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The history of the Yoldia Sea in Northern Estonia: palaeoenvironmental conditions and climatic oscillations

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Late glacial and Early Holocene sediment sequences from Northern Estonia were investigated using diatom and pollen analysis and the accelerator mass spectrometry (AMS) ^{14}C dating. The results of diatom analysis indicate that freshwater conditions prevailed during the initial and final phases of the Yoldia Sea in the investigated area. A near-bottom saline water current that penetrated into the Baltic Sea Basin during the brackish phase of the Yoldia Sea spread into the Gulf of Finland at *ca*. 11 300–11 200 calendar years BP. Coastal upwelling probably caused mixing of the water column and the circulation of brackish water up to the surface in certain near-shore areas in the Gulf of Finland. A slight change in the pollen composition may suggest deterioration in the climate and can be correlated to the Preboreal Oscillation. AMS ^{14}C dates on aquatic plant macrofossils suggest a reservoir effect more than 1000 year for the brackish phase of the Yoldia Sea.

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INTRODUCTION

The history of the Baltic Sea Basin has been an important subject for the Quaternary geological studies around the Baltic area and much research has been carried out to understand the peculiarities of its development (e.g. Gudelis and Königsson, 1979; Björck, 1995). There seems to be an agreement upon the main outlines of the Baltic Sea evolution since the last deglaciation. The late glacial and Holocene development of the Baltic Sea Basin has been subdivided into four major stages: the Baltic Ice Lake (freshwater lake dammed above the ocean level; from deglaciation to *ca*. 11 550 years BP), the Yoldia Sea (partially brackish-water basin; *ca*. 11 550–10 700 calibrated years BP), the Ancylus Lake (freshwater basin; *ca*. 10 700–9500 calibrated years BP) and the Litorina Sea (brackish-water basin; *ca*. 9500 calibrated years BP to the present). The alternations of the fresh and brackish-water stages were regulated in particular by interactions between the deglaciation dynamics, glacio-isostatic land uplift and eustatic sea level changes, which affected the location of the thresholds and the outlet and inflow passages and the magnitude, duration and direction of the water exchange between the Atlantic Ocean and the Baltic Sea Basin.

An extensively discussed issue concerning the evolution of the post-glacial Baltic Sea Basin is the palaeoenvironment of the Yoldia Sea stage, and especially the extent and timing of the saline water intrusion. The Yoldia Sea stage was named after the arctic marine bivalve *Portlandia arctica*, previously called *Yoldia arctica*, first recorded from glacial varved clays in the vicinity of Stockholm (Fries *et al*., 1863). The Yoldia Sea formed when the final drainage of the Baltic Ice Lake at *ca*. 11 550 GRIP (Greenland Ice Core Project) ice core years BP (Andrén *et al*., 2002) took place, the water level dropped approximately 25 m to the level of the Atlantic Ocean and a connection with the ocean opened across south-central Sweden. The Yoldia Sea stage terminated when the glacioisostatic uplift emerged the connecting straits above sea level at *ca*. 10 700 calibrated years BP (Andrén *et al*., 2000), so that the waters of the Baltic Sea Basin were dammed up, and the Ancylus Lake stage began. The Yoldia Sea stage close to the inflow area in south-central Sweden and the Baltic Sea proper has been subdivided into three phases with brackish conditions during the middle phase (Svensson, 1989; Wastegård *et al*., 1995). The initial 200–300 years of the Yoldia Sea were characterized by freshwater conditions due to vast amount of freshwater produced by melting ice sheet discharging out from the still shallow and narrow straits (Svensson, 1989; Strömberg, 1994; Björck, 1999). This was succeeded by a phase with brackish-water conditions that lasted presumably during a short period of 60–200 years (Strömberg, 1989; Svensson, 1991; Wastegård *et al*., 1995). This Early Preboreal ingression of saline water into the Baltic Sea Basin has been detected by diatom flora, calcareous benthic fauna and symmict varved clays all the way from the western coast of Sweden (Schoning *et al*., 2001) into Lake Vänern Basin (Fredén, 1988), through the Närke Strait (Wastegård *et al*., 1998) into the Stockholm area (Brunnberg, 1995) and further south and eastwards into the Baltic Sea proper (Abelmann, 1985; Lepland *et al*., 1999). A possible late glacial connection between the White and Baltic Sea basins has been disproved (Saarnisto *et al*., 1995). Diatom records indicate that freshwater conditions again existed during the final phase of the Yoldia Sea stage at *ca*. 11 100–10 700 years BP (Andrén *et al*., 2000).

Despite much study on the Yoldia Sea stage at the inflow area the question of the salinity of the Yoldia Sea in the eastern part of the Baltic Sea Basin is still unsolved. The balance between saline water intrusion from the Atlantic Ocean and the freshwater discharge from the rapidly melting Fennoscandian ice sheet probably determined how far east into the Baltic Sea basin the brackish-water flow could have reached. Two major alternatives have been suggested. The occurrence in the Yoldia Sea sediments of an ecologically mixed diatom assemblage, featuring both freshwater and salinity-tolerant diatoms, was interpreted as a consequence of increased salinity in the Gulf of Finland (e.g. Alhonen, 1971). Moreover, based on the attempts to correlate the Swedish and Finnish clay-varve chronologies, Donner (1969) and Strömberg (1990) have calculated that a delay of some 80–90 years could be presumed for the influx of saline water from Sweden to Southern Finland. According to the second approach (Hyvärinen *et al*., 1992; Raukas, 1994, 1995), brackish-water water did not reach the eastern part of the Baltic Sea Basin and the Gulf of Finland at all and the presence of marine and brackish-water diatoms was explained by redeposition from the Eemian Interglacial deposits.

