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GEOIDAL-EUSTATIC CHANGES INDUCED BY THE DEGLACIATION OF FENNOSCANDIA

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Relative sea level changes in Fennoscandia have long been known to be a result of processes connected to the last glaciation. The post-glacial sea level changes have commonly been thought of as a result of global variations of the ocean water volume and isostatic movements (connected to the deglaciation). However, changes of the ice loads bring about gravimetric changes, and resulting eustatic changes will vary significantly over the globe.

The importance of the geoid changes related to the deglaciation in Fennoscandia is illustrated by theoretical simulations, which show that the resulting sea level movements differ significantly over the globe. During a fast deglaciation there is not a worldwide rise in sea level due to increased volume of ocean water, but in the region near the former glacier there may actually be a fall in sea level.

By simulations of the deglaciation history it is also shown that the associated sea level history varies even within a small area, and may differ by up to 20–30 m from the Barents Sea to central Scandinavia. This is really a significant difference, compared to the overall pattern of sea level change of 100 m for the last 15 ka. Thus no eustatic curve is valid globally.

INTRODUCTION

Eustasy has often been thought of as globally uniform sea level changes. Change in the shape of the geoid is an often overlooked effect of deglaciation, although the effect was advocated as the cause of shoreline tilting in Fennoscandia a hundred years ago (von Drygalski, 1887). Woodward (1888), using theoretical calculations, found that the effect was certainly significant. The effect seems then to have been forgotten for many years, until Jensen (1972) revived the subject. A more detailed historical overview is given by Mörner (1979).

Geoidal-eustasy is changes of the ocean water distribution, caused by variations in the earth's gravity field. This is an important eustatic factor, because no eustatic changes operate without significantly affecting the gravity field, resulting in non-uniform sea level changes over the globe.

An up-to-date definition of eustasy is: vertical changes of sea level, regardless of causation (Mörner, 1976). Three types are defined: (1) glacial-eustasy, controlled by variation of the ocean water volume; (2) tectono-eustasy, controlled by variation of the ocean basin volume; and (3) geoidal-eustasy.

In recent years several authors on post-glacial uplift and sea level changes have taken this effect into account (e.g., Cathles, 1975, 1980; Clark *et al.*, 1978; Farrell and Clark, 1976; Fjeldskaar, 1978, 1981; Fjeldskaar and Kanestrøm, 1980; Nakada and Lambeck, 1987; Peltier, 1980; Wolf, 1985). As most of these studies are concerned with global post-glacial sea level changes, the importance of geoidal-eustasy near previous ice sheets is not easily extracted.

The intention of this paper is to illustrate the importance of the geoidal-eustatic effect. It will be shown that the theoretical late- and post-glacial eustatic changes varies even within a limited area, from the Barents Sea to Scandinavia, because of significant geoid deformations associated with the deglaciation and crustal uplift. Implications for some published eustatic sea level curves will also be considered. It is strongly suggested that any eustatic sea level curve claimed to be of global significance may be questioned.

GEOIDAL-EUSTATIC EFFECT OF DEGLACIATION

In the following section the calculations show the isolated effect of geoidal-eustasy in connection with glaciation/deglaciation and related crustal uplift in Fennoscandia and the Barents Sea.

The calculations are based on ice models given by Denton and Hughes (1981). The maximum extent (at 20 ka BP) of the last ice sheet in Europe is shown in Fig. 1a. The ice load is analyzed into its harmonic components by the Fourier transform technique.

Instantaneous Deglaciation

Let us first assume an instantaneous melting of the ice sheet. This is not what really happened, but it gives us a feeling for the geoidal effect of a fast glaciation/deglaciation. For a harmonic load the geoid-deformation is then given by the analytical expression (Cathles, 1975):

$$S(L) = \frac{4h(L)\varrho_1 \cdot \pi \cdot G \cdot R}{(2L + 1)g_0} \tag{1}$$

where L is the order number of the ice load ($L = 2\pi R/\lambda - 1/2$); $h(L)$ and ϱ_1 are the amplitude and density of the ice load, respectively. G is the gravitational constant and g_0 is the surface gravity.

