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Land uplift and relative sea-level changes in the Loviisa area, southeastern Finland, during the last 8000 years

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September 1999

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LAND UPLIFT AND RELATIVE SEA-LEVEL CHANGES IN THE LOVIISA AREA, SOUTHEASTERN FINLAND, DURING THE LAST 8000 YEARS

Tiivistelmä – Abstract

Southeastern Finland belongs to the area covered by the Weichselian ice sheet, where the release of the ice load caused a rapid isostatic rebound during the postglacial time. While the mean overall apparent uplift is of the order of 2 mm/yr today, in the early Holocene time it was several times higher. A marked decrease in the rebound rate occurred around 8500 BP, however, since then the uplift rate has remained high until today, with a slightly decreasing trend towards the present time. According to current understanding there have neither been temporary increases nor decreases in the rate of uplift during the postglacial time. Even so, it is not known for sure whether there are regional irregularities on the rebound in Finland.

Concurrently with land uplift, relative sea-level changes in the Baltic basin were also strongly affected by the global eustatic rise of sea-level. During the early Litorina Sea stage on the southern coast of Finland around 7000 BP, the rise in sea-level exceeded the rate of land uplift, and resulted in a short-lived transgression. The most accurate information on relative sea-level changes in an uplifting area may be obtained from radiocarbon dated events of isolation in small lake basins, as they were cut off from larger bodies of water. The isolations of such basins from the sea may be reliably determined by the recorded changes in the diatom flora in the sediment sequences, at horizons which may be radiometrically dated.

In the present study, the isolation-horizons of 13 basins were dated by 26 conventional and 2 AMS radiocarbon dates. According to the available sets of dates, the time span of emergence extends from 8300 BP to the past few hundred years, for lakes from c. 30 m to 1.1 m above the present sea-level. Due to the global rise in sea-level, during the period of 7500-6500 BP, the sea-level rise clearly exceeded the rate of uplift, and resulted in the Litorina transgression, which had an amplitude of around one metre. The shoreline displacement curve of the Loviisa area both indicates a relatively regular uplift and an overall relative sea-level lowering during the last 6500 years. Overall, then the results indicate that land uplift has proceeded in an even manner, and that its rate has only being slowly decreasing during the past 8300 ^{14}C-years.

Avainsanat - Keywords
isostatic land uplift, sea level changes, isolation of lake basins

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MAANKOHOAMINEN JA MERENPINNAN SUHTEELLINEN KORKEUSVAIHTELU VIIMEISEN 8000 VUODEN AIKANA LOVIISAN ALUEELLA KAAKKOIS-SUOMESSA

Tiivistelmä – Abstract

Kaakkois-Suomi kuuluu Veiksel-jäätikön peittämään alueeseen, jossa jäätikön painon vapauduttua on tapahtunut isostaattista maankohoamista. Nykyinen maankohoamisnopeus Loviisan alueella on noin 2 mm/v, mutta varhais-Holoseenin aikana maankohoaminen oli huomattavasti nopeampaa. Maankohoaminen oli nopeinta heti jäätikön sulamisen jälkeen yli 8500 radiohiilivuotta sitten, ja on sen jälkeen vähitellen hidastunut. Nykykäsityksen mukaan maankohoamisnopeudessa ei ole tapahtunut lyhytaikaisia vaihteluja, mutta ei tiedetä varmasti, onko joillain alueilla esiintynyt paikallisia maankohoamisen epäsäännöllisyyksiä.

Maankohoamisen lisäksi maailmanlaajuiset merenpinnan korkeuden vaihtelut vaikuttavat Itämeren suhteellisen merenpinnan vaihteluihin. Litorinavaiheen alkupuolella noin 7000 radiohiilivuotta sitten, merenpinnan kohoaminen oli Etelä-Suomen rannikolla maankohoamista nopeampaa, jonka seurauksena oli lyhytaikainen merenpinnan transgressio. Järvialtaiden kuroutumistutkimuksilla saadaan tarkimpia tuloksia tutkittaessa suhteellisen merenpinnan liikkeitä isostaattisen maankohoamisen alueella. Tällöin Itämerestä kuroutuneiden järvialtaiden pohjasedimenteistä määritetään litostratigrafian ja piilevien avulla kuroutumishorisontit, jotka ajoitetaan radiometrisin menetelmin.

Tässä tutkimuksessa tehtiin 13 altaan kuroutumishorisonteista 26 konventionaalista ja kaksi AMS radiohiiliajoitusta. Altaiden kuroutumishistoria ajoittuu 8300 radiohiilivuodesta muutama sata vuotta nykyhetkestä taaksepäin, altaiden korkeuden ollessa n. 30 - 1,1 metriä nykyisen merenpinnan yläpuolella. Maailmanlaajuisen merenpinnan kohoamisen vuoksi merenpinta ylitti maankohoamisnopeuden aiheuttaen 7500-6500 vuotta sitten Litorinatransgression, jonka amplitudi oli metrin luokkaa. Loviisan alueen rannansiirtymiskäyrä osoittaa suhteellisen merenpinnan korkeuden tasaista laskua viimeisen 6500 radiohiilivuoden aikana. Tulosten perusteella maankohoaminen on ollut tasaisesti hidastuvaa viimeisen 8300 vuoden aikana.

Avainsanat - Keywords
isostaattinen maankohoaminen, merenpinnan korkeusvaihtelu, järvialtaiden kuroutuminen

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1 INTRODUCTION

Pronounced land uplift has occurred in Fennoscandia since the melting of the Weichselian ice sheet, which covered northern Europe during the last ice age. The explanation for the occurrence of the uplift following deglaciation is glacio-isostasy. Because the load of the thick glacier ice had depressed the earth's crust by several hundred meters, its release as the ice sheet was shrinking set off a vigorous isostatic rebound which then caused the crust to rise up. Though it has been estimated that the maximum depression in the central area of the former Weichselian ice sheet in northern Sweden was over 650 m approximately 15 000 years ago (Fjeldskaar 1994), there is no geological data to verify these figures because a great part of the uplift took place under the melting and thinning ice. The uplift was extremely rapid during and immediately following the deglaciation. A marked decrease in the land uplift rate occurred around 8500 BP years ago, however, since then, it has remained high until today, with a gradually decreasing trend into the present time (Fig. 1; Ekman 1989).

Owing to the uplift and consequent tilting of the land, there exist several water connections between the Baltic and the open ocean, which were closed at various points in times during the late Weichselian and the Holocene. Concurrently with land uplift, relative sea-level changes in the Baltic basin were strongly affected by the global eustatic rise in sea level. The highest shore marks of the Baltic waters in Finland are now to be found well beyond 200 m above the present sea level (Eronen 1990, Eronen and Ristaniemi 1992). Further, the postglacial evolution of the coastlines in the northern part of the Baltic basin has been dominated by the emergence of new land areas. Although morphological raised shorelines (boulder fields, wavecut benches, beach ridges) may be found at various levels, the most useful information on shoreline displacement is obtainable in the sediments of small lake and bog basins. The isolation of such basins from the waters of the Baltic Sea can be identified by means of diatom analyses and dated by the radiocarbon method. In this report we present a number of new data obtained through the study of small-lake sediments in southeastern Finland, followed by a discussion of the general pattern of postglacial shoreline displacement and land uplift in Finland.