Time-synchronous marker horizons are an important tool for long distance geochronological correlation between different geological archives. Geologically short-lived events, which have left some traces in the sedimentary records, such as volcanic eruptions, earthquakes, meteorite impacts, climatic events and sea level changes, are comparatively rare and may be employed for correlation purposes (Whittaker *et al*., 1991). The onset of the Holocene is regarded as a rapid global warming of the climate, however, proxy records from around the North Atlantic region provide evidence of a short-lived climatic deterioration very early in the Holocene, an episode that has been termed the Preboreal oscillation (e.g. Björck *et al*., 1996; Fisher *et al*., 2002; Van der Plicht *et al*., 2004). Sediment records from the Nordic countries display the Preboreal oscillation in the form of a decrease in pollen concentration in combination with decreased tree-pollen and increased herb pollen frequencies and a decline in carbon content (Björck *et al*., 1997). This climatic reversal is also reflected as a markedly colder event in the oxygen isotope signal from the GRIP ice core centred on 11 200 GRIP ice core years BP (Walker *et al*., 1999). The Preboreal Oscillation started *ca*. 300 years after the termination of the Younger Dryas. The timing of the Early Preboreal cooling coincides with the brackish phase of the Yoldia Sea (Björck *et al*., 1996).

The aim of the present work is to document the palaeosalinity records of the Yoldia Sea stage in Northern Estonia, to determine the distribution and dynamics of the ingression of saline water into the eastern part of the Baltic Sea Basin and to test, whether that short brackish phase of the Yoldia Sea can be used as a synchronous time marker for comparative studies in the region. For this purpose several sediment sequences in Northern Estonia were analysed in detail by means of diatom and pollen analysis and AMS ^{14}C dating. For the palaeoenvironmental reconstruction of the Yoldia Sea our data was compared with proxies from the inflow area in south-central Sweden as well as with offshore sediment records from the Baltic Sea proper and the Gulf of Finland.

STUDY AREA AND PREVIOUS INVESTIGATIONS

The study area (Fig. 1) is situated in Northern Estonia, around Tallinn. An outstanding escarpment with the height up to 20–30 m, the North Estonian klint, divides the area into the foreklint lowland and a limestone plateau on the klint. In the basal part of the klint Cambrian terrigenous rocks crop out, whereas the crest of the scarp consists of Ordovician limestone

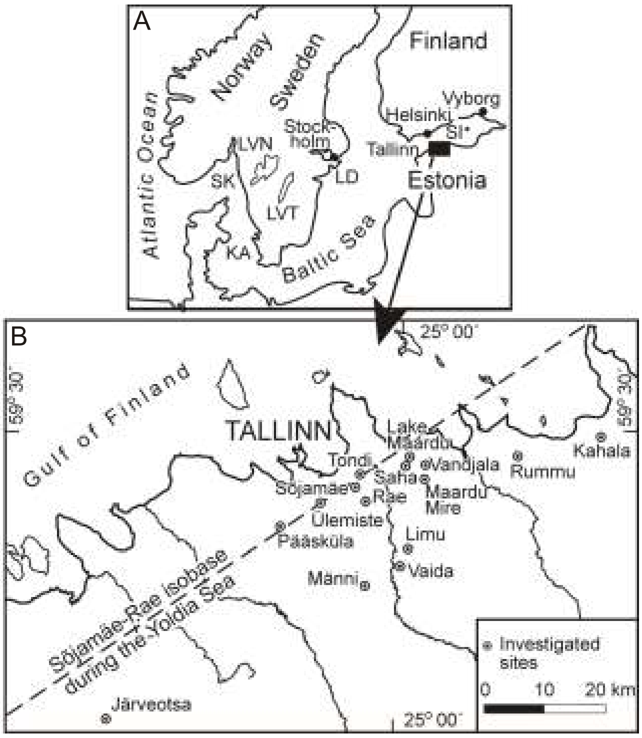

Fig. 1. The Baltic region with geographic names mentioned in the text

A — study area, B — location of the sites investigated; SK — Skagerrak, KA — Kattegat, LVN — Lake Vänern, LVT — Lake Vättern, LD — Landsort Deep, SI — Suursaari Inland

and dolomite. The thickness of Quaternary deposits along the limestone plateau is normally rather thin. In the klint bays, which are often associated with ancient buried valleys, the Baltic Sea sediments can be of significant thickness. Coastal formations of the Yoldia Sea are fragmented and scattered in the region. The present land uplift observed in Northern Estonia is 1 mm y^{-1}. Glacio-isostatic land uplift was fairly rapid during the Younger Dryas/Preboreal transition, approximately 3 cm y^{-1} (Kessel and Miidel, 1973). The extrapolated shore level for the Tallinn area prior to the final drainage of the Baltic Ice Lake is 75 m a.s.l. (Kessel, 1961). During the drainage the water level of the Baltic Ice Lake dropped to around 50 m a.s.l., and the regression of the shore-line continued during the Yoldia Sea at least to 28 m a.s.l. (Saarse *et al*., 1997). The culmination of the Ancylus Lake transgression reached an altitude of 34 m a.s.l. (Veski, 1998) in the area, partly inundating the Yoldia Sea shoreline. Despite the topography in Northern Estonia is generally flat, the area around Tallinn is relatively rich in small lake and mire basins, which were isolated from the Baltic Sea Basin during the Yoldia Sea stage.

Kessel and Raukas (1979) and Saarse *et al*. (1997) have earlier investigated the Holocene shoreline displacement in the Tallinn area. Vegetation development of many basins were studied and several conventional ^{14}C dates from sediment sequences representing isolation from the Yoldia Sea stage of the Baltic Sea Basin were obtained in the area (Poska, 1994; Kihno, 1996; Veski, 1998; Saarse *et al*., 1999). Unfortunately, still few diatom records are available from the Yoldia Sea sediments in Estonia. Eight investigated deep boreholes are located on the foreklint lowland that reflect the Yoldia Sea depositional setting, with the water depth between 25 and 70 m (Lepland *et al*., 1995), show a low abundance of diatoms and a mixed marine, brackish-water and freshwater littoral assemblage (Kessel and Punning, 1969; Kessel and Pork, 1971). However, high turbidity and low transparency of the Yoldia Sea surface water preclude possible reproduction of benthic diatoms in such a deep environment. Therefore most probably these diatoms are transported from the coastal area or even partially reworked from the older deposits, and for that reason these records must be used with caution for palaeosalinity reconstruction purposes. The lagoonal deposits of the Sõjamäe Basin, that contain some poorly preserved fragments of littoral brackish-water diatoms, were correlated with the Yoldia Sea (Kessel and Punning, 1969). Recently a new site, the Tondi Mire, was studied and a slight influence of brackish water in the littoral environment during the Yoldia Sea has been suggested (Lepland *et al*., 1995; Kimmel *et al*., 1996). Pre-isolation sediments of Lake Kahala that had accumulated during the Younger Dryas and the Early Preboreal are characterized by large-lake freshwater diatom assemblage (Saarse *et al*., 1999).

