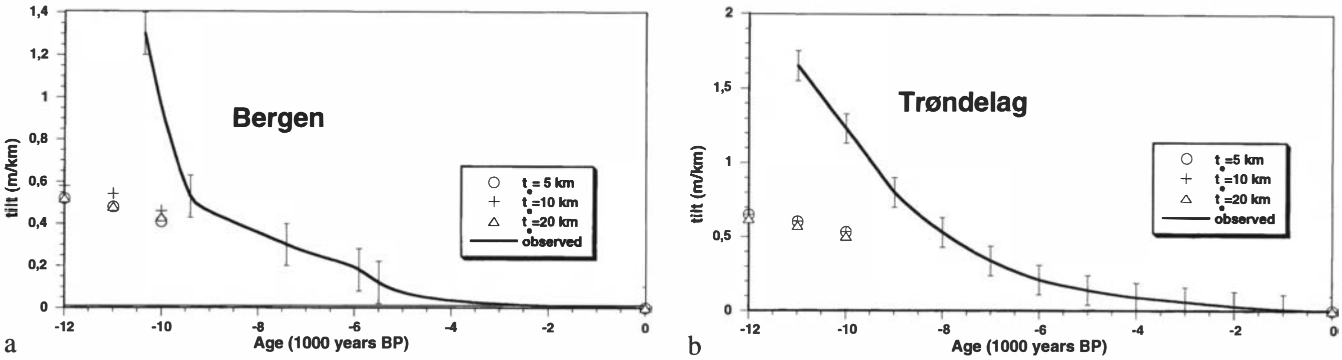


*Fig. 7.* Observed (from Kaland 1984; Kjemperud 1986) and theoretical shoreline tilting for the Bergen (a) and Trøndelag (b) areas. The theoretical shoreline tilting is calculated for a mantle viscosity of $1.0 \times 10^{21}$ Pa s, a 75 km thick asthenosphere of viscosity $7 \times 10^{19}$ Pa s and elastic thickness of the lithosphere of 5, 10 and 20 km (a flexural rigidity of 0.01, 0.1 and $1.0 \times 10^{23}$ Nm), respectively.

## Discussion

There is clearly a discrepancy between the observed data and the theoretical values based on the ice-sheet model with ice-free mountains. The reasons for this can be grouped into two sets. The first is connected to the modelling; the second to the assumption that the entire post-glacial uplift is caused by glacial isostasy.

1. The earth model rheology used in the calculations is not the only possible solution. Could alternative Earth models give a different result? Based on the arguments below, the answer to the question is negative.

A. Models without a low-viscosity asthenosphere: It was shown by Fjeldskaar (1994) that viscosity models without a low-viscosity asthenosphere give tilts that are even lower than those for models which include a low-viscosity asthenosphere. Changing the Earth model will thus not change the conclusions of this study. The model used here is a flat Earth approximation. However, the difference from a model with an isotropically elastic, uniformly thin, spherical shell is shown to be insignificant in Fjeldskaar (1997).

B. Lateral change in the elastic properties: The seismic lithosphere in Fennoscandia is reported to have a lateral change in thickness, from 90 km at the western coast of Norway to 190 km under the Gulf of Bothnia (Panza 1985). It is thus a reasonable assumption that the elastic lithosphere thickness is also not constant over the area. However, it has been shown that simple parabolic disk loads on a model with a linear change in lithosphere thickness (from 50 km outside the ice margin to 150 km under the ice centre) give a maximum 10% difference in isostatic uplift compared to a model with a uniformly thin (50 km) lithosphere (Kaufman et al. 1997). A lateral increase in elastic lithosphere from, say, 20 km at the western coast of Norway to 40 km under the Gulf of Bothnia will thus not significantly change the estimated tilt at the Bergen or Trøndelag locations.

2. A basic assumption in the modelling is that the post-glacial uplift is entirely a consequence of the melting of the Late Weichselian Scandinavian ice sheet. Could there be another mechanism operating? Is glacial isostasy the only mechanism, or is there a tectonic component in the Fennoscandian uplift?

Mörner (1980) proposed that the uplift from 4000 yr BP to the present reflects a large-scale tectonic uplift of Fennoscandia unrelated to the last glaciation. He argues primarily with the change from exponentiality to linearity in the uplift curves, shoreline profiles and subsidence curves. However, this is not a very convincing argument, because the time resolution and precision of the curves are not sufficiently high. The present rate of uplift seems to be essentially 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. Thus it is here suggested that the observational and modelling data conflict with Mörner's hypothesis.

## Conclusion

The theoretical present rate of uplift and the shoreline gradients versus time based on the very thin ice model (Nesje & Dahl 1990) show significant deviations from the observations. The theoretical late-glacial tilting of the palaeo shorelines of western Norway is less than 50% of what is observed. The pattern of the present rate of uplift in peripheral areas has, in contrast to the observations, uneven spacing of the isolines. These results seem to rule out the thin ice model as a viable option.

However, these conclusions are based on the assumption that the observed post-glacial uplift is entirely due to glacial isostasy. If this is not the case, there is another mechanism active, a mechanism that has to explain significant parts of the present rate of uplift, as well as the late- and post-glacial uplift.

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