The uplift of Fennoscandia

The Fennoscandian uplift is a classic concept in international geology and geophysics. The true benchmark paper is De Geer's doubble-paper of 1888-1890, where he was able to document the main geometry of glacial deformation and to formulate the theory of glacial isostasy. A second benchmark paper was Lidén's paper of 1938, where he was able to assign exact varve dates to the individual delta terraces in the center of uplift. A third benchmark paper is Mörner's paper of 1979 where he was able to show that the total uplift amounted as much as 830 m. A fourth point of major significance is the observation by Mörner that the uplift, in fact, is composed of two different factors (Mörner, e.g. 1973, 1977, 1991a). Fig. 1-2-1 summarises the old and new concept of uplift

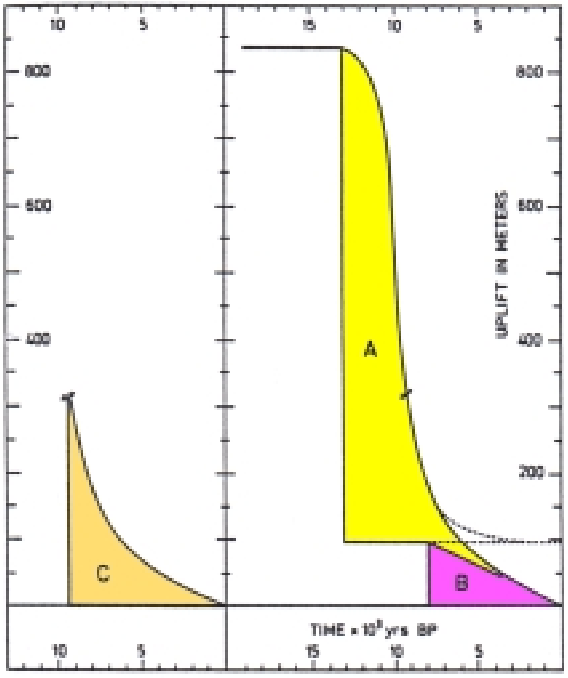

Fig. 5. *Records of uplift in the area of maximum uplift: (left) Lidén's (1938) original shorelevel displacement curve corrected for eustasy (C), (right) Mörner's (1979, 1980) uplift curve from the same area extended back to the onset of uplift (3700 years before the free-melting of the area) and separated into an exponential (A) and a linear (B) uplift factor.*

Fig. 1-2-1. Old (C) and new (A+B) concept of uplift (from Mörner, 1991a). The onsel of uplifting commenced ~3700 years before the free-melting. The uplift is composed of one exponential (A) and one lineal (B) factor.

Because the isostatic and eustatic components had been identified and separated (Mörner, 1969), the sea level records and shorelines could be converted to lines of absolute uplift. At the Stockholm international meeting in 1977 on “Earth Rheology, Isostasy and Eustasy”, Mörner presented the geometry of isostatic deformation and forebulge compensation. Later, he converted these data to actual mass figures and mass transfer (Mörner, 1980, 1979).

The total uplift

Fig. 1-2-2 gives the2ueometry of absolute uplift in the last 13,000 years; an elliptic uplift cone surrounded by a subsidence trough (from Mörner, 1979). The mass in the uplift cone and the mass is in the subsidence trough is roughly as 1:1, suggesting that the glacial isostatic deformation was totally compensated by horizontal mass flow.