The calculated geoidal-eustatic effect in central areas of the ice sheet is more than 80 m (Fig. 1b). This is the

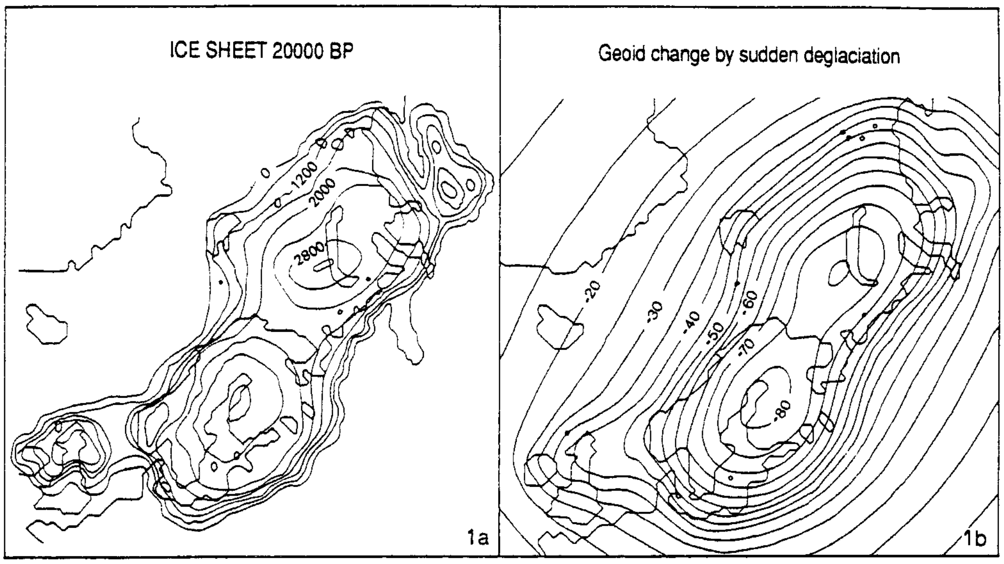

FIG. 1. (a) The European ice sheet at the last glacial maximum (20 ka BP). Contour interval is 400 m. (Redrawn after Denton and Hughes, 1981.) (b) Theoretical deflection of the geoid caused by an instantaneous deglaciation of the ice sheet in Fig. 1a. Contour interval 5 m.

fall of the geoid caused by a rapid (instantaneous) deglaciation, or the rise of the geoid caused by a rapid glaciation. Notice the big difference in geoidal effect between the North Sea and the Barents Sea, up to 30–40 m.

It should be pointed out that this result is based on the 'maximum' ice cover model given by Denton and Hughes (1981). There are other models suggesting a thinner ice cover, which are not considered here. However, the resulting geoidal-eustatic change by a thinner ice cap (with the same lateral extent) is easily estimated from Fig. 1b, as a uniform reduction of the ice thickness gives equivalent reduction in the geoidal-eustasy: e.g., 50% reduction of the ice thickness gives 50% reduction of the geoidal-eustasy.

Modelling the Deglaciation History

A realistic simulation of the geoidal-eustatic effects connected to the deglaciation in Fennoscandia requires consideration of the deglaciation history. From marginal moraines of different ages we know that deglaciation took place over a time span of about 10 ka. The deglaciation history used (Figs 1a, 2a–d) is compiled by Andersen (Denton and Hughes, 1981). During deglaciation the crust is uplifted to approach a new state of equilibrium consistent with the removal of ice. This is the isostatic process. When there is a very slow deglaciation the related geoidal-eustatic deflections tend to be smeared out, because lost ice mass is compensated by increased crustal masses.

To simulate the isostatic process the earth is modelled by a non-spherical viscoelastic fluid, in which the viscosity varies with depth, and overlain by a uniformly thick elastic lithosphere. The model is described in detail in Fjeldskaar and Cathles (1991).

It has been shown that data on post-glacial uplift in Fennoscandia (shoreline tilting history and present rate of uplift) indicates a lithosphere of mechanical thickness 50 km and a mantle viscosity of 1.0×10^{22} poise (1 poise = 0.1 Pa s) except for a 75 km asthenosphere of viscosity 1.3×10^{20} poise (Fjeldskaar and Cathles, 1991).

In the dynamic model, the geoidal-eustasy is a measure of the degree of compensation (or rather uncompensation). The geoidal-eustasy s(L) is:

$$s(L,t) = \frac{4[h(L,t)\varrho_1 - d(L,t)\varrho_2]\cdot\pi\cdot G\cdot R}{(2L + 1)g_0} \qquad (2)$$

where $h(L,t)$ is the ice thickness and $d(L,t)$ is the isostatic deflection at time t. ϱ_1 and ϱ_2 are the density of the ice and mantle, respectively.

