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Flandrian and Eemian Shore Levels in Finland and Adjacent Areas — a Discussion

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Discussion, eustacy, earth crust, shoreline displacement,
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Abstract: A comparison is made of Flandrian and Eemian movements in the earth's crust mainly within Fennoscandia. The Flandrian phases of the Baltic and the movements associated with these are well known in broad outline. The predominant factor involved in postglacial shoreline displacement in the northern part of the Baltic area has been land uplift, which was very rapid immediately after the deglaciation, but had slowed down considerably in the early Holocene time. The centre of land uplift is located close to the assumed centre of the ice sheet towards the end of the Weichselian.

Only fragmentary information is available on movements in the earth's crust during the Eemian interglacial, but those deposits which have been studied would seem to suggest that no shoreline displacement of the type recorded in Late Weichselian and Flandrian times took place at all during the Eemian. Thus it is obvious that the isostatic crustal movements that took place at that time must have differed fundamentally from the postglacial pattern. The differences have been explained mostly by suggesting that a large part of the Eemian land uplift may have taken place beneath the rapidly melting Saale ice sheet, which had already decreased in thickness and begun to stagnate over extensive areas, and that the centre of the ice sheet at the end of the Saale (Warthe) glaciation probably lay considerably further east than that of the Weichselian ice. This would have meant that the isostatic depression and corresponding rebound in the earth's crust differed both spatially and temporally from the circumstances in postglacial times.

[Flandrische und Eem-zeitliche Strandniveaus in Finnland und angrenzenden Gebieten — eine Diskussion]

Kurzfassung: Die flandrischen und Eem-zeitlichen Bewegungen der Erdkruste überwiegend innerhalb Fennoskandias werden verglichen. Die flandrischen Entwicklungsphasen der Ostsee und die mit ihnen verbundenen Bewegungen sind in groben Zügen bekannt. Vorherrschender Faktor der Strandlinien-Verschiebungen im nördlichen Teil der Ostsee ist dabei die Landhebung gewesen. Sie verlief unmittelbar nach dem Abschmelzen des Eises sehr rasch,

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verlangsamte sich aber im frühen Holozän erheblich. Das Zentrum der Landhebung liegt nahe dem für die ausklingende Weichsel-Kaltzeit angenommenen Zentrum des Eisschildes.

Über die Bewegungen der Erdkruste während des Eem-Interglazials liegen nur bruchstückhafte Informationen vor. Die untersuchten Ablagerungen schienen aber darauf hinzudeuten, daß während des Eem keine Strandlinien-Verschiebungen von dem für das Weichsel-Spätglazial und das Holozän ermittelten Typ stattgefunden haben. Deshalb müssen sich die isostatischen Krustenhebungen damals offensichtlich grundsätzlich vom postglazialen Bewegungsmuster unterschieden haben. Diese Unterschiede führt man hauptsächlich darauf zurück, daß sich ein Großteil der Eem-zeitlichen Landhebung unter dem rasch schmelzenden, in seiner Dicke reduzierten und über weite Areale stagnierenden Saale-Eisschild vollzogen haben dürfte. Außerdem hat das Zentrum des Eisschildes gegen Ende der Saale-Vereisung (Warthe-Stadium) wahrscheinlich bedeutend weiter östlich gelegen als dasjenige des Weichsel-Eises. Dies würde bedeuten, daß sich die isostatische Depression und die ihr entsprechende Wiederaufwölbung der Erdkruste sowohl räumlich als auch zeitlich von den Ereignissen in postglazialer Zeit unterschieden haben.

It is now over a hundred years since the first scientific investigations were carried out into the postglacial phases of the Baltic, and we can now claim to have a fairly accurate knowledge of the Late Weichselian and Holocene patterns of shoreline displacement in the area. There are, of course, certain more specialized details which are still unresolved or upon which opinions differ, but we need not go into these in the present instance.