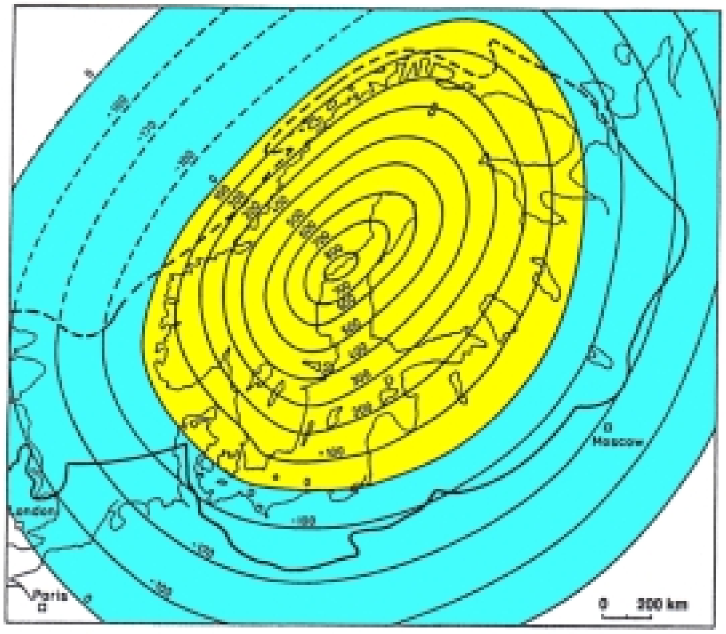

Fig. 1. *Contours of the total absolute uplift of the Fennoscandian Shield and surrounding subsidence in relation to the limits (heavy line) of last glaciation maximum. An elliptic uplift cone with a maximum central uplift of 830 m is surrounded by a subsidence trough (a forebulge) of maximum 170 m subsidence (from Mörner, 1979).*

Fig. 1-2-2. An elliptic uplift cone with apex at ~830 m is surrounded by a subsidence trough (from Mörner, 1979, 1980). He mass in the cone and the trough is as 1:1.

The mass motions and model of uplift

From the uplift profiles presented at the Stockholm symposium in 1977 (Mörner, 1977), Mörner calculated the amount of mass disappearing from the subsidence trough and appearing in the uplift cone for every 500 year from 13,000 radiocarbon years BP to the present (Mörner, 1979, 1980). Fig. 1-2-3 gives this disappearance/appearance of mass. It indicates that the entire process was a matter of horizontal mass-flow. It is interesting to note that the disappearance of mass from the subsidence trough stopped some 8000 radiocarbon years BP and that the appearance of mass in the uplift cone stopped some 4500 radiocarbon years BP.