Hydro-isostasy, the isostatic compensation due to changes in the water-load, is included in the calculations. The change in the water load is an artifact of the Fourier transform technique; it is assumed to be the DC component of the Fourier transformed ice load. The resulting curve (Fig. 3) is roughly in accordance with what is generally believed (as illustrated in Fig. 6).

The ice sheet is assumed to have been in isostatic equilibrium prior to 20 ka BP. Thus there is assumed to be no theoretical geoid deflection in the area at that time. In the model, we make the assumption that ice melting commenced at 20 ka BP and continued until the area became ice-free at 8.5 ka BP. The melting from one ice sheet configuration to the next (shown in Figs 1a, 2a–d) is modelled with uniform speed. The theoretical geoidal-eustatic change history based on this earth rheology and the deglaciation history above is presented in Fig. 4.

At 19 ka BP there was theoretically a small, but growing, geoid deformation in the Barents Sea area (Fig. 4a), because the modelled ice melting started in

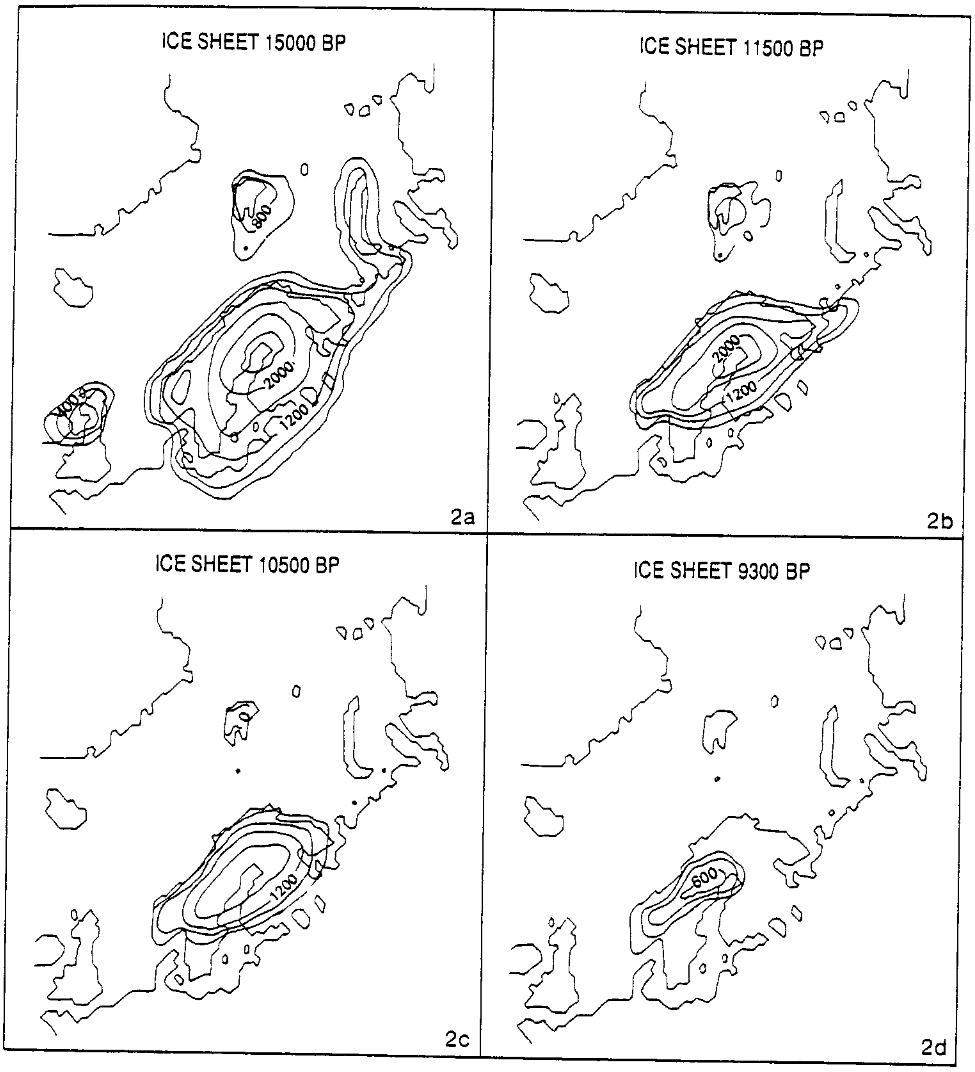

FIG. 2. The deglaciation history from 15 ka BP to 9.3 ka BP. The contour interval is 400 m, except for the 9.3 ka BP ice sheet (200 m). Ice sheet margins are redrawn after Denton and Hughes (1981).