The configuration of isostatic and eustatic phenomena since the last glaciation has meant that the Baltic basin has been connected with the ocean at some stages and isolated as a freshwater lake at others, the major phases recognized being the Late Weichselian Baltic Ice Lake and the Flandrian Yoldia, Ancylus Lake and Litorina Sea stages. These naturally involve variations in salinity, although such variations are not of the same importance in the present connection as is the general trend in shoreline displacement.

It is land uplift which has proved the chief factor governing shoreline displacement in the northern part of the Baltic basin in postglacial times, and this trend continues even today. All the ancient shore levels are now in supra-aquatic positions, the present heights above sea level of the Late Weichselian and early Holocene levels being those depicted in the map of the highest shoreline of the Baltic in Fig. 1. As may be seen, the ancient shorelines are now situated well inland, with the highest levels in Finland being found to the north-east of the northern tip of the Gulf of Bothnia, where they reach heights of around 220 m a. s. l. Baltic Ice Lake shore levels in Southern Finland rise to just over 160 m a. s. l.

Research into shoreline displacement phenomena tells us that land uplift was at its most rapid immediately after the deglaciation, so that extremely impressive figures are quoted for the Early Holocene period. In western Lapland, for instance, the water level is calculated to have subsided by about 100 m in less than 1000 years between 9000 and 8000 B. P. This figure may include a small measure of 'absolute' decline in the water level associated with the drop in the Ancylus Lake to close to the ocean level, but this would not seem to have been decisive as far as the overall trend was concerned. The rapid drop in water levels slowed down generally over the period 8500—8000 B. P. and has remained fairly steady since, declining very gradually towards the present day (Eronen 1983). Values for current land uplift are indicated in Fig. 2.

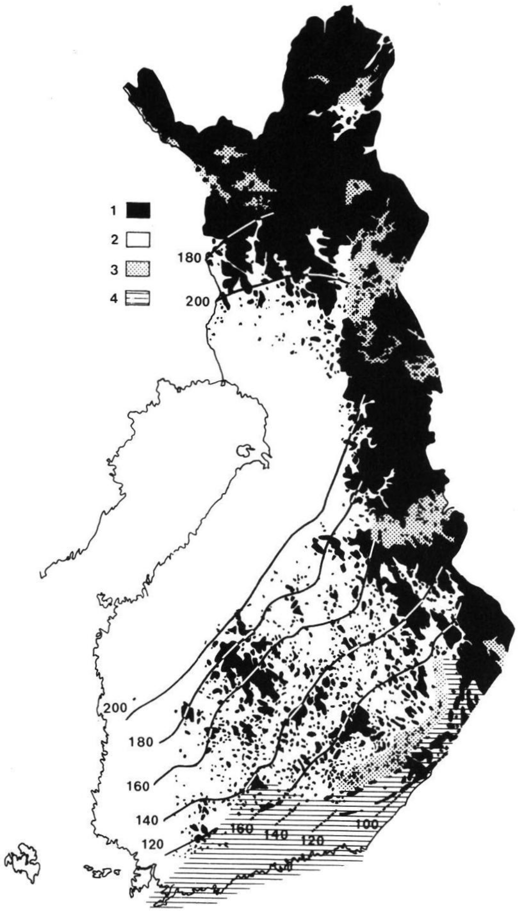

Fig. 1: Map of the highest shore of the Baltic in Finland.
1. Supra-aquatic areas. 2. Sub-aquatic areas. 3. Areas covered by ice-dammed lakes. 4. Areas covered by the Baltic Ice Lake. Solid lines are isobases (metres above sea level) for the metachronous early Holocene highest shore level. Dotted lines are isobases for the highest shore level of the late Weichselian Baltic Ice Lake on the Salpausselkä I end-moraine.
Map compiled by M. Eronen and H. Haila for the Atlas of Finland and published by permission of the Editorial Board.

All the old postglacial shore levels have naturally tilted in the course of time in a direction perpendicular to the isobases of current land uplift, in other words they increase in height towards the present centre of land uplift, which lies close to the assumed centre of the Weichselian ice sheet. The shorelines also tilt more the older they are.