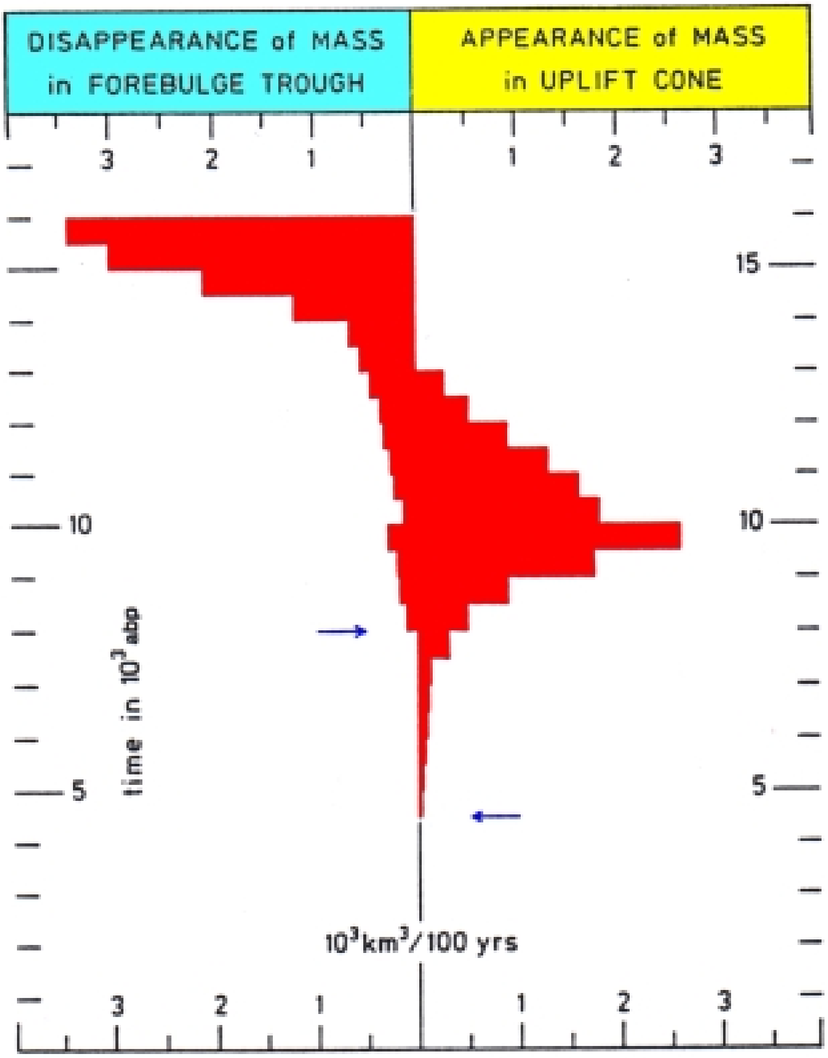

Fig. 2. *Rates of mass transfer (in 500 m steps) from the forebulge trough to the uplift cone (from Mörner, 1979). Arrows mark the end of mass disappearance and appearance, respectively.*

Fig. 1-2-3. Mass transfer from the subsidence trough to the uplift cone for every 500 years (from Mörner, 1979). Arrows indicate end of mass disappearance and appearance.

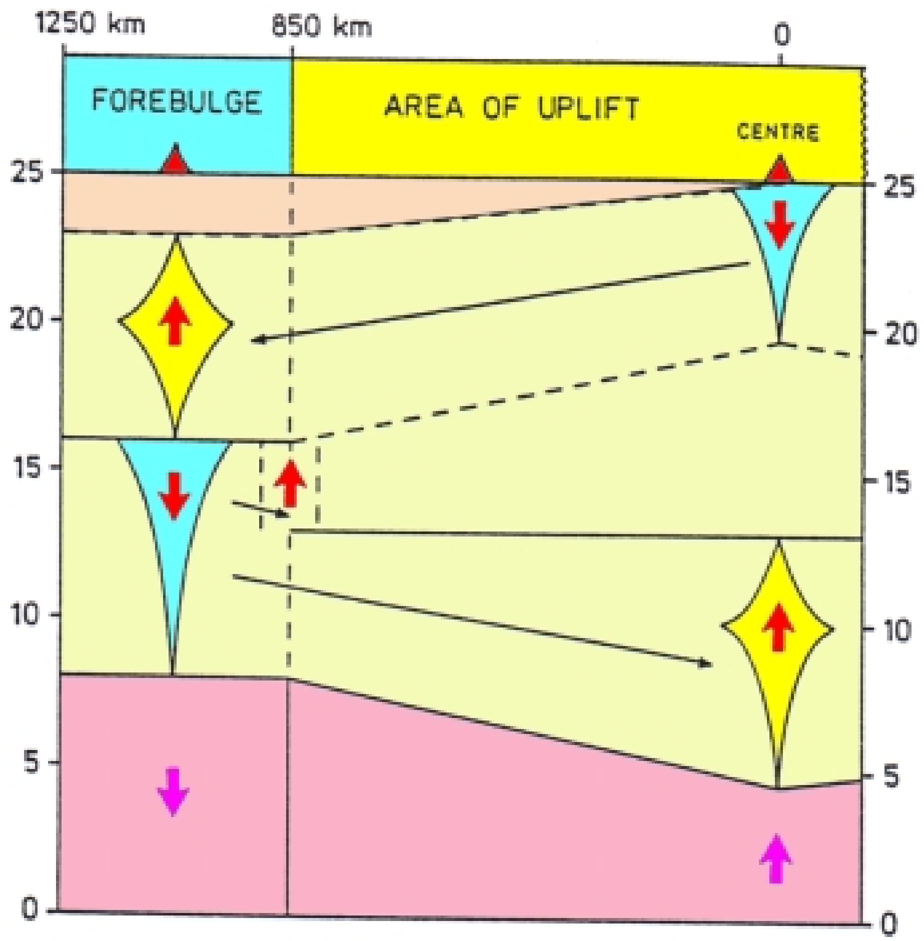

Fig. 3. *Uplift/subsidence (thick arrows), appearance/disappearance of mass (increasing/decreasing funnels) and mass flow between the area of uplift and the forebulge region (thin lines) forming three main phases or stages (marked by full or dashed lines).*

Fig. 1-2-4. Uplift/subsidence (thick arrows), appearance/disappearance of mass (increasing/decreasing funnels) and mass fransfer between the area of uplift and the forebulge (thin arrows) (from Mörner, 1991a).