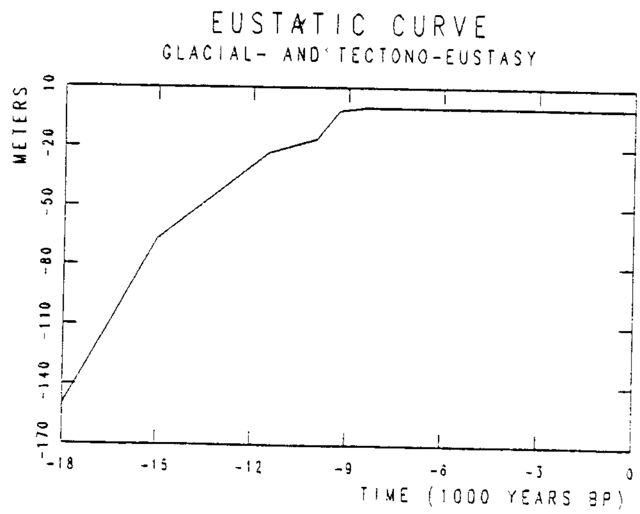

FIG. 3. Glacial- and tectono-eustatic sea level curve used in the calculations.

this area. The deformation in the Barents Sea increased to about 30 m at 15 ka BP (Fig. 4b). After 15 ka BP the deformation began to decrease, while deformation in Scandinavia was developing. At 13 ka BP the geoid deflection in the Barents Sea was approximately 18 m, and the deflection in Fennoscandia was approximately the same (Fig. 4c). At 9 ka BP the geoid was nearly back to normal in the Barents Sea, at the same time as the geoid deformation in Scandinavia was at a maximum of about 25 m (Fig. 4d). From 9 ka BP to present the geoid slowly returned to the undeformed state. At present the geoid is less than 2 m from equilibrium (Fig. 4e).

Geodial-eustatic curves for selected locations within the deglaciated area (Fig. 5) clearly show significant differences. The difference in the geoidal-eustasy is more than 20 m (15 ka BP) between the Barents Sea and central Norway.