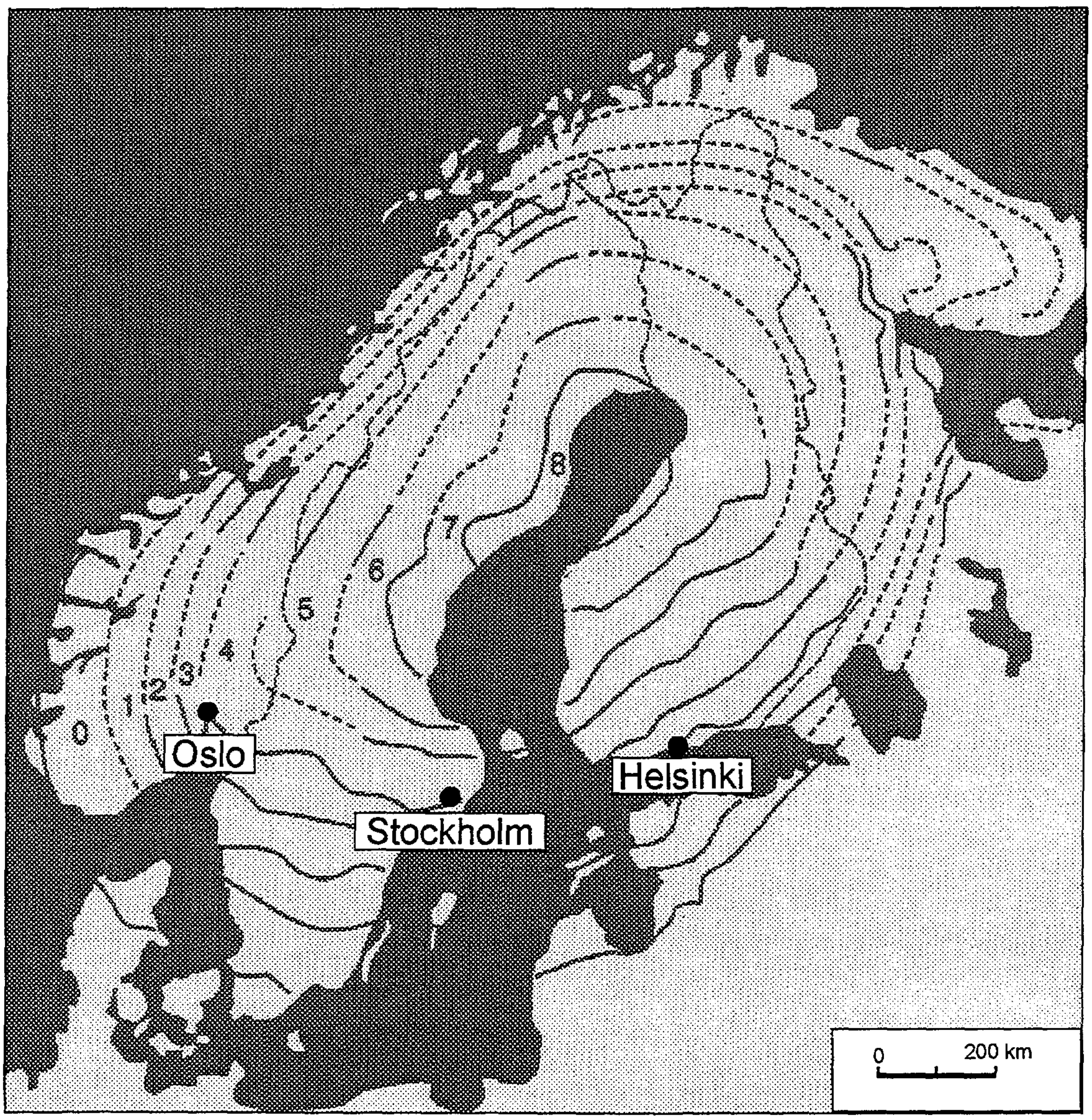

Fig. 1. The present apparent land uplift in Fennoscandia.

2 STAGES OF THE BALTIC SEA

The huge amounts of meltwater that were released from the waning ice sheet and collected in the southern part of the Baltic basin, formed the Baltic Ice Lake (Fig. 2), which had its outlet through Öresund (Björck 1995). The Baltic Ice Lake stage came to an end when its dammed waters were drained by an outlet through central Sweden, whereafter the lake level lowered by about 25 m in approximately 10 300 BP (Svensson 1991, Strömberg 1992, Björck 1995).

At the time of the final drainage of the Baltic Ice Lake, the water level in the Baltic basin dropped to the contemporary oceanlevel. Consequently, some influx of saline water from the ocean into the Baltic basin took place around 9900 BP, for a period lasting from 100-200 years (Svensson 1991), marking the Yoldia stage. It was primarily this flow over the Närke Strait in central Sweden that brought mildly saline water mainly to the southern Baltic, however a slight increase in salinity can be traced even further up to the southern coast of Finland (Eronen 1976). On the whole, salinity remained low throughout the basin, even in areas rather close to the Närke Strait. Due to this fact, there was no true "sea" in the Baltic basin during the Yoldia stage (Eronen 1974, 1983, Svensson 1991, Raukas and Hyvärinen 1992, Björck 1995, Påsse 1996, Lepland et al. 1999).

The rapid land uplift caused the severance of the connection between the Baltic basin and the ocean by 9500 BP. As a consequence, the water level began to rise above that of contemporary oceans, leading to the Ancylus Lake stage which was characterized by a widespread and rapid flooding. This flooding, known as the Ancylus transgression, occurred in the southern part of the Baltic, as the uplift there was slow or non-existent (Björck 1995). Water level rose also in southern Finland (Ristaniemi and Glückert 1988, Glückert 1991, Eronen and Ristaniemi 1992).

Due to the progressive retreat of the ice margin from the southeast to the northwest as the water levels were changing, the highest shoreline in the Baltic basin is highly diachronous. While in the southeast, it dates back to the Baltic Ice Lake, it was formed during the Yoldia and Ancylus stages further north. The shoreline reaches its maximum height in Finland north of the Gulf of Bothnia at ca. 220 m a.s.l. (Eronen 1983).

Then, the fresh-water lake of the Ancylus stage began to shrink due to a rapid fall in water level, when a new outlet through the present Store Belt in Denmark was eroded (Björck 1995). This outlet remained active until the eustatic rise of the sea level allowed the flow of marine water into the Baltic over the thresholds of the Danish straits in between 8200-8000 BP. The Ancylus stage then came to an end, and a new phase in the history of the Baltic began (Winn et al. 1986, Eronen et al. 1992, Björck 1995). The Ancylus lake was followed by a transitional and slightly saline phase, known as the Mastogloia phase, which proceeded the more brackish Litorina stage that then commenced. Because the water level in the Baltic was the same as that of the open ocean, the relative sea-level changes of the Baltic from that time can be correlated with the sea-level changes during the past c. 8500 ^{14}C years.

The name "Mastogloia" refers to a group of diatoms commonly found living in slightly saline waters. The frequent occurrence of such *Mastogloia* species among the diatom flora characterizes the intermediate phase, which occurred when the influx of marine water began to modify the former large-lake ecosystem of the Baltic basin. Moreover, the term Litorina Sea dates back to the 19th century, when the shells of this brackish water gastropod *Littorina littorea* were found on raised beaches in Sweden.

The saline water spread from the ocean to the Baltic from the southwest, flowing first to the deeper southern basins of the Baltic. The "filling" of the entire Baltic with brackish water probably took several hundred years and, due to this fact, the change from fresh-water to brackish conditions in the basin is time-transgressive. While in the southwest Baltic the weak salinity of the Mastogloia phase can be traced as early as the time of 8200 BP (Björck 1995), on the Finnish coasts it is first observable by 8000 BP (Hyvärinen 1984). The major part of the Baltic had clearly turned brackish by 7500 BP, which marks the onset of the Litorina Sea stage. This change, however, was delayed by c. 500 years in the area of the Gulf of Bothnia in the northernmost part of the Baltic (Eronen 1974).

This change in the brackish conditions in the Baltic also brought about an increase in the nutrients upon which the ecosystem of the Litorina Sea became more eutrophic than those of the earlier stages. Thus the onset of the Litorina Sea is an important horizontal marker, which can be seen in the sediments as a change from grey Ancylus (including Mastogloia) clays to organic-rich Litorina clay-gyttjas, or gyttja-clays (Winterhaller et al. 1981) (Fig. 3). A similar change is indicated by diatoms preserved in sediments as the replacement of flora dominated by fresh-water species by an entirely different brackish-water assemblage. The upper limit of the Litorina Sea is therefore reliably determined and dated by the highest occurrences of brackish-water sediments at the raised shore levels (Eronen 1990).

In the beginning of the Litorina Sea stage the transgression resulted from the rising global sea level. In fact, the eustatic rise caused by the melting of the ice sheets also occurred during the Mastogloia phase, after the inundation of the threshold in Denmark. Consequently, the rising ocean level must have caused a "Mastogloia transgression" in large areas of the Baltic as well. However, that episode is difficult to discern, because its layers are overlain by the brackish-water deposits from the following, larger Litorina transgression. The transgressive water flooded areas where uplift was slower than the sea-level rise. A marked decrease in the rate of uplift had occurred between 8500-8000 BP on the southern and southeastern coast of Finland, allowing the relative sea-level to rise during c. 1000 years after the beginning of the Litorina Sea stage (Eronen 1983, 1990). This transgression came to an end, when the eustatic rise first slowed down and later practically ceased around the time 6000-5000 BP (Pirazzoli 1991, 1996). During the past 6000 years the relative sea level has progressively fallen due to uplift while, at the same time, the salinity has decreased as a result of the narrowing of the connection to the ocean (Glückert 1976, Eronen 1983, Eronen 1990).