The model of uplift is given in Fig. 1-2-5 (from Mörner, 1979, 1980); a lithosphere of high crustal rigidity and an asthenospheric channel of low viscosity where the mass-flow occurred. The asthenospheric rigidity was calculated at 2x10^{19} PA. The crustal rigidity may be as high as 10^{25} Nm (Mörner, 1990).

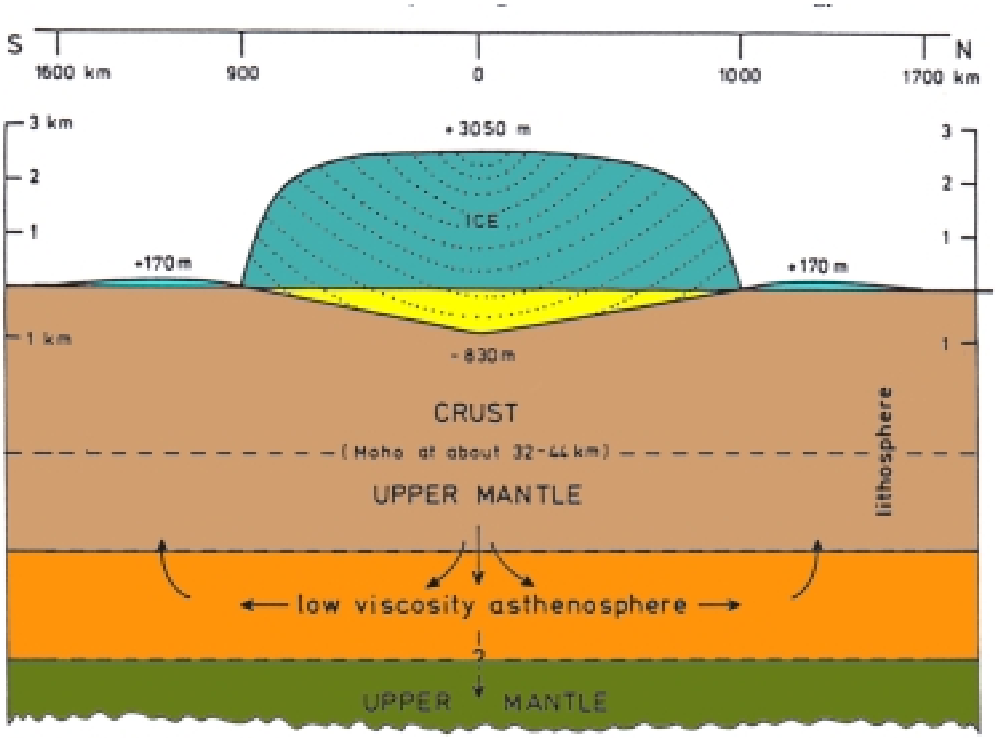

Fig. 1. Deformation of the crust by the Fennoscandian ice cap of the Last Glaciation (from Mörner 1979). The mass of the down-pressed elliptic cone and that of the surronding forebulge ring is as 1 : 1 indicating a full compensation via rapid motions in a low viscosity asthenosphere.

Fig. 1-2-5. Model of uplift (Mörner, 1979, 1980). A 3 km thick ice cap deforms the crust. The downwarping (peak value ~830 m) is compensated by horizonal mass flow in a low viscosity asthenospheric channel. The lithospheric flexural rigidity is high (straight shorelines). The downwarping (cone) is surrounded by a forebulge.

The onset of uplift

The finding that the center of uplift started to go up at about 13 ka or 12,700 radiocarbon years BP (Mörner, 1979, 1980) means that uplift commenced some 2000-2500 years before the ice left the central area, and when hardly any central thinning of the ice cap had started. Therefore, we must ask the question: what triggered the onset of uplift of the center of glaciation?

At 13,200 BP the virtual geomagnetic pole (VGP) was, quite suddenly displaced from arctic Siberea to arctic Canada (Mörner, 1991b). This transpolar VGP-shift seems to represent the relative displacement of two rotational symmetry axis. Therefore, one may speculate of a connected change in rotation (probably recorded in the sudden northward flow of warm Atlantic water into NW Europe and even the Barents Sea) and in geoid shape (if so, maybe, triggering the Fennoscandian uplift). This is illustrated in Fig. 1-2-6.