METHODS

Sediment samples were cored with a 1 m long Russian peat sampler with a diameter of 10 cm. At the sites where samples for AMS ^{14}C dating were collected we obtained up to 10 parallel cores from the isolation sediment sequence.

Samples for diatom analyses were heated in 30% H_2O_2 to get rid of organic material and thereafter fine and coarse mineral particles were removed by repeated decantation. If possible, in each sample *ca*. 400–500 non-*Fragilaria* spp. valves were counted. Because of mass occurrence, species of the genus *Fragilaria* are excluded from the total in the percentage calculations. The diatoms were grouped into brackish-water, large-lake, lagoonal and small-lake taxa according to their ecology and salinity preferences, and into planktonic and littoral taxa in accordance with their living habitats.

The pollen samples were prepared by the standard acetolysis method (Berglund and Ralska-Jasiewiczowa, 1986). More than 1000 arboreal pollen (AP) grains were counted at each level. The pollen percentages were calculated as arboreal pollen + non-arboreal pollen (NAP) = 100% (pollen sum). Pollen concentration was estimated by adding *Lycopodium* spores to a known volume of sediment (Stockmarr, 1971).

The organic (OM) and carbonate content ($CaCO_3$) were determined by loss-on-ignition at 550 and 825°C respectively. The ignition residue was estimated as the terrigenous fraction (TER).

Subsamples for AMS ^{14}C dating, which comprised 3–5 cm slices of sediment, were sieved through a 0.5 mm mesh. Extracted macrofossils were identified under a binocular microscope. Despite of large sample volumes terrestrial macrofossils were not detected. Therefore seeds of aquatic macrophytes were selected for radiocarbon dating. After identification, macrofossil samples were immediately dried in an aluminium foil package at 50°C overnight, and were stored in sterilized glass bottles to prevent uptake of modern CO_2 or effects of bacteria. Pre-treatment of macrofossils followed the standard hot acid-alkaline-acid technique (Possnert, 1990) and measurements were carried out using the tandem accelerator technique at Uppsala University.

The altitudes of isolation thresholds of basins were levelled and tied to the nearest benchmarks or estimated from topographic maps. The reconstruction of the shore displacement curve is based on the threshold altitudes of isolated basins. Isolation altitudes of the basins are projected to the Sõjamäe–Rae isobase for the Yoldia Sea running from north-east to south-west in Northern Estonia (Fig. 1). The earth has emerged a little bit faster in the west than in the east. For compensation of the differential uplift heights of the basin thresholds on the both side of the isobase are corrected.

RESULTS AND INTERPRETATION

PALAEOENVIRONMENTAL RECORDS

In Lake Rummu basal sandy silt and homogeneous clay at 580–505 cm core-depth contain large-lake diatoms, e.g. planktonic *Aulacoseira islandica* (O. Müller) Simonsen, littoral *Diploneis domblittensis* (Grunow) Cleve, *Gyrosigma attenuatum* (Kützing) Rabenhorst and *G. spencerii* (W. Smith) Cleve (Fig. 2), indicating a rather deep freshwater environment. This sediment unit is correlated with the initial phase of the Yoldia Sea. The isolation of the basin is recorded

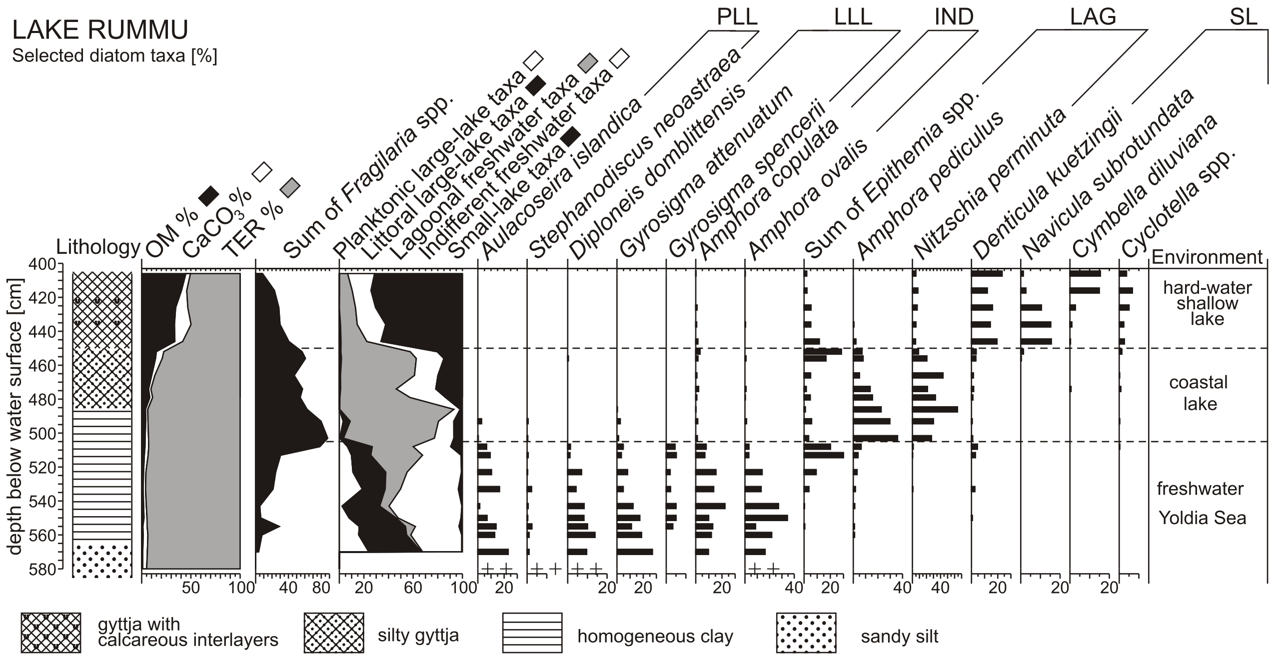

Fig. 2. Diatom diagram for the sediment core from Rummu Lake

PLL — planktonic large-lake diatoms, LLL — littoral large-lake diatoms, IND — indifferent freshwater diatoms, LAG — lagoonal freshwater diatoms, SL — small-lake diatoms, OM — organic matter, TER — terrigenous matter

at the core-depth of 505 cm. The number of epipsammic *Fragilaria* spp., *Amphora pediculus* (Kützing) Grunow, *Nitzschia perminuta* (Grunow) Peragallo and *Epithemia* spp. increases, whereas large-lake diatoms decline. A coastal lake with a shallow water depth and silty bottom probably developed in the basin. In the gyttja with calcareous interlayers diatom assemblage, such as *Denticula kuetzingii* Grunow and *Cymbella diluviana* (Krasske) Florin suggests a small shallow hard-water lake.