This land uplift phenomenon is undoubtedly linked to questions of glacial isostasy, since the form of the glacier must at some stage have influenced the form of the earth's curst in such a way that the area affected by land uplift assumed the shape that it

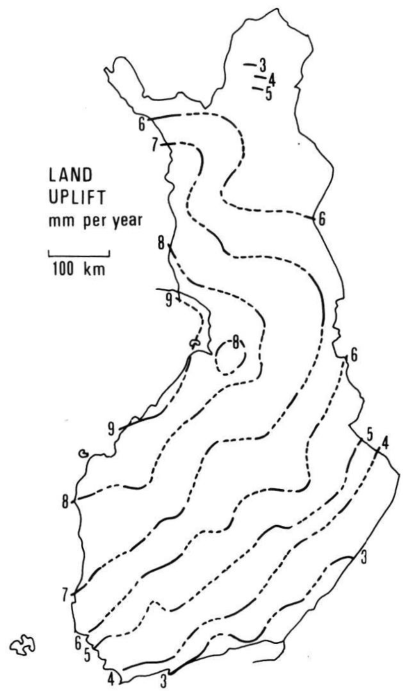

Abb. 2: Present land uplift in Finland. The Finnish land uplift values are calculated on the assumption of a continuous steady sea-level rise of 0.8 mm per year. Adapted from KIVINIEMI (1981).

did. Scarcely any attempt has been made to date, however, to contemplate which stage of the Weichselian glaciation may have been the decisive one in this respect. Similarly it remains uncertain to what extent the isobases of land uplift have changed in direction since the deglaciation, in other words, to what extent the direction of tilting of the land surface has altered. It has not yet been possible to reconstruct ancient shore levels from the known shoreline markers sufficiently well that such changes could be seen. It is probable, however, that no significant changes in the direction of tilting have taken place since the middle of the Flandrian, and not very many since the beginning of the Litorina Sea stage around 7500—7000 B. P. In any event, the present pattern of land uplift, which has apparently continued to act in more or less the same direction for the majority of the Holocene, will also have caused the earlier shorelines to tilt in this same direction.

The present isobases of land uplift cannot be said for certain to reflect the ice thicknesses which prevailed at the peak of the Weichselian Ice Age, since we know nothing of what may have gone on in the extensive central area of the ice sheet at that stage (RAINIO & LAHERMO 1976; AARIO & FORSSTRÖM 1979; HIRVAS et al. 1981; FORSSTRÖM 1984). They can, however, be said to reflect the form of the retreating ice sheet from which we may conclude that the deglaciation history of the area must have had a considerable influence upon trends in land uplift.

Shoreline displacement during the Eemian interglacial

Since only scattered pieces of information are available on Eemian shore levels in the Fennoscandian land uplift area, it is quite impossible to formulate any consistent picture of the shorelines of the 'Eemian Sea' (KÖNIGSSON 1979). Material has nevertheless gradually been accumulating, to the extent that some interesting points can now be raised for discussion.

DONNER (1983) has recently discussed the connections between postglacial shoreline displacement and certain interglacial and interstadial finds, taking as his starting point the assumption that shoreline displacement at the beginning of the Eemian interglacial followed something of the same pattern as that which has taken place since the Weichselian glaciation. Largely for this reason, DONNER concludes that certain terrestrial organic deposits interpreted as Eemian in origin cannot be connected with that phase because they are located nowadays so close to sea level that they would have lain in a subaquatic position immediately after the Saale deglaciation. Thus he prefers to correlate these deposits with the more recent Peräpohjola interstadial (KORPELA 1969), sites for which exist relatively close to present sea level. The terrestrial deposits concerned include those at Oulainen, about 80 m a. s. l. (FORSSTRÖM 1982, 1984), and Vimpeli, about 120 m a. s. l. (AALTO et al. 1983; DONNER 1983). The highest sea level at the beginning of the Flandrian was around 200 m in both areas, and the lower of the two, the Oulainen site, emerged from beneath the waters of the Baltic only after the onset of the Litorina Sea phase (Fig. 3 and 4).