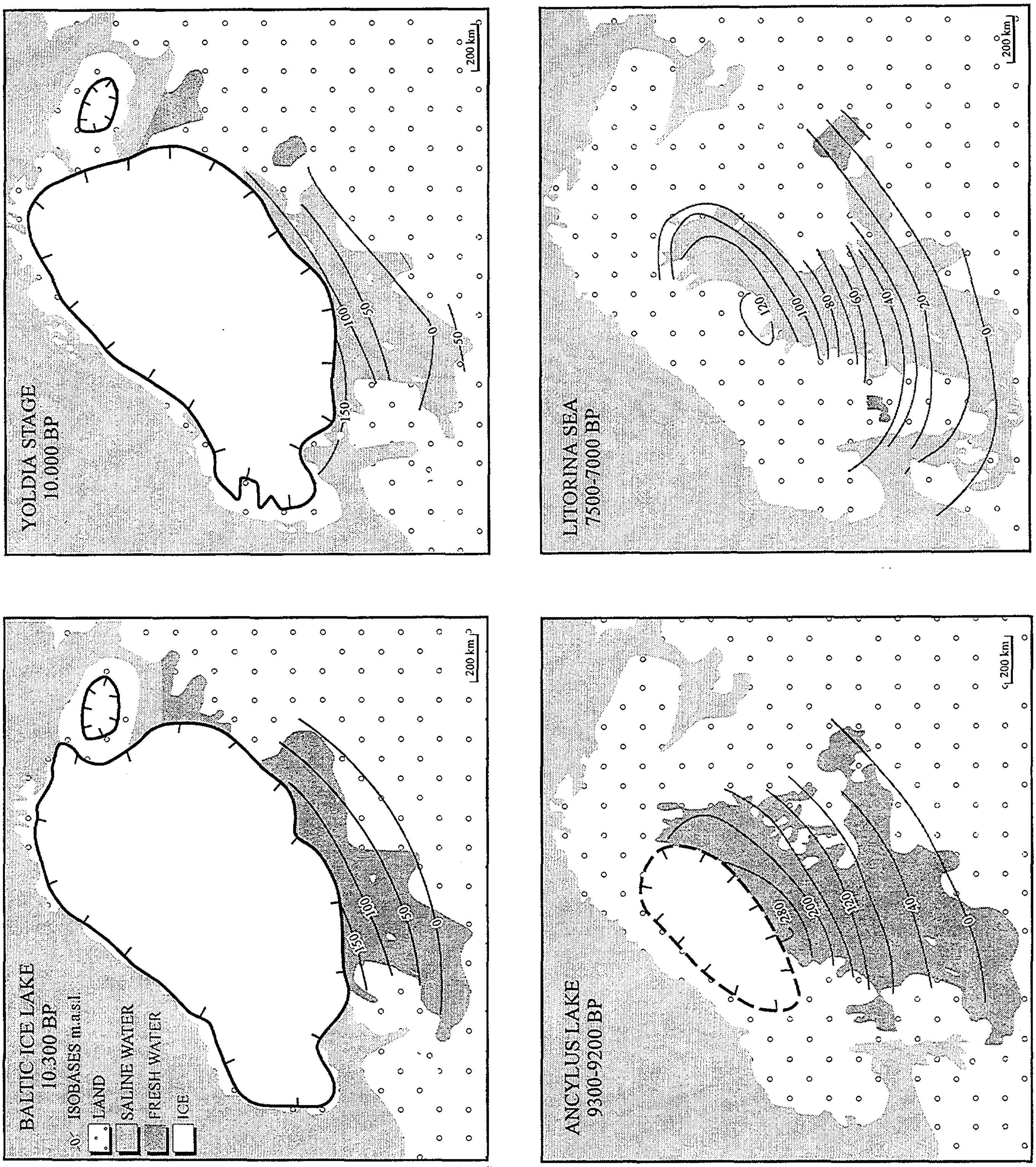

Fig. 2. The main stages in the development of the Baltic Sea.

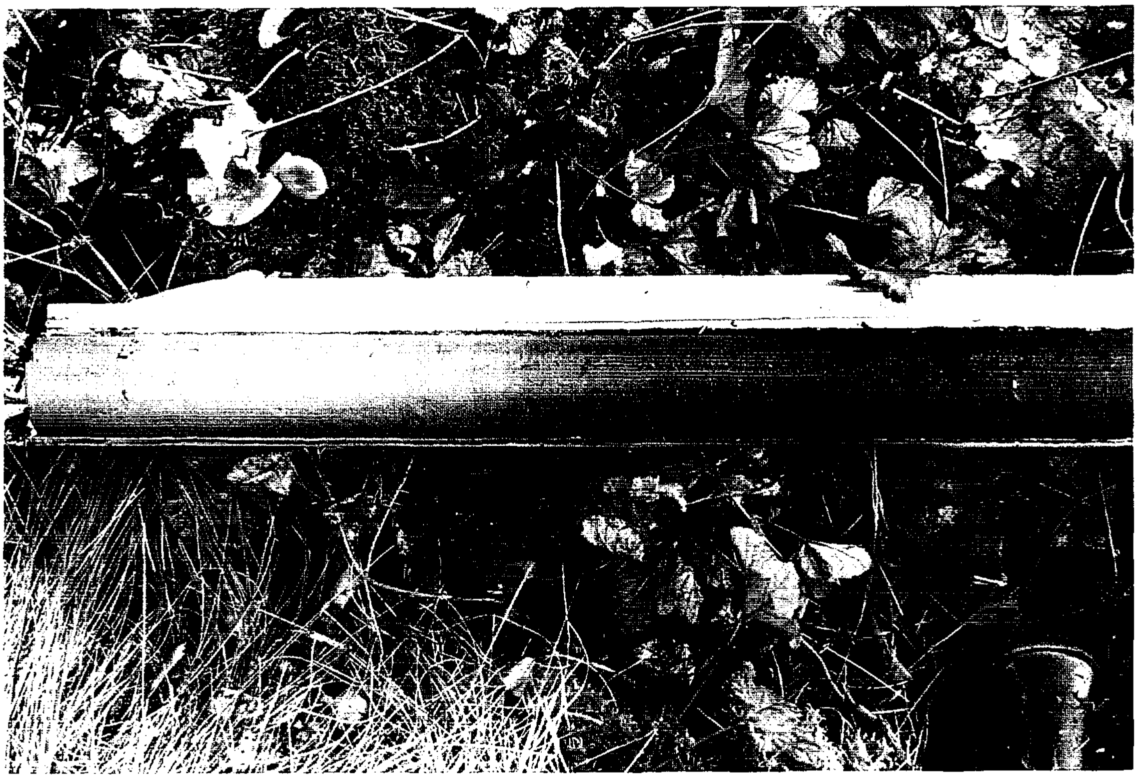

Fig. 3. A sediment sample, taken with a Russian peat corer. Bog Degermossen 20.8.1998. The transition from greyish clay deposited in the Ancylus Lake to greenish clay-gyttja deposited in the Litorina Sea.

3 STUDY AREA

The size of the study area is about 38 x 20 km, and it extends from Ruotsinpyhtää to Porvoo (Fig. 4). As the topography of the study area is relatively flat, the number of small lakes are relatively small. For this reason, sediment cores were also collected from mire basins. Because the greater part of the mires have been reclaimed in southern Finland, there were also problems in finding suitable coring sites. However, a sufficient number of small lakes and mire basins were found at varying elevations above the sea level, so the region was suitable for studies on relative sea level changes.

The bedrock in the eastern part of the study area (including Loviisa Hästholmen) consists of younger Proterozoic rocks, known as Rapakivi granite (age 1.6 Ga) (Rämö et al. 1998). The western part of the study area, east of Loviisa, consists of early Proterozoic igneous rocks, that are mainly composed of granite (age > 1.8 Ga) (Nironen 1998).