In the Pääsküla Mire core an abrupt change from large-lake diatom assemblage to the brackish-water taxa, such as *Diploneis smithii* (Brébisson) Cleve, *Tryblionella navicularis* (Brébisson) Ralfs and *T. punctata* W. Smith takes place at 445 cm (Fig. 3). This shift in the diatom composition correlates with the spread of saline water into the coastal area of Northern Estonia. The expansion of *Fragilaria* spp., disappearance of brackish-water diatoms and predominance of small-lake taxa at the boundary between the clay and the silt reflects the isolation level.

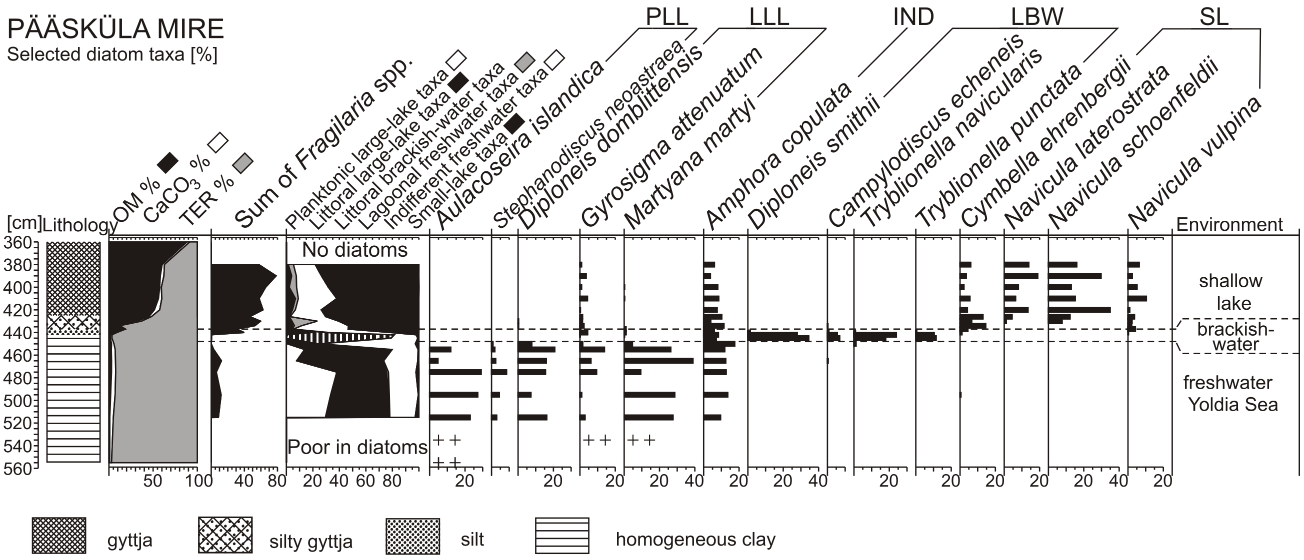

Fig. 3. Diatom diagram for the sediment core from the Pääsküla Mire

LBW — littoral brackish-water diatoms, for other explanations Figure 2

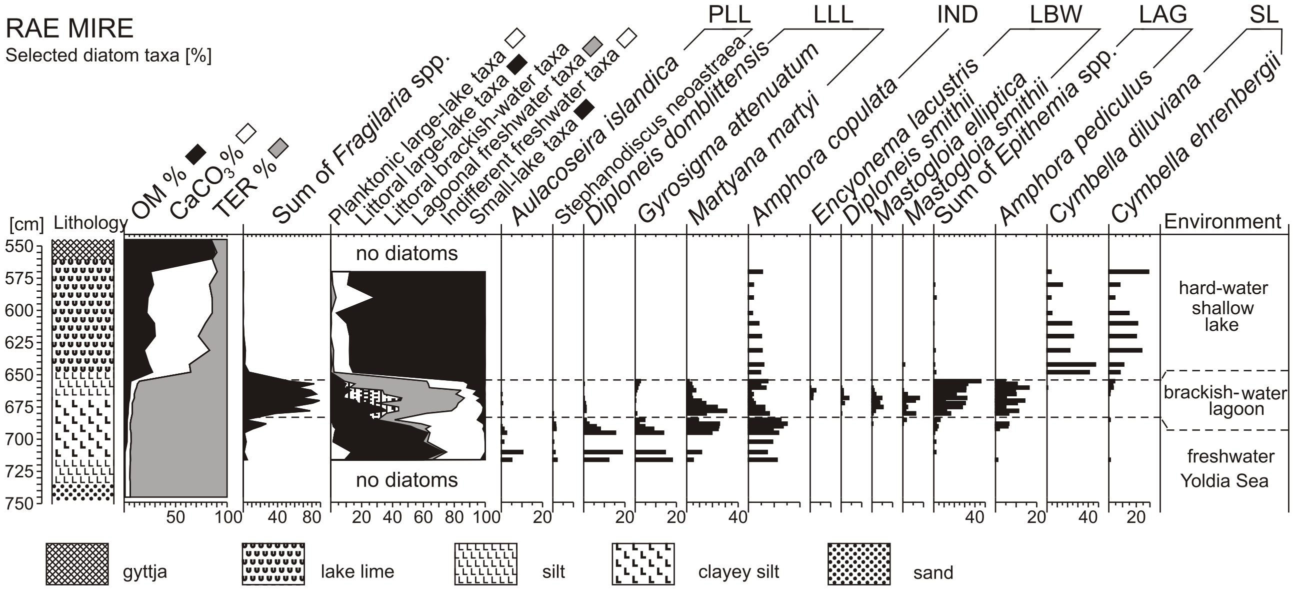

Fig. 4. Diatom diagram for the sediment core from the Rae Mire

For other explanations see Figures 2 and 3

In the Rae Mire the lower part of clayey silt contains mostly of large-lake diatoms (Fig. 4), the frequency of planktonic diatoms constantly decreases and the share of littoral species simultaneously increases. This suggests that the regression of the initial freshwater Yoldia Sea led to a continuous drop of the water level in the basin. A distinct change in the fossil diatom assemblage is recorded at the core-depth of 685 cm. An increase of *Fragilaria* spp., expansion of lagoonal epiphytic *Epithemia* species and epipsammic diatom *Amphora pediculus*, together with a rise in slightly brackish-water species infer that a sheltered lagoon, which was connected with the brackish Yoldia Sea by shallow straits developed in the Rae Basin. The final isolation of the Rae Basin is recorded in the transition between the silt and the lake lime and is characterized by the predominance of a diatom composition, which resembles a shallow hard-water lake.

PALAEOCLIMATIC RECORDS

The basal sandy and clayey silt in Lake Rummu at 580–510 cm is characterized by a Younger Dryas pollen flora with redeposited AP pollen grains such as *Alnus*, *Picea*, *Corylus*, *Ulmus*, *Quercus* and *Carpinus* (Fig. 5). The pollen values for *Pinus* and *Betula* are rather uniform, the latter is mostly represented as *Betula nana*-type. Of the other locally

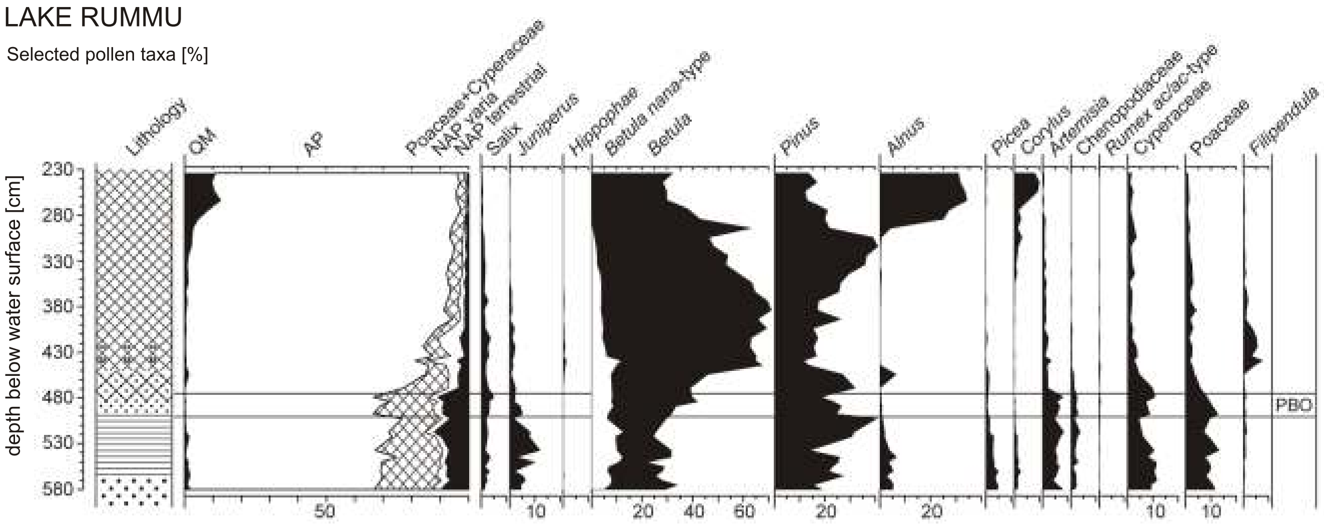

Fig. 5. Pollen diagram from Lake Rummu