The pollen flora at Oulainen suggests that this deposit represents the beginning of the thermomer, without the actual climatic optimum being visible at all. The relatively large numbers of *Corylus* grains and occasional examples of *Carpinus* in the upper parts

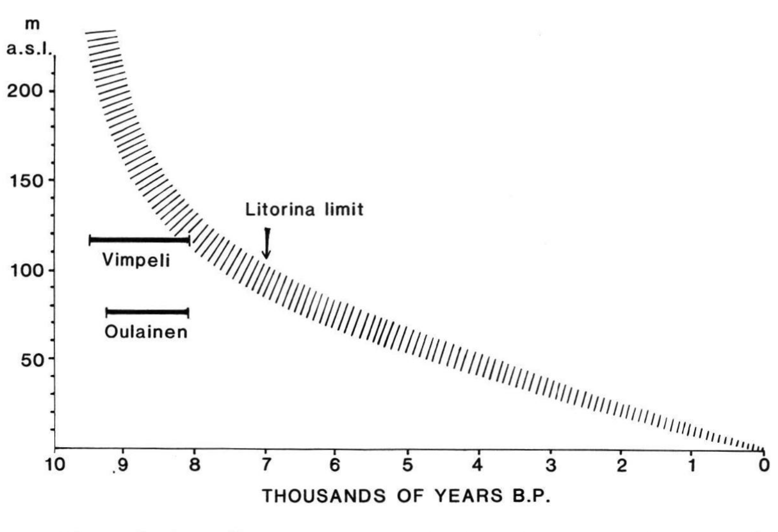

Fig. 3: Schematic shore displacement curve for the Pohjanmaa region, east of the Gulf of Bothnia. The heights of the interglacial deposits at Oulainen and Vimpeli are shown by the straight lines. The lengths of the segments indicate the time and duration of the interglacial sediment deposition in relation to corresponding deposition during the Flandrian time.

of the sediments that have been preserved nevertheless represent a typical Eemian pollen spectrum and are indicative of a very much warmer climatic phase than the birch-dominated cool climate vegetation denoted by the Peräpohjola interstadial finds in Finnish Lapland. Finds correlated with the Eemian are also reported from Lapland in which the pollen flora, with its high proportions of pine, is easily relatable to the Oulainen deposits (FORSSTRÖM 1982). Similarly the plant macrofossils from Oulainen (AALTO 1982) and the Coleoptera fauna (MOSELEY, in preparation) are descriptive of a warm interglacial climate.

The pollen record in the Vimpeli deposit (AALTO et al. 1983) corresponds well to that found at Oulainen, but unfortunately here again the sediments representing the climatic optimum are missing. The macrofossils present which are indicative of a warm climate, *Lycopus europeus, Carex riparia* and *Thalictrum lucidum,* are nevertheless sufficient to demonstrate that the climate was undoubtedly warmer at that time than it is nowadays at that site.