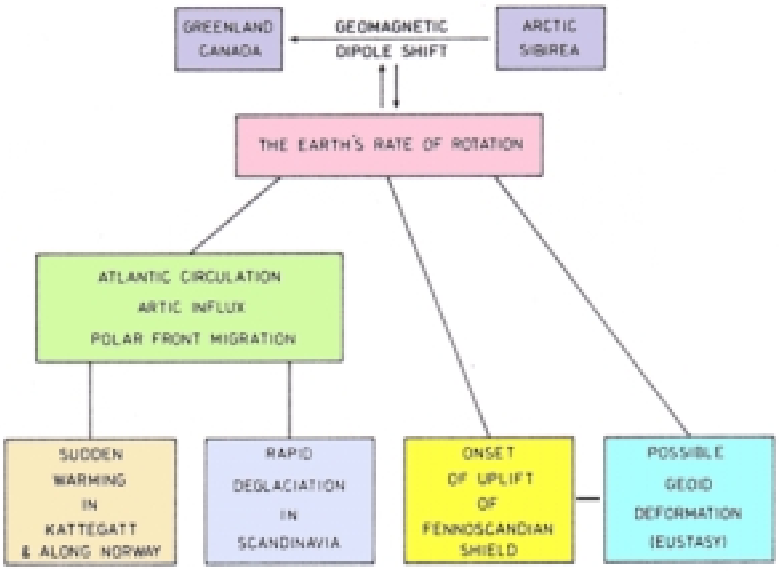

Fig. 1-2-6. At 13,200 radiocarbon years BP the VGP-paths exhibit a trans-polar shift (Mörner, 1991b). The sudden onset of uplifting, despite little of no glacial thinning, might perhaps be causally linked to this event and related changes in rotation and geoid level.

The present linear uplift factor

Converting the eustatically calibrated shorelines of the last 7000 radiocarbon years into lines of rates of uplift and comparing these lines with the present rates of uplift from mareographs and repeated levelling (Fig. 1-2-7), it became obvious (Mörner, 1973) that the process of uplift, in facts, was composed by two different mechanisms; one typical glacial isostatic factor that exponentially died out with time and distance from the periphery, and one novel factor, responsible for the present uplift, that has remained linear for about 8000 years. This was later duplicated and varified for the Swedish east coast in a profile across the center of uplift (Mörner, 1977) as illustrated in Fig. 1-2-8.

1. the ongoing uplift is linear and has remained linear for 8000 years,
2. the zero-point of linear uplift/subsidence has remained stable for 8000 years,
3. the linear factor seems to have commenced at around 8000 radiocarbon years BP,
4. the horizontal asthenospheric mass-flow (Fig. 1-2-3) was over in Mid-Holocene time,
5. the linear uplift corresponds to a viscosity of 10^{21} PA,
6. the center of present uplift lies far more to the north than the true glacial isostatic center,
7. in the center of uplift, the direction of tilting reversed in Late Holocene time.