PBO corresponds to the Preboreal oscillation; QM — quercetum mixtum; AP — arboreal pollen; NAP — non-arboreal pollen; for other explanations see Figure 2 produced AP *Juniperus* and *Salix* are well represented. The share of NAP is around 30%. The values of organic fraction are very low in the pre-isolation sediments (Fig. 2). At 510 cm *Betula nana*-type and *Juniperus* decline, so do the NAP, *Artemisia* and Chenopodiaceae. This shift indicates the onset of the Holocene warming. From 500 cm the NAP curve abruptly rises, there is a rise also in *Salix*, *Juniperus*, *Betula nana*-type, *Artemisia*, Chenopodiaceae and Ericaceae (*Empetrum nigrum*) culminating at 475 cm. A decline in *Filipendula* occurs at the same level. These changes may suggest a cooling of the climate. There is also a slight increase in terrigenous fraction at 475 cm, otherwise the content of terrigenous matter is stable and decreasing in the sediment interval 500–475 cm. From 475 cm and upwards the AP/NAP ratio changes again in favour of the first and presumably indicates vegetation response to the termination of climatic cooling event.

The pollen record of the Pääsküla Mire shows a higher percentage of herbs from 445–435 cm (Fig. 6). Contemporaneous peaks of *Juniperus*, *Betula nana*-type and Ericaceae occur at the same level. The pollen evidence may be interpreted as a slight cooling. Increase of pollen taxa indicating deterioration of the climate occurs simultaneously with the appearance of brackish-water diatoms in the sediment sequence.

The 2 metre section of sediment investigated from Rae Mire shows a transition from Younger Dryas to Early Holocene (Fig. 7). There seems to be a gradual warming from 730–700 cm, with increasing total pollen concentration (TPC) and AP, at the same time, decreasing percentages of *Betula nana*-type, *Artemisia*, Chenopodiaceae and herbs in general. There are two decreases in TPC at 680 and 650 cm respectively, the latter being more pronounced. Associated with those decreases in TPC are peaks of *Betula nana*-type, dwarf shrubs (Ericaceae: *Empetrum nigrum*), NAP in general, *Artemisia*, Chenopodiaceae, *Selaginella* and *Rubus chamaemorus*. The documented pollen pattern again suggests a cooling of the climate. Above 650 cm, together with the change in lithology from silt to lake lime the TPC and the values of AP rise remarkably, the values of NAP, dwarf shrubs and *Betula nana*-type decrease. The pollen evidence shows a distinct warming of the climate.