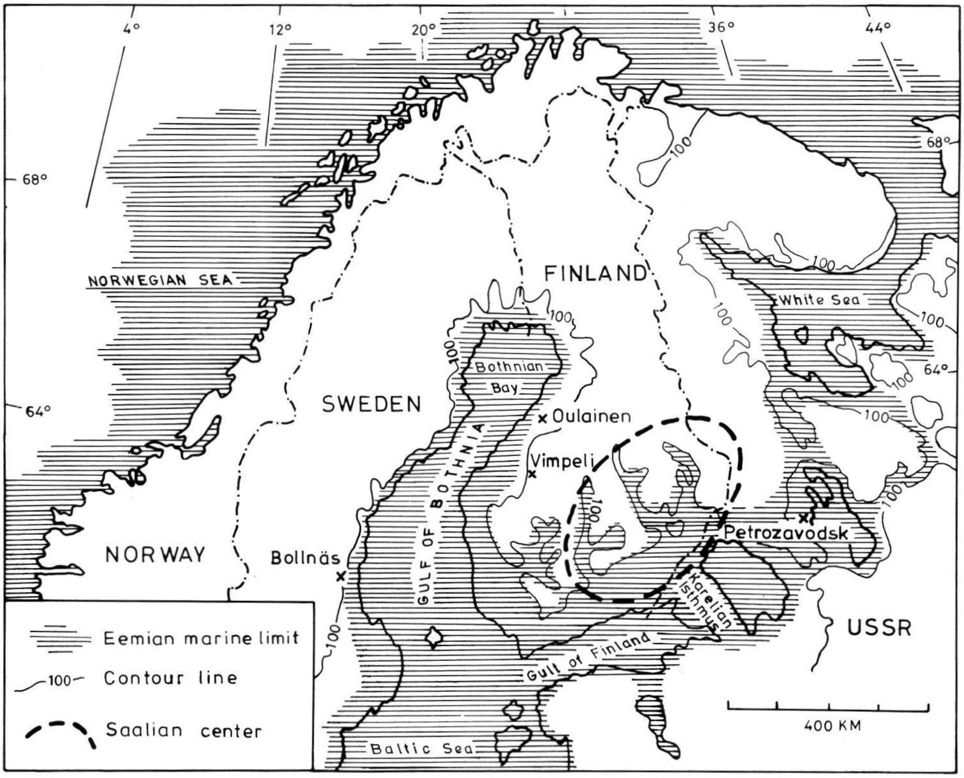

Fig. 4: Map showing the assumed extent of the Eemian Sea in the northern Baltic area and in Karelia. The interglacial sites discussed in text are marked on the map. The centre of the ice sheet during later phases of the Saale glaciation may have been somewhere around southeastern Finland. That conclusion is reached from the maximum extent and assumed thickness variations of the Saale (Warthe) ice sheet (cf. Fig. 5).

The Eemian deposit at Bollnäs in central Sweden lies at a height of approx. 90 m a. s. l., which is of the same order as the Oulainen and Vimpeli sites (HALDEN 1948; see Fig. 4), and although the 2 m gyttja and peat horizon may have moved slightly from its original position, it is scarcely likely to have moved so far as to cause any essential change in its height. The diatoms in these sediments show that the lower part of the profile was laid down under freshwater conditions, whereas in the upper part brackish water species were also present. At this time spruce was growing in the area, whereas by the time spruce had spread there during the Flandrian the site was already about 50 m above sea level (HALDEN 1948). Large amounts of spruce pollen are to be found fairly early on in the Eemian in Denmark (ANDERSEN 1965), so that it may be that it also came to Bollnäs from the south at a relatively early stage, and the marine transgression in the area may be due to the continuing eustatic rise in sea level (cf. ZAGWIJN 1983). Another explanation for the transgression could be depression of the earth's crust, possibly isostatic in nature, provided that the area were situated sufficiently far away from the centre of land uplift, or that the depression occurred for other reasons.

The marine Eemian deposits reported at Petrozavodsk are located at 30—40 m a. s. l., far higher than the Flandrian marine phases ever reached (LUKASHOV et al. 1982; see Fig. 4). There could well have been a marine connection between the Baltic and the White Sea at that stage, even though it does not represent the Portlandia transgression proposed for the White Sea by ZANS (1936), which apparently occurred only after the Eemian. The Karelian Isthmus was also covered by the sea for some time during the Eemian, as was southern Finland, although the evidence is not particularly strong in the latter case (DONNER 1983).

The Eemian sea level did not reach far beyond present sea levels on the south coast of the Gulf of Finland or in the southern Baltic (KÖNIGSSON 1979), and in the North Sea area it even remained below present levels, its markers lying at approx. 8 m below sea level (ZAGWIJN 1983). The extent of land subsidence in Holland since the Eemian is indeed in good agreement with the long-term rate of subsidence, so that it could be attributable to tectonic factors (ZAGWIJN 1983), although glacial isostasy may also have been involved (WU & PELTIER 1983). The Eemian shoreline displacement attributable to movements in the earth's crust in the southern Baltic and the North Sea region was nevertheless sufficiently restricted in scope that it tends to be obsccured by the relatively large eustatic variation in sea levels (cf. ZAGWIJN 1983) and the not inconsiderable changes in the form of the geoid (WU & PELTIER 1983). For this reason, any assessment of differences in land uplift behaviour between Eemian and Flandrian times could be carried out much more successfully in areas situated close to the centres of land uplift, where glacial isostasy is inevitably the major factor affecting shoreline displacement, even though we do suffer from a dearth of data regarding the Eemian marine phase in such areas.