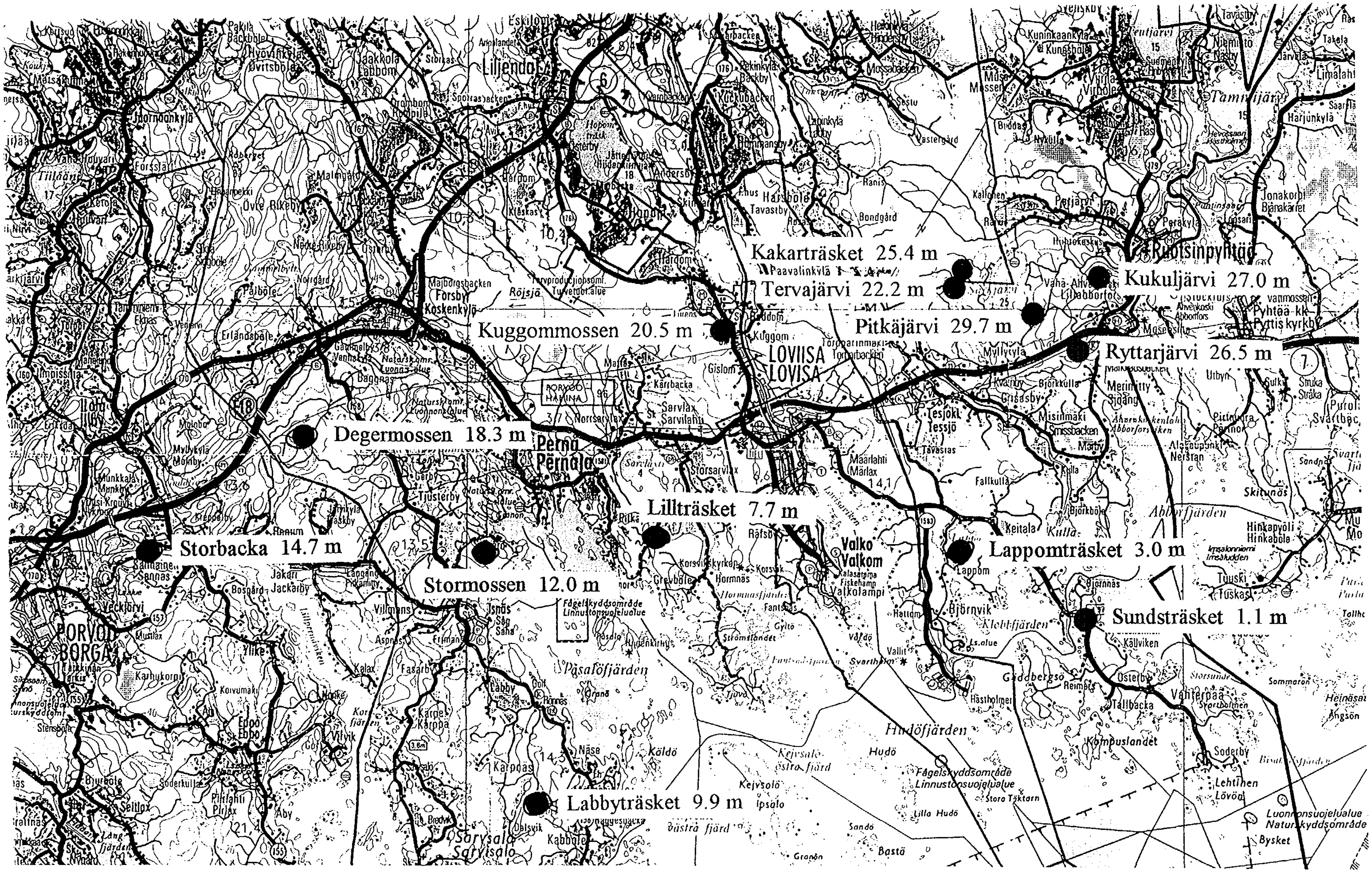

Fig. 4. The study area and coring sites.

4 MATERIALS AND METHODS

Nowadays the best and most accurate information on Holocene shoreline displacement is obtained from small lake and mire basins, where the emergence from a larger body of water may be determined in the sediment sequence by means of diatom analyses, and dated by radiocarbon method.

Over 200 radiometric dates have been obtained for the purpose of shoreline investigations from lakes and mires in Finland, so far (Eronen et al. 1995). These data consistently show that land uplift was very rapid in the early Holocene times, though it decelerated thereafter (Glückert 1976, Matiskainen 1989, Eronen 1990, Donner 1995, Ristaniemi et al. 1997). New data were collected in the course of the present study from the lakes and mires to find out, if any small-amplitude oscillations could be discerned in the relative sea-level lowering in southeastern Finland during the past 8000 years. It was hypothesized that short-term sea-level variations in the Baltic could possibly be correlated with contemporaneous events in the open ocean sea level.

Suitable sites for coring were located using base maps at a scale of 1:20 000. Sediment cores were collected from 10 lakes and 5 mires in the winter and summer of 1998. Most lakes were cored from the ice at their centre, however it was necessary to do part of the coring during the summer from the mires.

A Russian peat sampler was used in the collection of sediment cores. The stratigraphy of the lake and peat sediments were examined and the isolation was identified by visual inspection. Usually it can be easily seen as a change upward from greyish sediment deposited in the Baltic basin to greenish or brownish small lake gyttja. One metre long cores extending below and above the isolation contact taken from 10 lakes and 5 mires, were found suitable for the present research. In all of the sampled lakes the water depths did not exceed a maximum of a few meters.

The sediment cores were studied at the Department of Geology, University of Helsinki. Loss-on-ignition was determined by drying the samples for 12 hours at 105° C, and subsequent combustion at 550° C. Samples for diatom identifications (1 cm^3) were taken from the cores at intervals of five cm. They were first treated with hydrogen peroxide (30%) in order to bleach and destroy the organic matter. The coarse mineral grains were then removed by repeated decanting and diluting of the diatom fraction by suspending it in water. An adequate amount of condensed suspension was transferred to a cover slip, and permanent mounts were made in Caedax hartz.

The organic content of the sediment measured by loss-on-ignition was the parameter used in this study as an indicator of lake basin emergence (Fig. 5a,b,c). As a rule, the sediment deposited in small lakes is organic-rich gyttja, and thus the onset of its deposition in a core indicates that the basin has risen above the sea level of the time of sedimentation. More conclusive evidence of the change from marine or brackish environments to a fresh-water lake are obtainable from the diatom studies. In the present study, preliminary diatom analyses were only made to determine the isolation contacts, and define the appropriate range of the core suitable for radiocarbon samples. First, the dominant species indicating brackish or fresh-water conditions were identified. Such preliminary studies allowed the rejection of some cores that were considered unsuitable for the present purposes, due to hiatuses or perturbations in the sediments. This study was, therefore, based on the remaining 13 cores.

Sediment samples (5-10 cm) from suitable cores were cut from the uppermost brackish-water, or transitional sediment, and lowermost layer of fresh-water gyttja for radiometric dating. Consequently, two ^{14}C dates were available for each isolation-horizon. In one lake basin, an additional dating was made (Table 1). Most of the dates are bulk samples. Two AMS dates were made from plant fragments extracted from the sediments. The bulk sediment dates were preferred, because the sediment at the isolation-contact was usually fine detritus gyttja in which it was difficult to find any coarse plant remains. Altogether, 26 conventional and 2 AMS radiocarbon dates were used to draw the separate shore line curve (Fig. 6). The radiocarbon dating was made at the Dating laboratory of the University of Helsinki. The dates were calibrated to calendar years with a programme developed by van der Plicht (1993), which uses bidecadal tree-ring data.