RADIOCARBON DATES

The results of the AMS ^{14}C dating are summarized in Table 1. The uppermost sample (Ua–15322) from the post-isola-

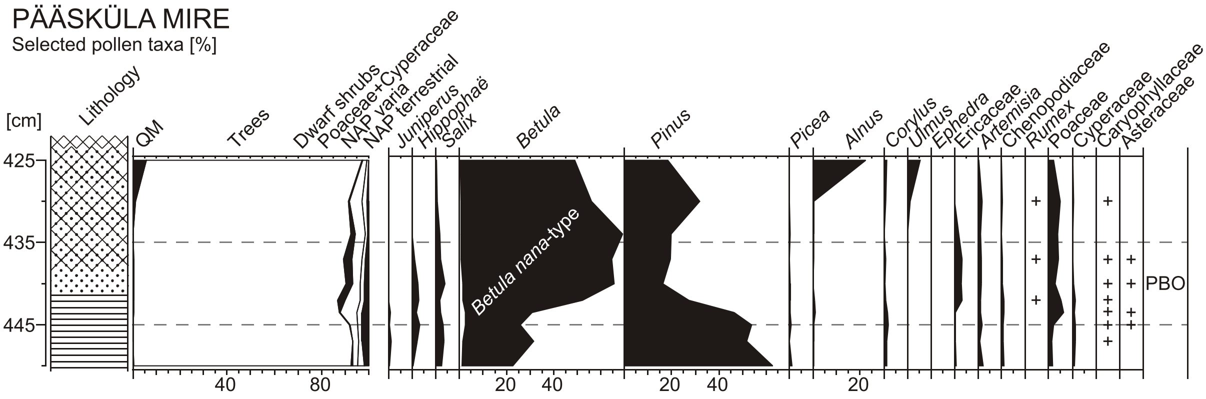

Fig. 6. Pollen diagram from the Pääsküla Mire

PBO corresponds to the Preboreal oscillation; for other explanations see Figure 3

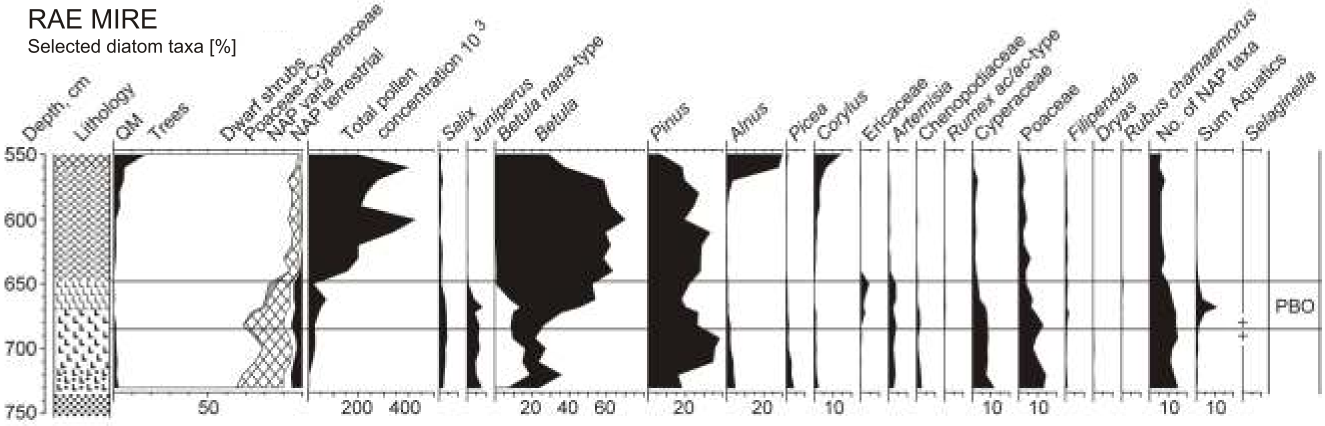

Fig. 7. Pollen diagram from the Rae Mire

PBO corresponds to the Preboreal Oscillation; for other explanations see Figure 4

Table 1

AMS ^{14}C dates on plant macrofossil from Northern Estonia

Site	Depth [cm]	Environment	Material dated	^{14}C age BP (±1σ)	δ^{13}C ‰ PDB	Lab code
Pääsküla Mire	420–425	post-isolational	seeds: *Schoenoplectus lacustris*	8 630±100	–24.5	Ua–15322
Pääsküla Mire	432–437	post-isolational	seeds: *Potamogeton natans*	10 605±95	–12.3	Ua–15321
Pääsküla Mire	437–441	pre-isolational	seeds: *Potamogeton natans*	11 360±115	–15.8	Ua–15320
Pääsküla Mire	441–445	pre-isolational	seeds: *Potamogeton* spp.	11 420±95	–13.9	Ua–15319
Rae Mire	643–648	post-isolational	seeds: *Potamogeton* spp.	10 305±110	–9.0	Ua–15328
Rae Mire	650–653	post-isolational	seeds: *Potamogeton* spp.	10 485±105	–10.9	Ua–15327
Rae Mire	658–664	lagoon	seeds: *Potamogeton* spp.	11 060±125	–10.2	Ua–15326
Rae Mire	670–675	lagoon	seeds: *Potamogeton* spp.	11 070±115	–11.7	Ua–15325

tional sediment of Pääsküla Mire yielded an age that either infers to the hiatus in the sediment record. Measurements from the post-isolational sediments of Pääsküla and Rae basins (Ua–15321, Ua–15328, Ua–15327) are obviously older by several hundred years than the age obtained according to the isolation altitude and pollen stratigraphy, and might be related to the hard-water effect. Both the relatively high values of $CaCO_3$ fraction and the diatom assemblage tolerant of carbonate-rich water (Fig. 4) reveals that a lake in the Rae Basin was fed by hard groundwater. In addition, six measurements on the floating-leaved aquatic macrophyte seeds from the sediments corresponding to the brackish-water phase of the Yoldia Sea yielded inconsistent and too old ages. The high age of radiocarbon dates obtained from these pre-isolation sediments might be attributed to a considerable marine reservoir effect in the Baltic Sea Basin during the Early Holocene.