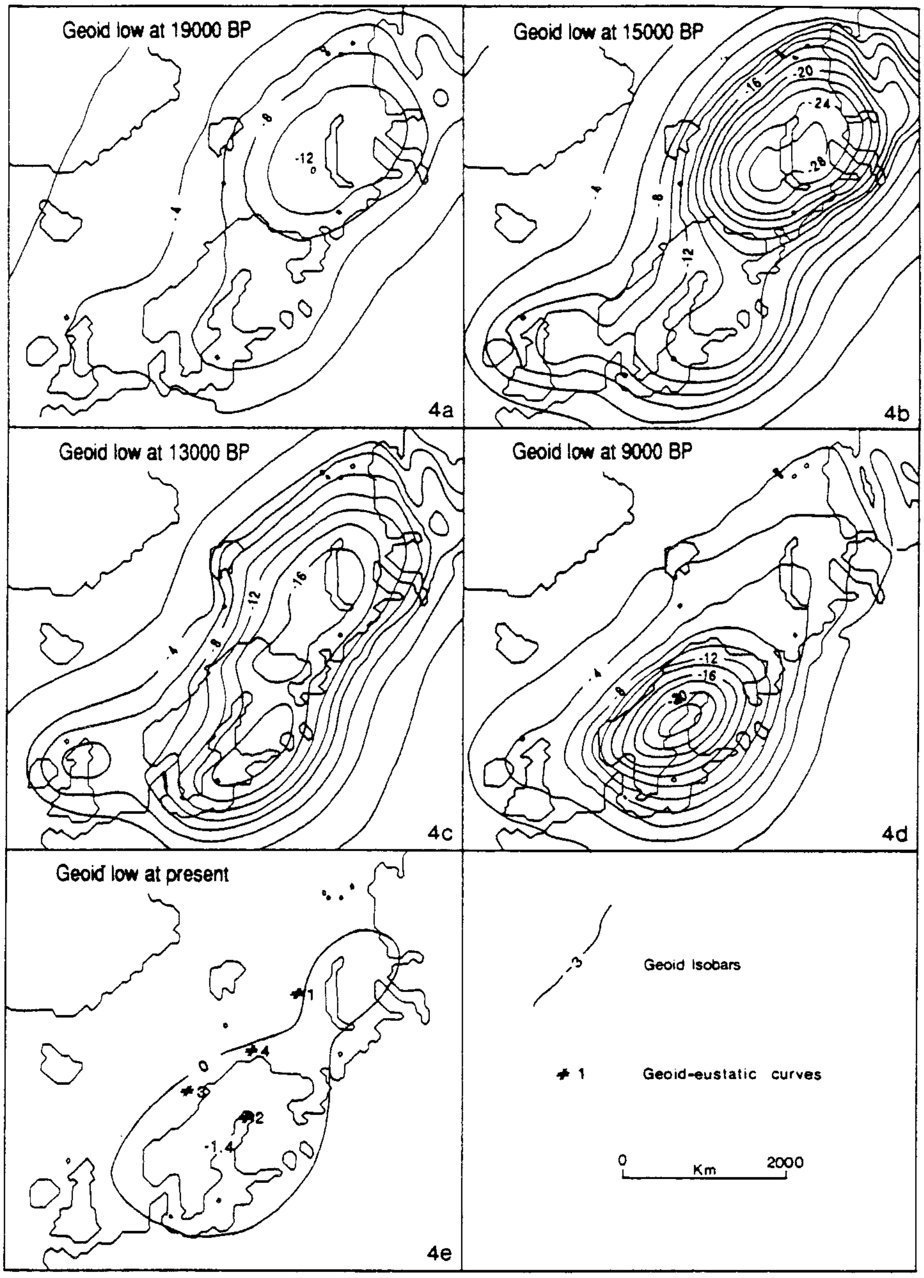

FIG. 4. Theoretical geoid deformation for post-glacial time caused by the proposed deglaciation history.

IMPLICATIONS FOR GLOBAL EUSTATIC CURVES

Quite a number of eustatic curves, often assumed to give a global picture of the post-glacial sea level variations, have been presented in the literature. A few of them will be evaluated in the following discussions in terms of the results outlined above.

One eustatic curve is that of Fairbridge (1961), which is a synthesis of global information (Fig. 6). It was stated that "the eustatic hypotheses are of world-wide application" and that "a very close correlation is observable between minor oscillations of sea level and climatic events". As is illustrated above, these basic assumptions of the curve turn out to be wrong, because one climatic event may produce a regression in one area and a transgression in another. The information on sea level changes provided by this curve may be strongly misleading.

The curve of Shepard (1963) is based on data recorded from so called 'stable areas' (Fig. 6). The results of the geoidal eustatic factor imply that the curve is not valid world-wide. However, this curve can be interpreted to describe the 'uniform' component of the global eustatic change (the sum of glacial- and tectono-eustasy), even if the idea of coastal stability may be questioned.

The curve of Mörner (1969) is based on the idea that the eustatic curve must be constructed regionally in areas where crustal movements can be separated from eustatic fluctuations. This curve (Fig. 6) is constructed by subtracting isostatic response from the observed sea

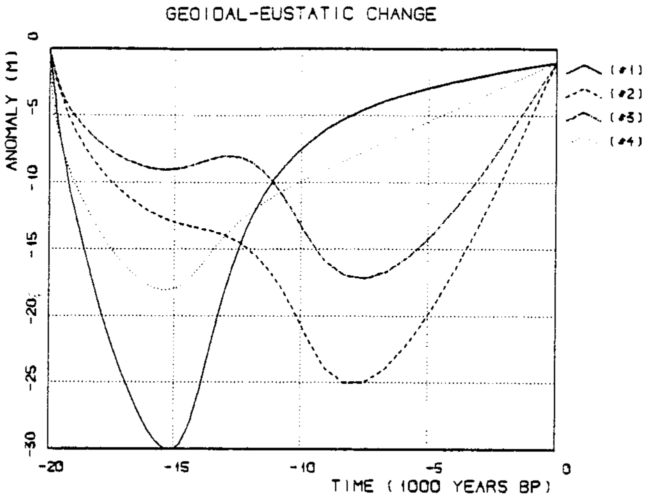

FIG. 5. Geoidal-eustatic curves for the central Barents Sea (number 1), the Baltic Sea (number 2), and the coasts of central (Nordland, number 3) and northern Norway (Finmark, number 4). The locations are shown in Fig. 4e.

can be realized that this curve is not a eustatic curve, but rather a meltwater curve (curve of water volume) converted to sea level change assuming uniform distribution of sea water. The curve gives an interesting picture of the glacial-eustatic factor.