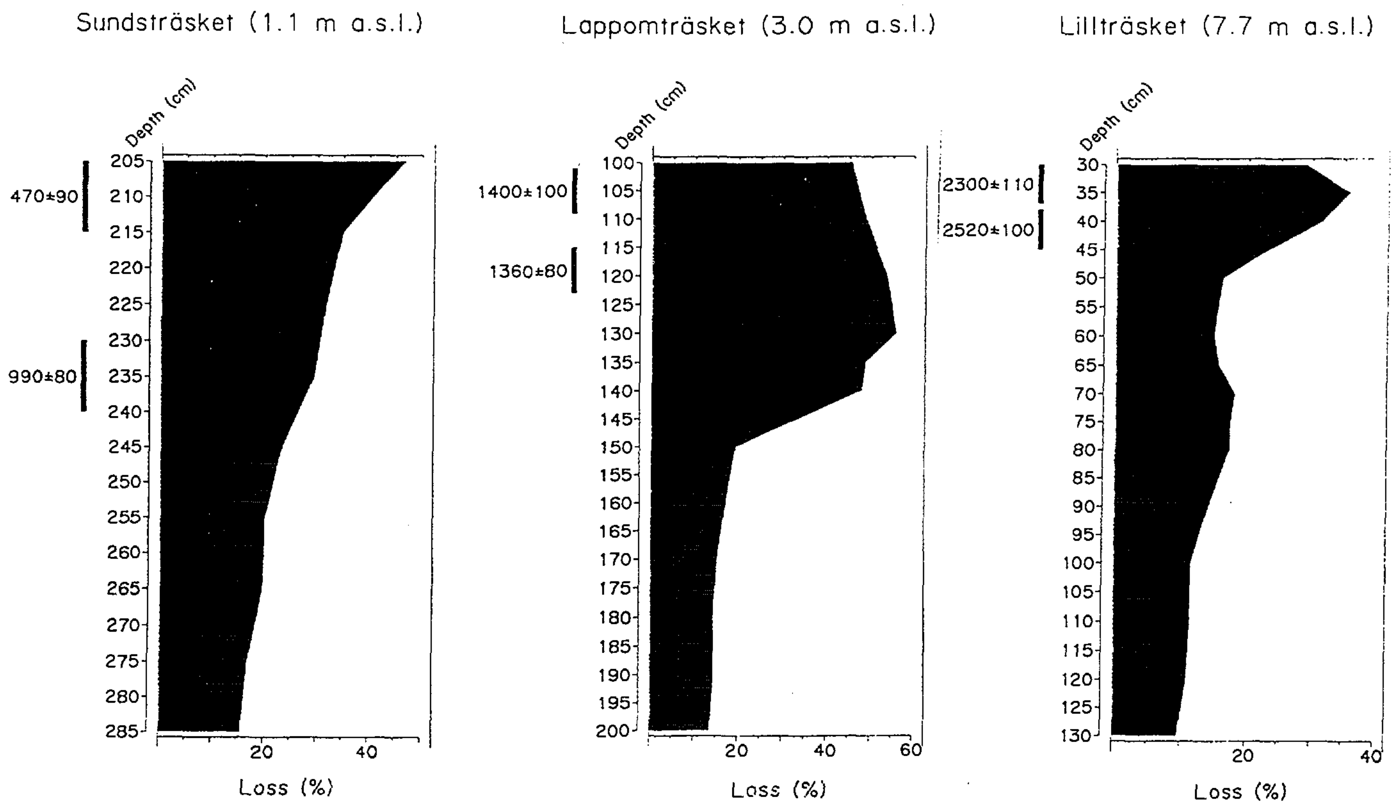

Fig. 5a. Loss-on-ignition curves of the studied lake sequences and the radiocarbon dates made from below, middle or above the isolation horizons.

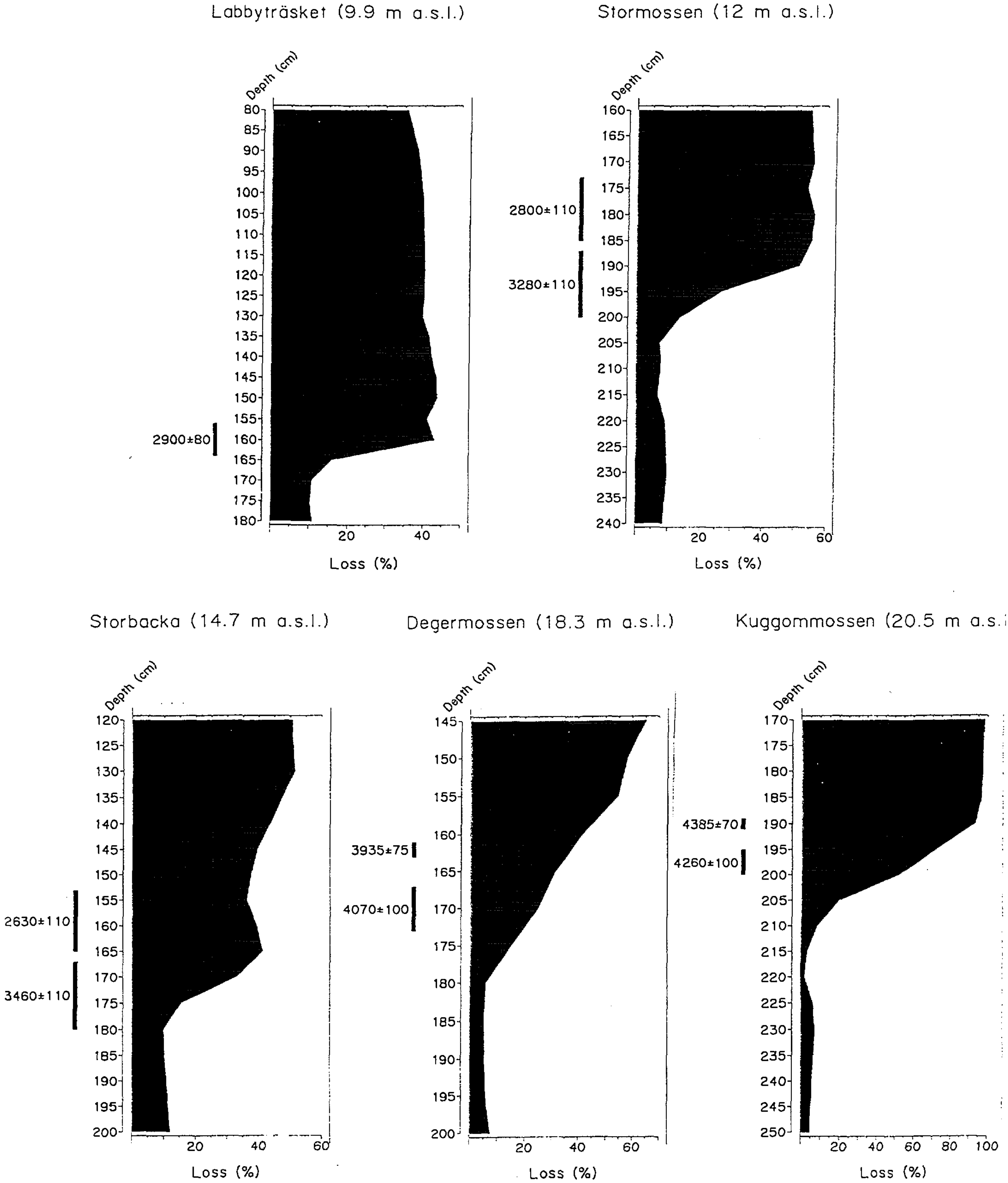
Labbyträsket (9.9 m a.s.l.)
Depth (cm)
2900±80
Loss (%)
Stormossen (12 m a.s.l.)
Depth (cm)
2800±110
3280±110
Loss (%)
Storbacka (14.7 m a.s.l.)
Depth (cm)
2630±110
3460±110
Loss (%)
Degermossen (18.3 m a.s.l.)
Depth (cm)
3935±75
4070±100
Loss (%)
Kuggommossen (20.5 m a.s.l.)
Depth (cm)
4385±70
4260±100
Loss (%)

Fig. 5b.