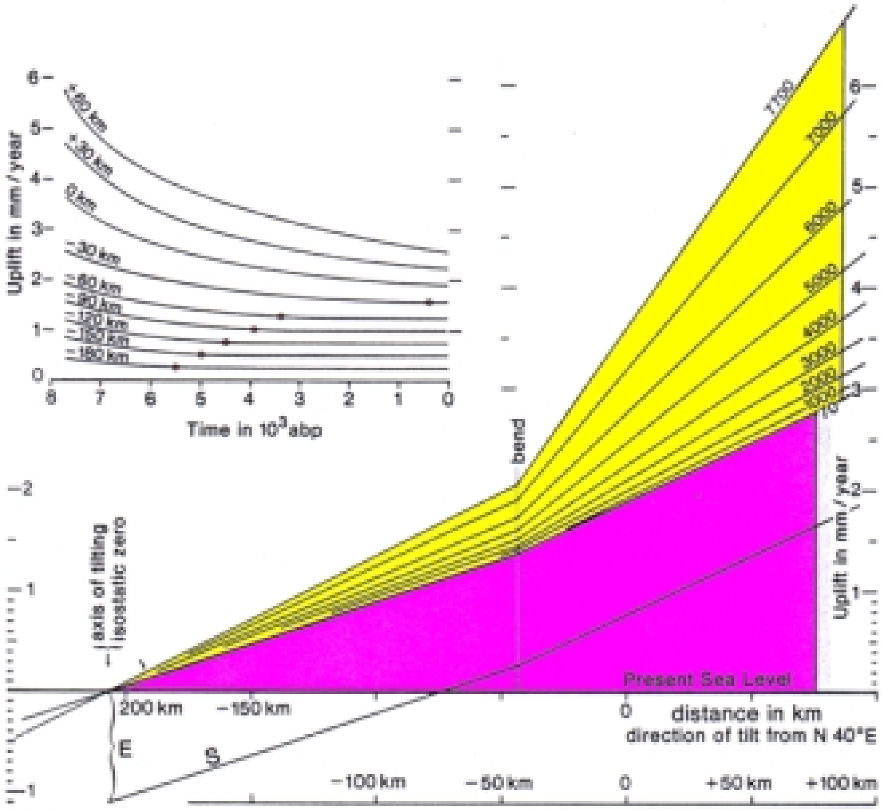

Fig. 1-2-7. The West Coast profile (Mörner, 1973) exhibiting an exponentially decaying uplift factor (yellow) and a linear factor (purple). The repeated levelling and mareograph data (S-line) must be corrected by 1.1 mm/yr (= the eustatic component; E) to be compatible with the shoreline sectrum.

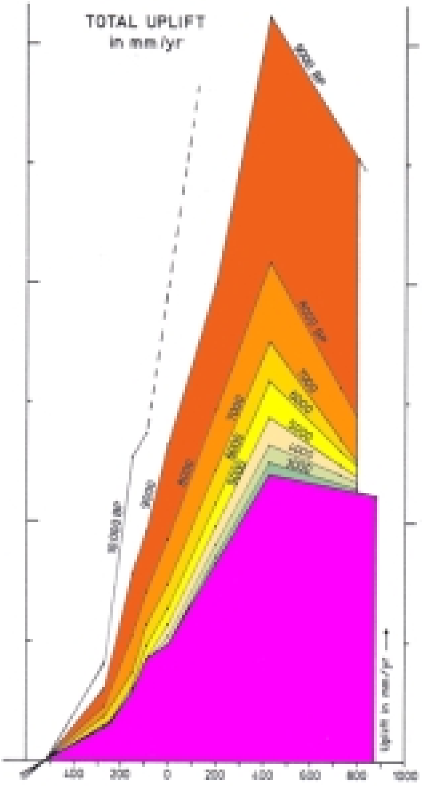

Fig. 1-2-8. The East Coast profile (Mörner, 1977, 1980) exhibiting an exponentially decaying, typical glacial isostatic, factor (orange-yellow) and a strong linear factor (purple).

The rates of uplift

The observed point rates of absolute crustal uplift peak at around 10,000 radiocarbon years BP with rates amounting such remarkable rates as 40-50 cm/yr in the central area, 15 cm/yr in the Stockholm area and some 10 cm/yr in the south (Mörner, 1979, 1980). Fig. 1-2-9 gives the rate of uplift in the center of uplift according to the original calculations of Mörner (1980). This rate has recently been varified by the recording of the shoredisplacement from the marine limit down to a tsunami-level occurring over a time period covering about 20 annual varves (Mörner, 1999). This is illustrated in Fig. 1-2-10.