The most recent curve is the one by Fairbanks (1989), which is based on radiocarbon dated coral reefs drilled offshore of Barbados. The resulting curve (Fig. 6) spans from 18 ka BP to present. The curve seems to be based on sound methods, and gives a very accurate picture of the sea level changes at Barbados. But what about the global implications? To be able to give an answer, at least two factors have to be considered: (1) hydro-isostasy and (2) geoidal-eustasy. The geoidal-eustasy of this time period is probably mainly connected to the deglaciation of the large ice sheets, and as is also pointed out by the author, the gravitational variations from the northern hemisphere ice sheets have affected the Barbados sea level only to a small

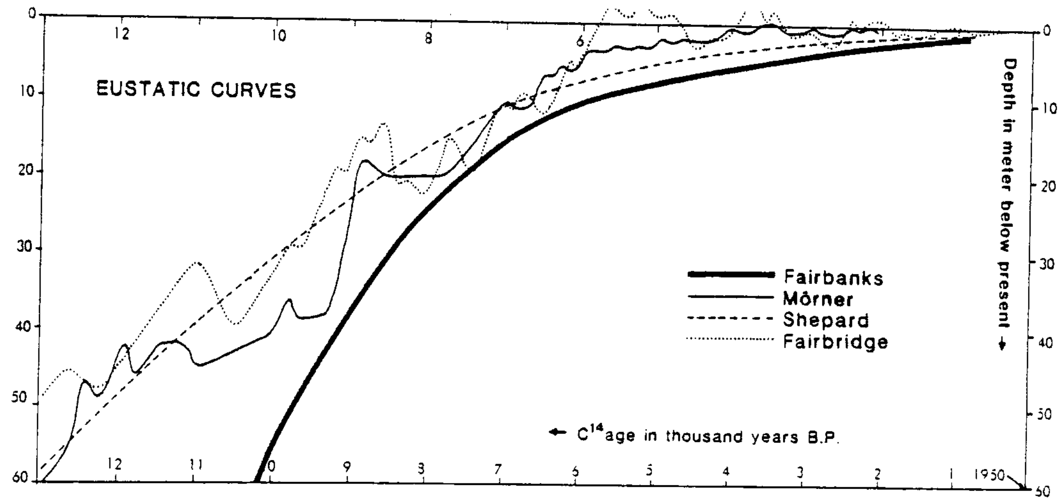

FIG. 6. Eustatic sea level curves from Fairbridge (1961), Shepard (1963), Mörner (1969) and Fairbanks (1989).

level on the Swedish south coast. The shoreline diagrams (time/gradient curves) are used to give a measure of the isostatic response; oscillations on these curves are caused by the isostasy. This philosophy enables the construction of a eustatic curve for the area, a curve that can, at best, be interpreted as a true eustatic curve (glacial-, tectono- and geoidal-eustasy) for the area of data collection (southern Sweden), and not for the entire area of northwest Europe (as suggested by Mörner, 1979).

The curve of Shackleton and Opdyke (1973) covering the last 120 ka, is constructed on the basis of Oxygen Isotope analyses on marine fossils from deep sea cores. The variation in the fossil isotope content may be caused by two factors: (1) ocean temperature variation or (2) variation in the ocean isotope content. The second factor is connected to the continental ice volumes. On the basis of the definition of eustasy, it

extent. However, any sea level change causes deflection of the ocean floor, hydro-isostasy, to attain isostatic equilibrium. An interesting implication of hydro-isostasy is the fact that the sea level history will differ between oceanic islands and continental margins. An island, such as Barbados, moving with the sea floor will record the full sea level change, while points near the continents record quite different sea level changes. Accordingly, this curve is here assumed to be a good measure of the global glacial eustatic sea level change in late- and post-glacial time.

CONCLUSIONS

The geoidal-eustatic change connected to the last glaciation in Fennoscandia, is shown to be a significant factor in sea level changes. The results of these calculations indicate a fall in the geoid in the vicinity of the former ice cap, caused by gravity change related to the deglaciation. Even within limited geographical areas, such as the Barents Sea and Fennoscandia, there may be significant differences in the geoidal response to the deglaciation history.

Eustatic sea level changes are never globally uniform, because any cause of sea level change simultaneously affects the earth's geoid. Ocean level reconstruction is thus more complicated than is usually imagined.

Eustatic changes have three main causes: (1) glacial-eustasy, (2) tectono-eustasy, and (3) geoidal-eustasy. Glacial-eustasy and tectono-eustasy are the globally uniform eustatic changes. For glacial time these are well described by the curve of Fairbanks (1989) established from data for Barbados.

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