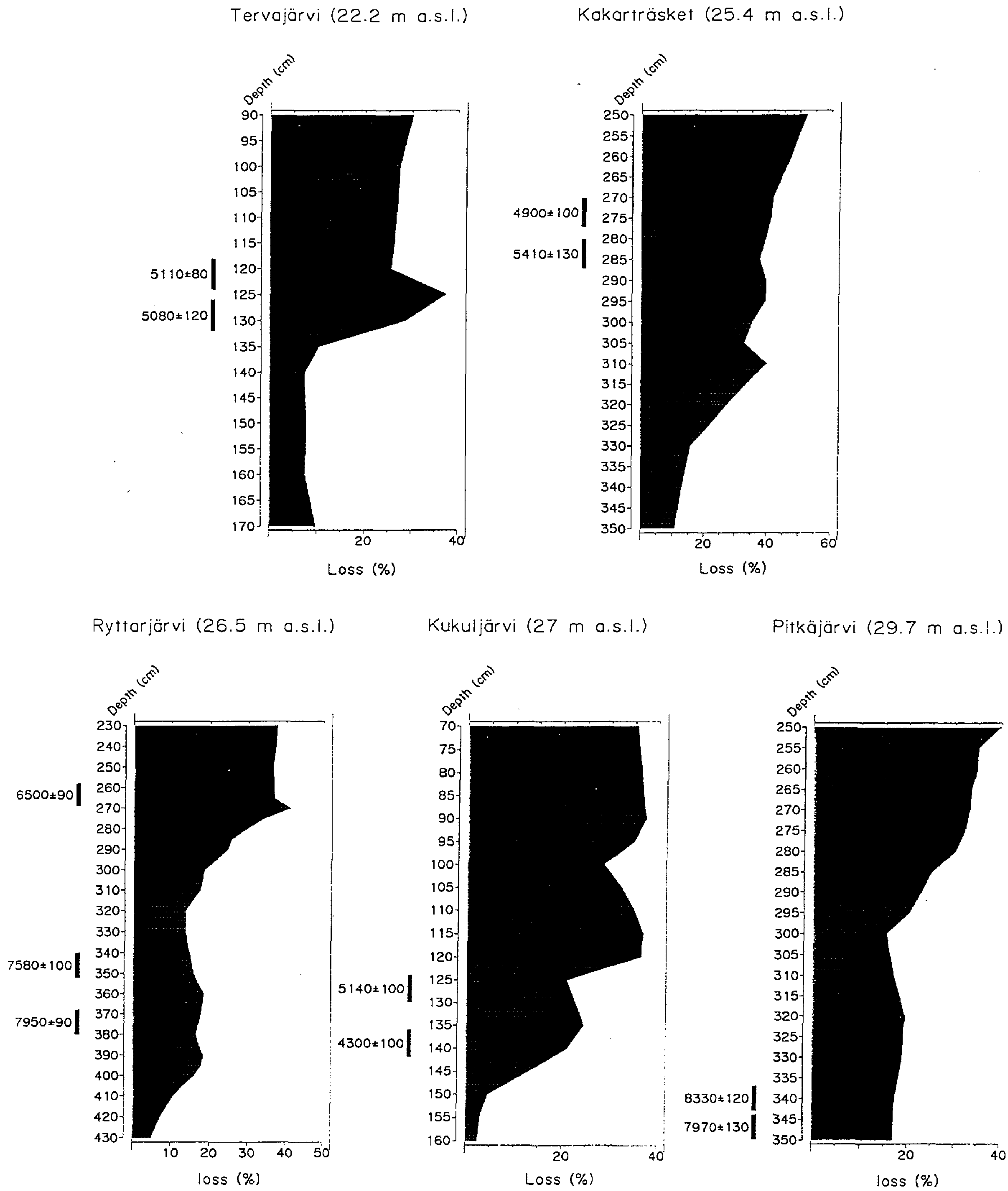
Tervajärvi (22.2 m a.s.l.)
Depth (cm)
90 95 100 105 110 115 120 125 130 135 140 145 150 155 160 165 170
5110±80
5080±120
20 40
Loss (%)
Kakarträsket (25.4 m a.s.l.)
Depth (cm)
250 255 260 265 270 275 280 285 290 295 300 305 310 315 320 325 330 335 340 345 350
4900±100
5410±130
20 40 60
Loss (%)
Ryttarjärvi (26.5 m a.s.l.)
Depth (cm)
230 240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430
6500±90
7580±100
7950±90
10 20 30 40 50
loss (%)
Kukuljärvi (27 m a.s.l.)
Depth (cm)
70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145 150 155 160
5140±100
4300±100
20 40
Loss (%)
Pitkäjärvi (29.7 m a.s.l.)
Depth (cm)
250 255 260 265 270 275 280 285 290 295 300 305 310 315 320 325 330 335 340 345 350
8330±120
7970±130
20 40
loss (%)

Fig. 5c.

5 RADIOCARBON-DATED SHORE LEVELS

The radiocarbon-dated sediments from the isolation horizons potentially offer highly accurate information about past sea-level stands. They are especially useful in the Baltic Sea area where the tidal range is negligible. Also, in Finland there are approximately 187 000 lakes from which to select suitable sites for stratigraphical investigations on shoreline displacement (Atlas of Finland 1986).

Because the region of the present study area is located near the current coast, which does not stand high above the present sea level, early Holocene shore levels are not recorded here. The highest basin studied is Lake Pitkäjärvi, at 29.7 m a.s.l., and the oldest radiocarbon date also derives from Lake Pitkäjärvi, at c. 8300 BP (Table 1). The date indicates the time of an isolation from the Ancylus Lake. That marks the point in the past from which the sea-level records reconstructed in this study begin. At that time, the rapid regression of the Anclys Lake was in operation. Very soon after that, the regression of the Ancylus lake had come to an end, water in the Baltic basin had reached the same level as that in the open ocean, and the relative sea levels were therefore affected by the eustatic rise of the sea level and the isostatic uplift of the land.

Table 1. Radiocarbon dates of biostratigraphically studied lake and mire basins in the Loviisa area, in southeast Finland.

Basin	Height m a.s.l.	^{14}C-age BP	Lab no.	Cal. age	Dated sediment
Sundsträsket	1.1	470+/-90	Hel-4180	510	isolation contact
		990+/-80	Hel-4181	930	Litorina sediment before isolation
Lappomträsket	3	1400+/-100	Hel-4182	1300	isolation contact
		1360+/-80	Hel-4183	1290	Litorina sediment before isolation
Lillträsket	7.7	2300+/-110	Hel-4207	2330	isolation contact
		2520+/-100	Hel-4208	2710	Litorina sediment before isolation
Labbyträsket	9.9	2900+/-80	Hel-4167	2990	isolation contact
Stormossen	12	2800+/-110	Hel-4252	2870	small lake sediment after isolation
		3280+/-110	Hel-4253	3470	Litorina sediment before isolation
Storbacka	14.7	2630+/-110	Hel-4250	2750	small lake sediment after isolation
		3460+/-110	Hel-4251	3690	isolation contact
Degermossen	18.3	3935+/-75	Hela-278	4410	small lake sediment after isolation
		4070+/-100	Hel-4226	4530	isolation contact
Kuggommossen	20.5	4385+/-70	Hela-260	4880	peat sediment after isolation
		4260+/-100	Hel-4238	4840	small lake sediment after isolation
Tervajärvi	22.2	5110+/-80	Hel-4187	5900	small lake sediment after isolation
		5080+/-120	Hel-4188	5890	Litorina sediment before isolation
Kakarträsket	25.4	4900+/-100	Hel-4192	5640	small lake sediment after isolation
		5410+/-130	Hel-4193	6260	isolation contact
Ryttarjärvi	26.5	6500+/-90	Hel-4254	7380	isolation contact
		7580+/-100	Hel-4255	8360	small lake sediment before Litorinatransgression
		7950+/-90	Hel-4266	8800	small lake sediment after isolation from Ancyluslake
Kukuljärvi	27	4300+/-100	Hel-4195	4860	small lake sediment
		5140+/-100	Hel-4194	5900	small lake sediment after isolation
Pitkäjärvi	29.7	8330+/-120	Hel-4209	9370	small lake sediment after isolation
		7970+/-130	Hel-4210	8940	small lake sediment

6 DIATOM INDICATORS

The isolation of a basin from the sea is a gradual process which may require tens to several hundreds of years depending on the rate of uplift and local shore facies. Even in areas with negligible tidal range, the local sea level may vary considerably due to changing meteorological conditions. For instance, nowadays, in the gulfs of the Baltic sea, the sea level may vary locally by 2.8 m between a low level during a high pressure stand, and a high level during the following cyclonic low-pressure (Atlas of Finland 1986). The short term fluctuations of sea level may bring saline water to recently isolated lakes which are now only slightly above sea level. On the Finnish coast there is even special terminology for those still brackish lakes slightly above sea level, which are called "glo", as opposed to entirely fresh-water basins, called "flada" (Munsterhjelm 1987). Similarly, the basins isolated in the distant past must have gone through these phases, from glo to flada, and these phases can be traced in the sediment deposits through diatom analyses.