Comparison of Eemian and Flandrian crustal movements

The Weichselian glaciation in Fennoscandia may be assumed to have covered quite extensive areas during a period extending from around 75,000 B. P. up to the deglaciation, since the oxygen isotope relations in deep-sea cores indicate the total volumes of the world's glaciers to have been relatively large over the whole of that time (FORSSTRÖM

1982, 1984). The centre of the glacier may well have been located somewhere in the Bothnian Bay area of the northern Gulf of Bothnia throughout, so that the earth's crust will presumably have achieved an isostatic equilibrium in that area with respect to the mean burden of ice, although an equilibrium may not necessarily have been achieved with respect to the maximum loading, which was of relatively short duration (cf. Wu & Peltier 1983). Melting was relatively slow for a considerable time following the glacial maximum, allowing an apprecciable part of the land uplift corresponding to the reduction in the ice burden to take place during this phase. The arrest of the ice margin at Salpausselkä then increased the importance of the deglaciation phases, however, so that it is quite understandable that the isobases of land uplift should represent fairly accurately the configuration of the ice sheet at that time and its probable variations in thickness.

When comparing movements in the earth's crust during the Eemian and Flandrian periods it is necessary to pay particular attention to the starting point for this comparison, i. e. to what level of the land surface these comparisons are to be related. If we argue that the present extent of land uplift and part of the Gulf of Bothnia gravity anomaly are due to glacial isostasy, the residual uplift would be of the order of 100 m at least, i. e. an amount corresponding to between —15 and —20 mgal (Balling 1980). Since this isostatic imbalance must have been the product of the concentrated pressure of the Weichselian ice sheet acting over a considerable length of time, it would be wrong to assume that the situation at the beginning of the Saale glaciation could correspond to that prevailing at present. It is far more likely that it was closer to a state of equilibrium, and that the bed of the 'Gulf of Bothnia' was higher than it is nowadays.

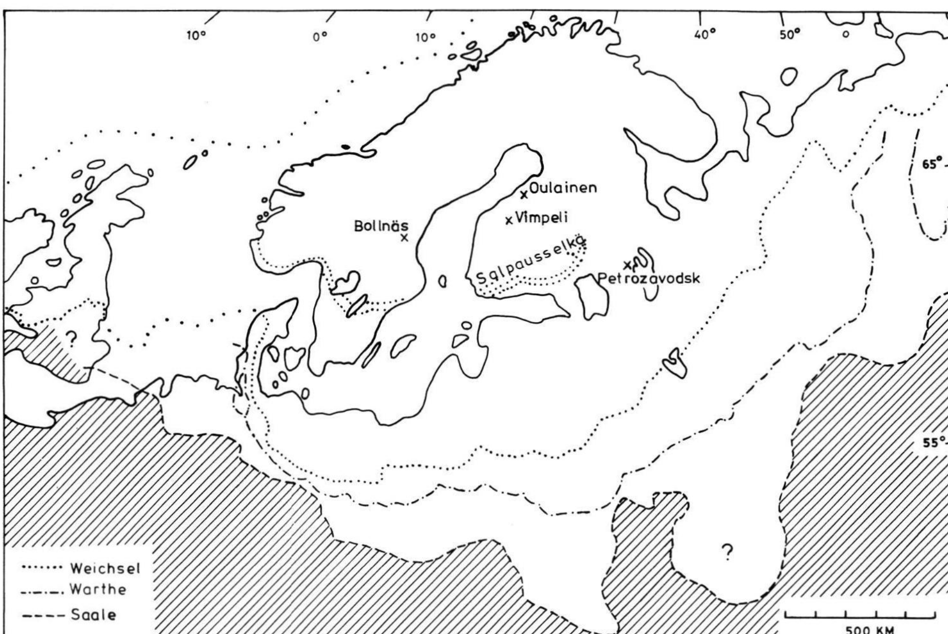

Fig. 5: Map showing the maximum extent of the Saale, Warthe, and Weichselian ice sheets. Compiled primarily after Woldstedt (1954) and Grosswald (1980).