SHORELINE DISPLACEMENT

During the final drainage of the Baltic Ice Lake water level dropped by around 25 m to the level of 50 m a.s.l. in Northern Estonia. Due to intensive land uplift the shoreline displacement was regressive throughout the Yoldia Sea stage (Fig. 8). After the retreat of the Yoldia Sea, coastal depressions of the emerging former sea bottom were occupied by fens. The sandy infertile near-shore sediments were a suitable substrate for pine forest immigration. The transgression of the Ancylus Lake led once more to the inundation of the area. The layers of peat and buried pine stumps underlying the transgressive Ancylus Lake deposits allow us to glance at the extent of the Yoldia Sea lowstand. A buried peat in Lake Ülemiste at an altitude of 25.5 m a.s.l. and a piece of wood in Lake Maardu have been dated to 9500 ^{14}C BP (Saarse *et al*., 1997). A thin peat layer in Lake Maardu at an altitude of 24 m a.s.l. is the lowest layer of buried organic matter observed in the area of the Tallinn and probably is related to the lowest shore-level of the Yoldia Sea, indicating that the total amplitude of regression for the Yoldia Sea in the study area amounted to some 25 m (Fig. 8).

DISCUSSION

PALAEOENVIRONMENTAL CONDITIONS FOR THE YOLDIA SEA

The final drainage of the Baltic Ice Lake took place *ca*. 35 years before the Younger Dryas/Preboreal transition (Andrén *et al*., 2002) and the consequent rapid warming which is dated to *ca*. 11 550 GRIP ice core years BP (Björck *et al*., 1998). The varved clays that accumulated in the Baltic Sea proper (Abelmann, 1985; Andrén *et al*., 2000) during the initial phase of the Yoldia Sea are almost barren of diatoms. The small number of planktonic large-lake diatom *Aulacoseira islandica* probably suggests that the offshore areas were still occupied by freshwater. Diatom productivity was low during the beginning of the Yoldia Sea probably because of high turbidity and low transparency from silt and clay introduced by melt-water from the retreating ice sheet. Diatom scarcity can also be attributed to the very high sedimentation rates causing a pronounced dilution effect in the sediment. Several pre-isolation sediment records in Northern Estonia (Table 2; Heinsalu, 2000) indicate freshwater condition in the littoral areas along the southern coast of the Gulf of Finland during the initial 250 years of the Yoldia Sea (Fig. 8). In very shallow littoral zone, whereas light penetrated down to the bottom, conditions for photosynthesis of large-lake periphytic diatoms existed.

The onset of the brackish phase of the Yoldia Sea can be placed at 11 310 calendar years BP (Björck, 1999). Wastegård *et al*. (1998) clearly demonstrated that the main saline water ingression into the Baltic Sea Basin during the Yoldia Sea followed the deglaciation of the Närke Strait. As the brackish Yoldia Sea phase almost coincides with the Preboreal oscillation, Björck *et al*. (1996) implied that this cooling event probably triggered a temporary entry of saline water into the Baltic Sea Basin in connection with diminished meltwater discharge from the ice sheet and correspondingly decreased freshwater transport from the Baltic Sea Basin. The climatic cooling during the Preboreal oscillation and possible reorganization of the ocean/atmophere circulation in the North Atlantic may have a

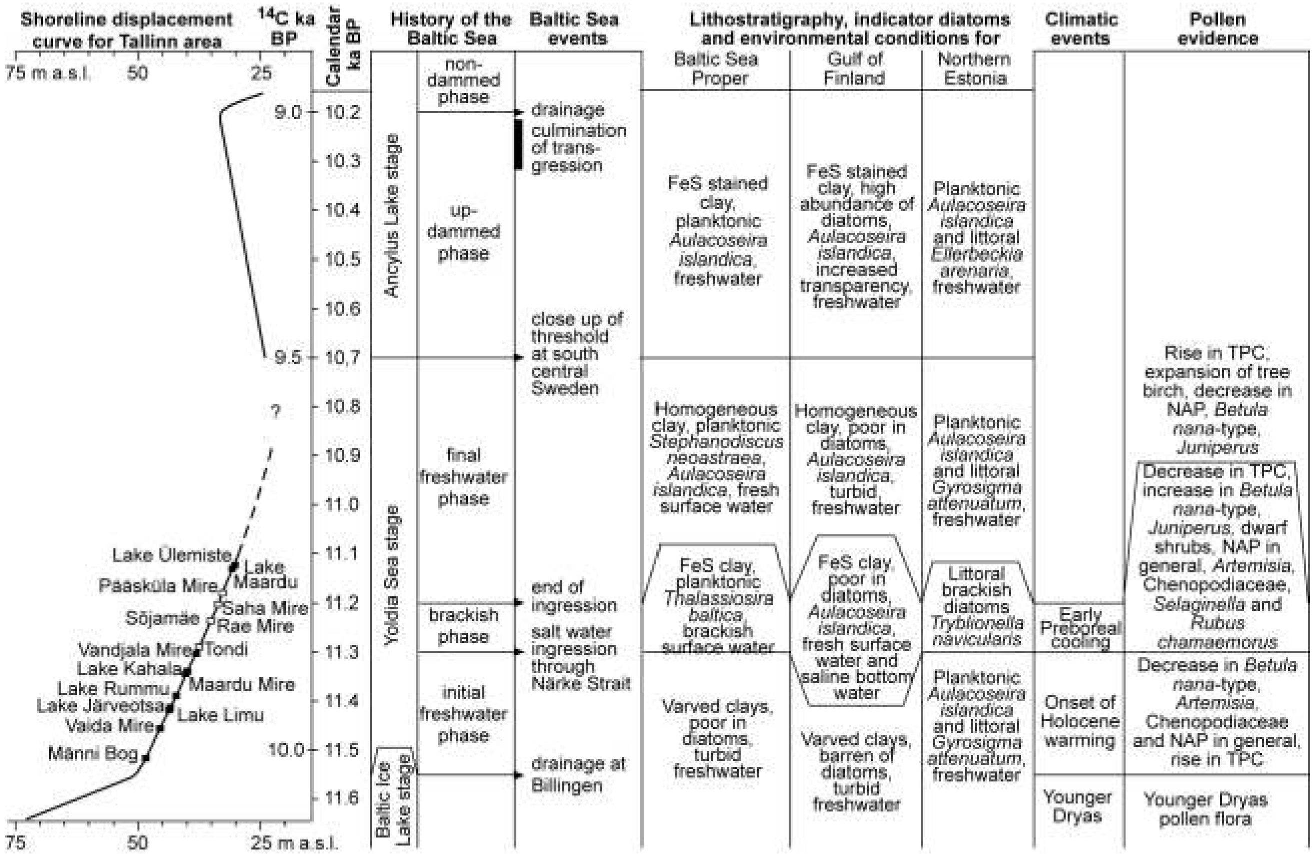

Fig. 8. Synthesis of the early post-glacial history of the Baltic Sea and palaeoenvironmental and climatic conditions in the studied area, the Gulf of Finland and the Baltic Sea proper