Typical diatoms of the Ancylus Lake are, e.g: *Aulacoseira islandica, Gyrosigma attenuatum, Campylodiscus noricus* and *Epithemia hyndmannii.* Diatom flora typical of an Ancylus Lake have been found in the sediments of Lake Pitkäjärvi and Lake Ryttarjärvi. Both lakes were isolated from the Ancylus Lake. The isolation event is typically represented by a mass occurrence of the *Fragilaria* species and diatom flora typical of a small fresh-water lake, such as *Aulacoseira* spp., *Fragilaria* spp., *Tabellaria* spp., and *Pinnularia* spp.

Evidence of the beginning of the transgressive Litorina Sea has been found in the sediments of Lake Ryttarjärvi, where a brackish diatom flora appeared, indicating the invasion of the Lake Ryttarjärvi basin by the waters of the Litorina Sea. The brackish flora mainly consist of littoral forms, such as: *Campylodiscus clypeus*, *Navicula peregrina* and *Nitzschia scalaris. Campylodiscus clypeus* is a very common diatom species of the brackish-water lagoons. It is so characteristic of the littoral facies of the Litorina Sea that the upper limit of this stage of the Baltic is often called the "Clypeus limit" (e.g. Eronen 1974, Hyvärinen 1984). *C. clypeus* was found to occur in abundance in the brackish-water sediments of the present data set.

The greater part of the basins studied in this study were isolated from the Litorina Sea. Above the isolation contact the sediment changed to gyttja and fresh-water small-lake diatoms become prevalent. However, at times, brackish-water species may still occur frequently in the sediment above that horizon. For instance, a common species in post-isolation layers is *Nitzschia scalaris*, which could survive in the basins long after they had been cut off from the sea. The survival of this species is probably explained by a relatively high nutrient level in the recently isolated lake. *Nitzschia scalaris* is commonly known to occur in small coastal lakes with high nutrient levels, thus, its existence does not necessarily indicate brackish conditions (Fontell 1926, Eronen 1974, Hyvärinen 1980, Miettinen and Hyvärinen 1997).

The loss-on-ignition curves together with the radiocarbon dates of isolation-horizons, are shown in Figs. 5a, b and c. Because of varying sedimentation rates, the isolation event is represented by a variable thickness of deposit. As a rule, however, the age difference between the lower and upper date for the isolation-horizons is not large. The conventional ^{14}C dates are sometimes practically the same for the brackish and fresh-water sediment, and a typical time difference is 100-200 years. This probably indicates that there is no marked reservoir effect in the coastal waters of the Baltic, which would otherwise make the brackish-water sediments consistently many hundreds of years older that the overlying lake sediments. These dates are largely in accordance with the stratigraphical sequence and with each other.

7 RECONSTRUCTION OF THE SHORELINE DISPLACEMENT CURVES

The shoreline displacement curve for the Loviisa area, based on preliminary diatom analyses and radiocarbon dates (Table 1), is presented in Figs. 6. and 7. In the Loviisa area the present annual rate of land uplift is about 2 mm/yr (Kääriäinen 1966, Suutarinen 1983 and Vermeer et al. 1988). One new relative sea-level curve has been constructed from the present set of data, using both conventional and calibrated radiocarbon dates. While the conventional dates indicate ages younger than the corrected calendar years, it is possible to infer real time span as well as the magnitude of the uncertainties of the dates from the latter (Eronen et al. 1993; 1995).

As pointed out by several authors (e.g. Andrews 1986, Pirazzoli 1991), it is extremely important to include the uncertainties in the data in the reconstruction of sea-level curves. The uncertainty of the present altitude data probably lies within ±0,5 m for most cases. The uncertainty in the chronology is shown as a standard deviational age range, drawn for both the conventional and calibrated radiocarbon dates. A confidence limit is generally 70-130 years for conventional dates, and 100-500 years for calibrated dates. In Fig. 6 the shoreline displacement curve has been drawn through the dated isolation events or between the dates of the Baltic and small lake sediments. If the organic content in the sediment below the isolation contact has been too small for radiocarbon dates, the dates have been done the sediment above the isolation contact, and the curve has been drawn just below the dates.

8 THE MAIN FEATURES OF THE RELATIVE SEA-LEVEL LOWERING

The shoreline displacement curve of the Loviisa area indicates a relatively regular uplift and an overall relative sea level lowering, with some remarkable features in part of the curve. In the early (upper) part of the Loviisa curve, the relative sea-level curve is transgressional, before going into a relatively steady lowering trend around 6500 BP. The transgression occurred in that area soon after the beginning of the Litorina Sea stage, as shown by evidence from the diatoms in sediments found in Lake Ryttarjärvi. The lake first became isolated from the Ancylus Lake in 8000 BP. The diatoms indicate an increase in salinity, i.e. a marine incursion and a net sea-level rise around 7500 BP. A clear lithological change from a typical small-lake sediment into Litorina Sea sediment was also seen in Lake Ryttarjärvi, when the basal values of the organic content dropped from 18% to 13%. The final emergence occurred from a Litorina lagoon around 6500 BP. The amplitude of the Litorina transgression in the Loviisa area is about one metre, and the highest possible limit of this transgression is about 27 m above present sea-level. These results are well compatible with earlier studies of the southeastern part of Finland.

Hyvärinen (1980) has not found any indication of a Litorina transgression in his detailed studies on the shoreline displacement near Helsinki, which is situated at higher isobase of land uplift than the Loviisa area. Eronen (1974) has found proof of the Litorina transgression from the Bastuberg bog, near Porvoo. In the area east of the present study, in Virolahti, which is situated at lower isobase of land uplift, the amplitude of the Litorina transgression has been four metres (Miettinen and Hyvärinen 1997). In addition, earlier studies of shore displacement in the Virolahti area include those by Hyyppä (1937), Salmi (1961) and Valovirta (1965). They have distinguished 2-3 Litorina transgressions based on lithological or diatom evidences. By modern standards, however, their arguments are clearly insufficient.

The Litorina transgression resulted from the global rise in sea-level, which affected the shoreline levels along all of the coastal areas in Finland, also including the Ostrobothnian coast in western Finland. In the latter area, however, the rate of uplift clearly exceeded the rate of sea-level rise. There, and in areas of rapid uplift, in general, the rise in global sea level is recorded by a decrease in the rate of relative sea-level lowering. In the Loviisa area, the sea-level rise clearly exceeded the rate of uplift in the period between 7500-6500 BP.

Even though it is known that the melting of the ice sheets markedly raised the global ocean level until 6000-5000 BP (Lambeck et al. 1990, Pirazzoli 1991), the regional eustatic effect of the world-wide sea-level rise is extremely difficult to accurately determine, because of the deglacial geoidal changes (Fjeldskaar 1989, 1994), and global crustal deformations following the last ice age (Pirazzoli 1991). Removing the influence of eustatic rise would steepen the upper part of the Loviisa emergence curve, which must be taken into account in estimating the magnitude of crustal deformation during the past 8000 ^{14}C years. The Loviisa curve approaches the shape of an exponential function, when the effect of the ocean-level rise prior to 6000-5000 BP is taken into account. It may be concluded that the land uplift in this area has proceeded at a rather steady rate, which is now gradually slowing down (Fig. 6).

On the grounds of the Loviisa shoreline displacement curve, the island of Loviisa Hästholmen first emerged from under the Litorina Sea around 3600 years ago. Since this time, the emergence of Loviisa Hästholmen has proceeded at a rather steady rate due to the isostatic land uplift.