The Saale ice sheet was more extensive than the Weichselian both at its maximum, the Drenthe, and during the later Warthe phase (Fig. 5), and the intervening Treene (Gerdau) period (LÜTTIG 1964; GRUBE 1967) was similarly not an especially pronounced melting phase (EHLERS et al. 1984). This agrees well with the deep sea oxygen isotope data, which indicate that the world's glaciers remained extensive for several tens of thousands of years towards the end of the Saale glaciation (cf. RUDDIMAN & MCINTYRE 1981). Nothing is known of the deglaciation phase of the Saale (Warthe) ice sheet, although the mutually consistent deep-sea data and palynological evidence would seem to provide reliable information on the manner of its melting. Detailed study of the planktonic foraminifera in the deep-sea cores from the north-east Atlantic indicate that at no time during the Brunhes epoch did the surface waters of that part of the Atlantic warm up as quickly from a typical glacial situation to a full interglacial period as they did at the transition between stages 6 and 5, i. e. from the Saale (Warthe) to the Eemian (RUDDIMAN et al. 1977). Similarly pollen assemblages zones from the beginning of the Eemian, as dated from varved diatomite, suggest that the transition to a warm interglacial vegetation took place very rapidly (MÜLLER 1974), even though the estimates for the earliest phases of all may err on the short side (ZAGWIJN 1983). The rapid warming of the climate at the boundary between the Saale (Warthe) and the Eemian probably served to melt the extensive Warthe ice sheet in a matter of a few thousand years, a radically different situation from that prevailing during the Weichselian deglaciation, which lasted almost 10,000 years.

Apart from knowledge of the deglaciation model, it would also be necessary from the point of view of land uplift behaviour at the beginning of the Eemian to know whether or not an isostatic equilibrium prevailed during the Warthe, but this is something on which one can do little more than speculate. An isostatic equilibrium is by no means inevitable when one bears in mind that the Warthe ice sheet, which was more extensive than the Weichselian, presumably covered virtually the whole of the northern regions, and that its ice burden pattern was a highly complex one (see GROSSWALD 1980). One may nevertheless assume that the earth's crust was relatively deeply depressed at the centre of the glacier, which may have been somewhere around southeastern Finland (Fig. 4).

The warm climate which marked the beginning of the Eemian presumably melted the ice at all its margins and reduced its thickness throughout, so that by the later phases there would not have been the same kind of thick, active ice sheet present as threre was during the Salpausselkä phase, but perhaps a number of separate stagnation glaciers much reduced in depth. The thinning of the overlying ice, and the resulting lifting of the burden on the earth's crust would thus have been compensated for in terms of rapid land uplift, so that at least the elastic rebound action of the crust would have taken place before the ice had finally melted away.

Conclusions

Eemian deposits discovered in the Gulf of Bothnia area and in Soviet Karelia allow us to conclude that the centre of land uplift during the last interglacial was not around the Bothnian Bay, as during the Flandrian, but somewhere in the region of southeastern Finland, where the centre of the Saale ice sheet was evidently also situated. The history of the Saale glaciation in turn leads us to presume that the isobases of Eemian land uplift did not follow such a steep gradient as their Flandrian counterparts, and that uplift subsequent to the melting of the ice was fairly slow. The coast of the Gulf of Bothnia was very much higher in relative terms early in the Eemian than it was at the beginning of the Flandrian, but depression perhaps occurred in central Sweden some time later in the Eemian. This site may represent the margin of the area affected by land uplift, which drops as the centre rises, or else this effect may, at least in part, be attributed to other factors bringing about movements in the earth's crust.

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