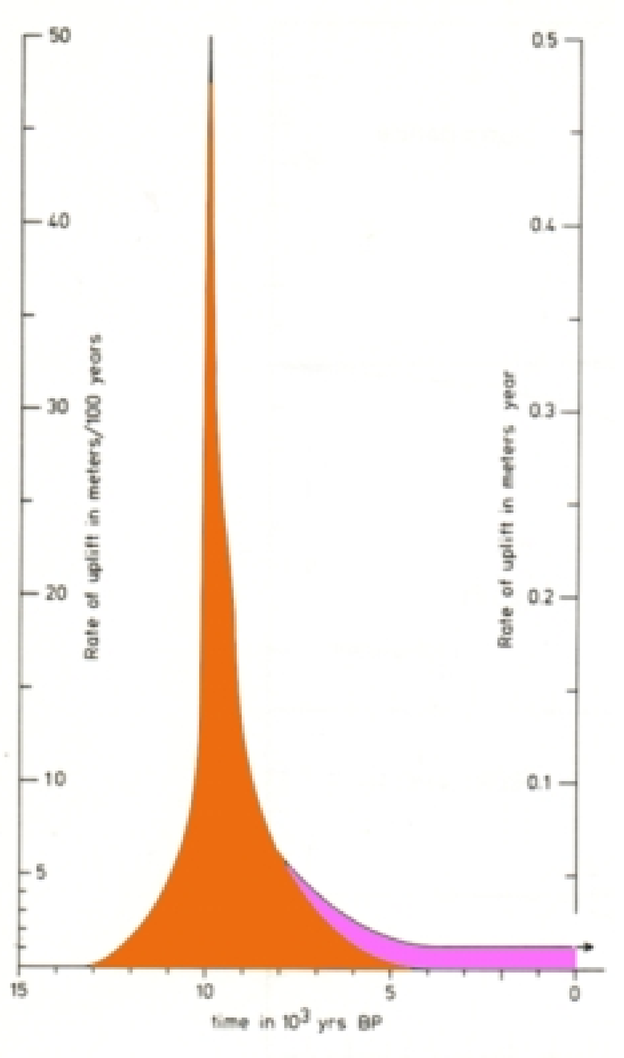

Fig. 1-2-9. Absolute rate of uplift (orange) in mm/yr at the center of uplift (Mörner, 1980).

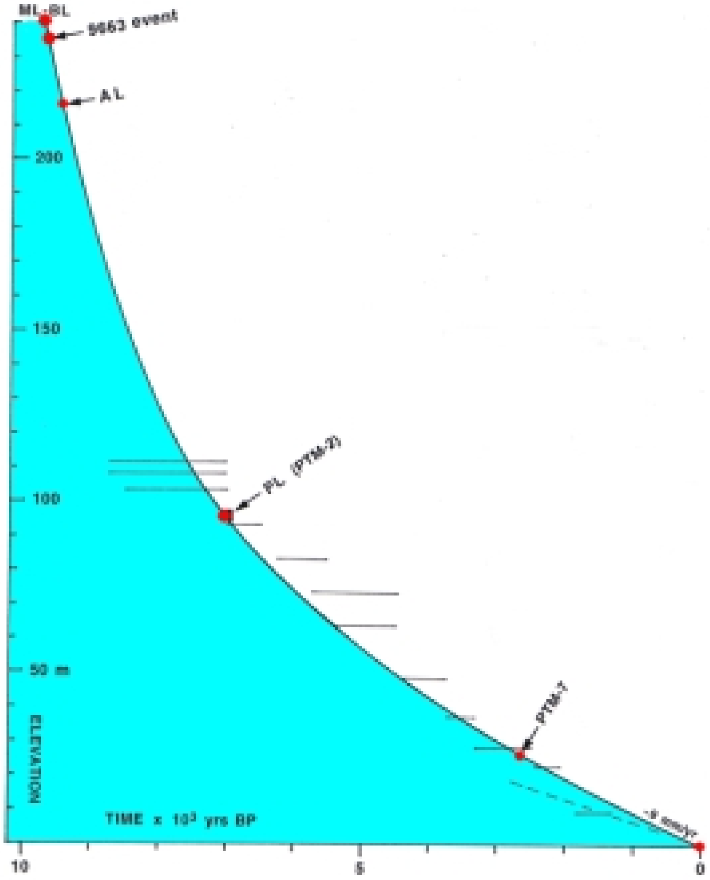

Fig. 1-2-20. Recently, the relative rate of uplift during the first 20 years after deglaciation was established as 30-40 cm/yr at Hudiksvall (from Mörner, 1999). With eustatic calibration (and distance to the center of uplift), this varifies the super high rates of uplifting proposed earlier (Mörner, 1979, 1980)

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