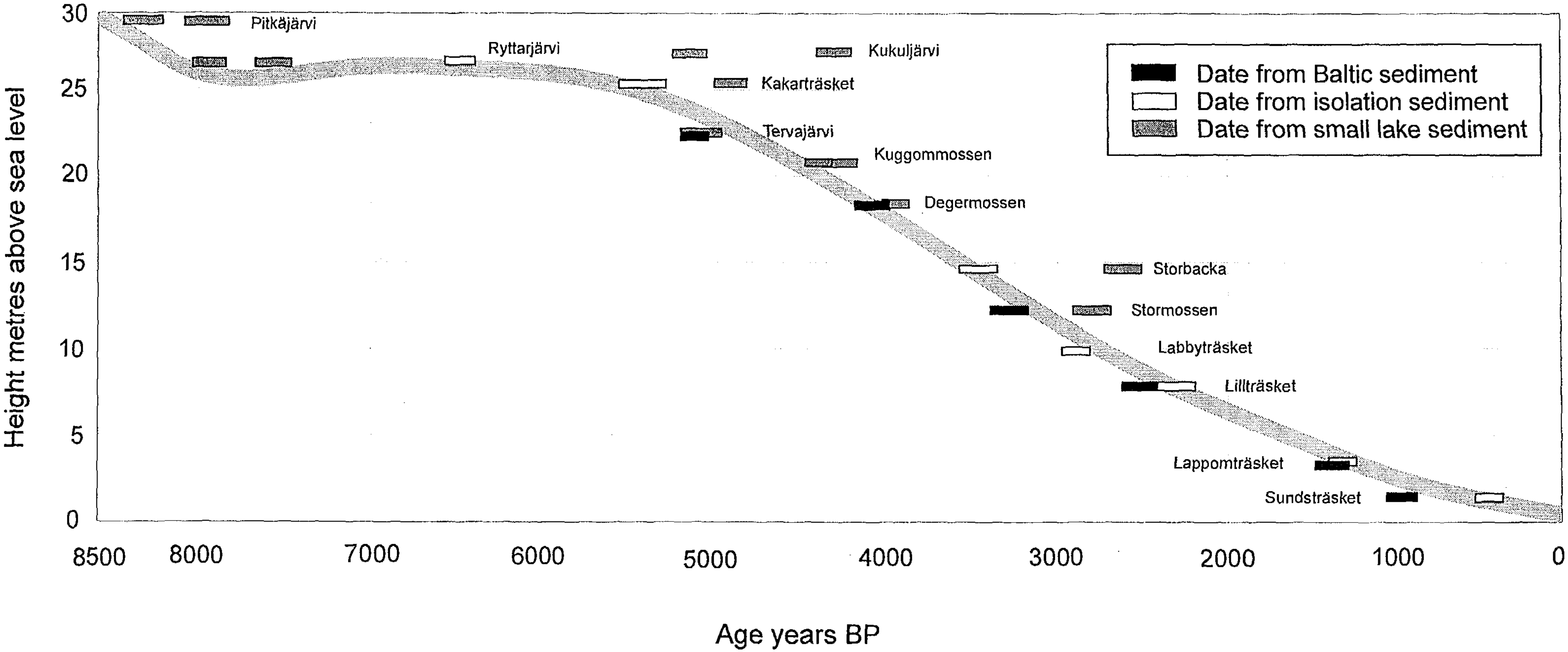

Fig. 6. Shoreline displacement curve for the Loviisa area. The bars indicate radiocarbon dates for each isolation within the calculated error limits.

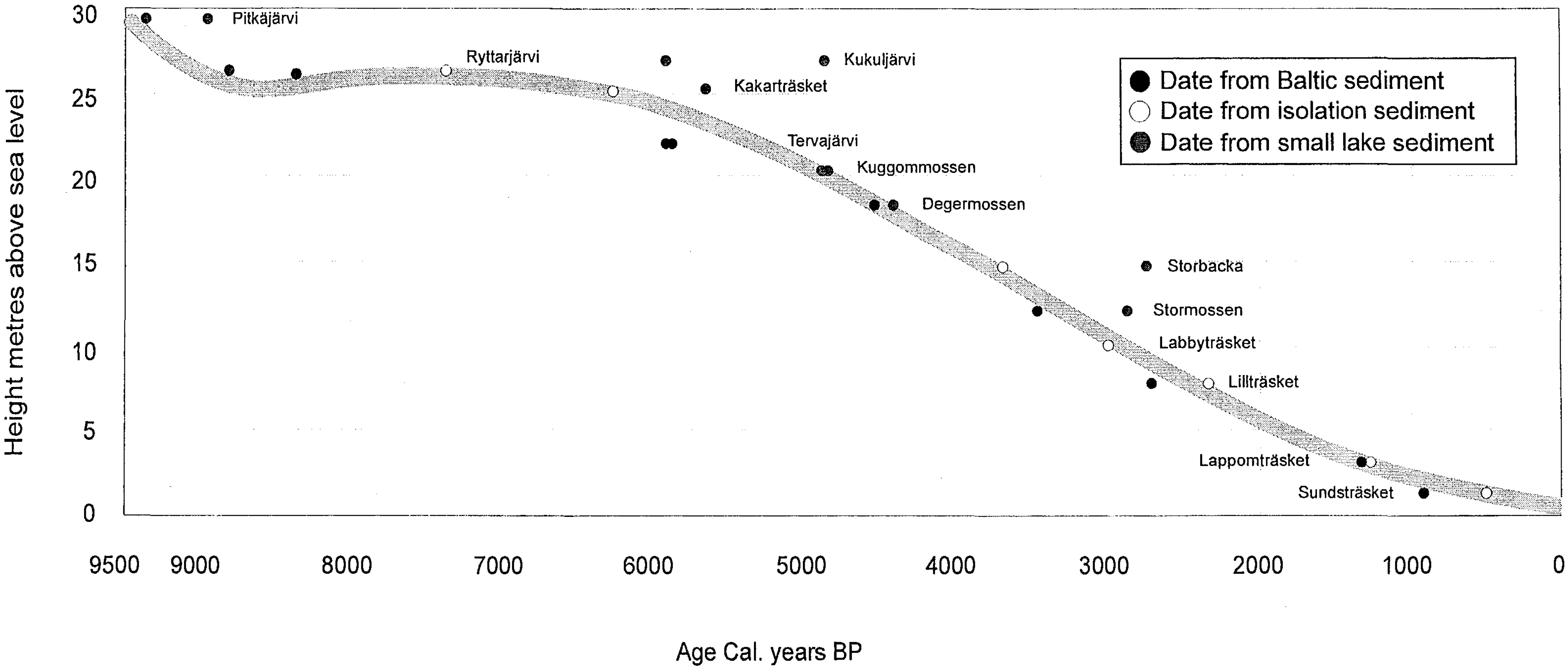

Fig. 7. Shoreline displacement curve for the Loviisa area. The points indicate calibrated radiocarbon dates for each isolation.

9 DISCUSSION

Sediment cores have given no stratigraphic evidence of any transgression after 6000 BP. Most of the isolation horizons provide fairly regular, progressively younger dates with descending height a.s.l. There are a few deviational ages, very probably caused by sources of error in the sediment. For example, in Lake Tervajärvi both conventional dates are probably slightly too old, but they did not cause difficulties in the reconstruction of shoreline curves. The hard-water effect does not present a problem here, as no limestones occur in the area underconsideration. The Finnish small-lake sediments are thus generally well suited to radiocarbon dating. Overall, there are no large age differences between the uppermost brackish-water Litorina sediment and the fresh-water sediment on top of it. This indicates that there is probably no marked reservoir effect in the coastal sediments of the Litorina Sea.

Neither the present nor earlier Finnish shoreline data provide evidence for vertical displacement between bedrock blocks. It is not excluded, however, that more detailed studies would reveal minor local disturbances of uplift caused by vertical faulting in the course of glacio-isostatic rebound. Marked vertical dislocations have occurred in northern Fennoscandia, but the resulting faults are in the supra-aquatic area, and date back to the early postglacial times when uplift was still extremely rapid (Lagerbäck 1990, Wahlström 1993).

The geophysical data indicate that the isostatic recovery will continue for thousands of years, even though there are uncertainties in the calculation of the residual uplift. The estimates vary from 30 to 150 m (Ekman 1989), but the most recent calculation suggest an amount of c. 90 m for the residual uplift (Ekman and Mäkinen 1996). Thus the lowering trends in sea-levels will prevail in the northern part of the Baltic for a long time, if the greenhouse warming does not cause strongly accelerated rise in world ocean level.

10 CONCLUSIONS

One main conclusion that can be drawn from the available data is that the uplift in southeastern Finland has proceeded in a very regular manner and, based on presently available evidence, it is not possible to distinguish any clear short-lived changes in its rate. Neither have there been large fluctuations in the sea level during the last 6000 years. Indications of a transgression in southeastern Finland before 7000 BP suggest a relatively rapid eustatic sea-level rise which, in places, exceeded the regional uplift for a short period of time. The rise in ocean level, which continued until 6000-5000 BP, affected the bend of the early part of the shoreline curve in such a way that this part has a gentler slope than it would have if the eustatic sea-level had been stable.

Despite its limitations, the available set of data represents is a valuable source of information and provides a good base for continuing work on relative sea-level changes and vertical crustal movement in the post-glacial time. These data continue to be valuable in testing geophysical models of the properties and behaviour of earth´s crust in Finland.

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