The rectangles on the shore displacement curve show the isolation altitudes of the basins investigated; the filled rectangles correspond to a freshwater environment and the opened rectangles indicate brackish-water conditions; the calendar years time-scale follows the event stratigraphy for the Early Holocene in south-central Sweden defined by Björck (1999)

Table 2

Location of the investigated basins (Fig. 1) in Northern Estonia with indication of threshold altitudes before and after the correction for difference in land uplift and corresponding pre-isolational environmental conditions by means of diatom analysis

Site	Latitude N	Longitude E	Threshold altitude [m a.s.l.]	Corrected altitude [m a.s.l.]	Pre-isolational environment
Männi Bog	59°17’00’’	24°54’30’’	43	48	freshwater
Vaida Mire	59°18’30’’	24°57’15’’	41	45.5	freshwater
Lake Limu	59°20’20’’	24°59’50’’	39	43.5	freshwater
Lake Järveotsa	59°05’45’’	24°09’15’’	41	43	freshwater
Lake Rummu	59°27’10’’	25°17’10’’	37	42	freshwater
Maardu Mire	59°24’45’’	25°02’20’’	37.5	40.5	freshwater
Lake Kahala	59°29’30’’	25°32’00’’	33.5	40	freshwater
Vandjala Mire	59°26’20’’	25°03’00’’	37.5	39	freshwater
Tondi site	59°26’30’’	24°51’40’’	38.5	38	brackish
Rae Mire	59°24’15’’	24°51’45’’	37.5	37.5	brackish
Sõjamäe site	59°25’45’’	24°50’10’’	37.5	37.5	brackish
Saha Mire	59°25’45’’	24°59’15’’	34	35	brackish
Pääsküla Mire	59°21’15’’	24°40’00’’	34	33.5	brackish
Lake Maardu	59°26’30’’	24°59’30’’	32	33	freshwater
Lake Ülemiste	59°23’30’’	24°46’15’’	31.5	31	freshwater

large impact for the generation of stronger westerly winds and strengthened storm tracks. The present water exchange between the Kattegat and the Baltic Sea is restricted by the shallow Danish Sounds. Only major inflows transport substantial amounts of highly saline water into the deep basins of the Baltic Sea (Matthäus and Franck, 1992). These rare inflows occur intermittently after periods of persistent strong westerly winds (Krauss and Brügge, 1991) and are possibly regulated by the North Atlantic oscillation (Hänninen *et al.*, 2000).

An inflow of dense brackish bottom water in the Stockholm area is registered by fossil finds of the arctic marine mollusc *Portlandia arctica*, benthic foraminifera and ostracods, as well as by the transition from grey diatactic varved clay to symmictic clay varves with reddish colour and FeS staining (Brunnberg, 1995; Wastegård and Schoning, 1997). Benthic calcareous fauna in the northwestern Baltic Sea proper infer bottom water salinity around 10‰ for the brackish phase of the Yoldia Sea (Schoning *et al*., 2001). A peak of the planktonic diatom *Thalassiosira baltica* (Grunow) Ostenfeld is well replicated in several sediment cores from the Baltic Sea proper and can be considered to be a significant evidence that the saline water pulse was strong enough to break the water column stratification. The high abundance of *T. baltica* is documented in a thin sediment sequence with black bands and lenses of amorphous Fe-monosulphides (e.g. Sohlenius *et al*., 1996; Lepland *et al*., 1999). The formation of FeS precipitation can indicate the presence of saline and anoxic bottom water (Huckriede *et al*., 1996). *T. baltica* prefers surface water with low salinity (Snoeijs, 1993). In addition, *T. baltica* inhabits sea ice in the modern Baltic Sea (Ikävalko and Thomsen, 1997). This evidence indicate a climatic cooling and supports simultaneity of the brackish Yoldia Sea phase and the Preboreal oscillation. Combination of the stratigraphic evidence suggests that a slightly brackish surface water layer above more saline water column distributed in the western part of the Baltic Sea Basin during the brackish phase of the Yoldia Sea (Fig. 9). Surface water salinity favoured coagulation of clay particles, transparency of the water column increased and sufficient light condition for blooming of planktonic diatoms was established.

Altogether five localities in Northern Estonia show abundant brackish-water diatom assemblages and indicate that brackish water reached the Gulf of Finland during the Yoldia Sea stage (Heinsalu, 2000). Two sediment records, in Pääsküla and Saha basins, reveal transition from the initial freshwater Yoldia Sea phase to the brackish phase. Large-lake diatoms almost disappeared and were replaced by abundant littoral brackish-water taxa, e.g. *Tryblionella navicularis*, *T. punctata*, *Diploneis smithii*, *D. interrupta* and *Mastogloia braunii*. According to the diatom assemblages the salinity during the brackish phase of the Yoldia Sea in the littoral areas of the Gulf of Finland was lower than that of today. In addition, littoral sediment sequences of the Yoldia Sea with similar brackish-water diatom assemblages are documented south of the Salpausselkä end moraine zone in Finland (e.g. Valovirta, 1965; Tynni, 1966), in the vicinity of Vyborg, Russian Karelia (Hyyppä, 1937) and on the Karelian Isthmus (Saarnisto *et al*., 1999). The mixing of the water column and circulation of brackish water up to the surface in certain areas along the coast of the Gulf of Finland (Fig. 9) was probably triggered by coastal upwelling generated by persistent strong winds blowing offshore or along the shore in the opposite direction to the permanent surface current, transporting the surface water away and lifting saline water from the deeper layers. Upwelling at the coasts of the modern Baltic Sea occurs frequently (e.g. Kahru *et al*., 1995; Alenius *et al*., 1998).

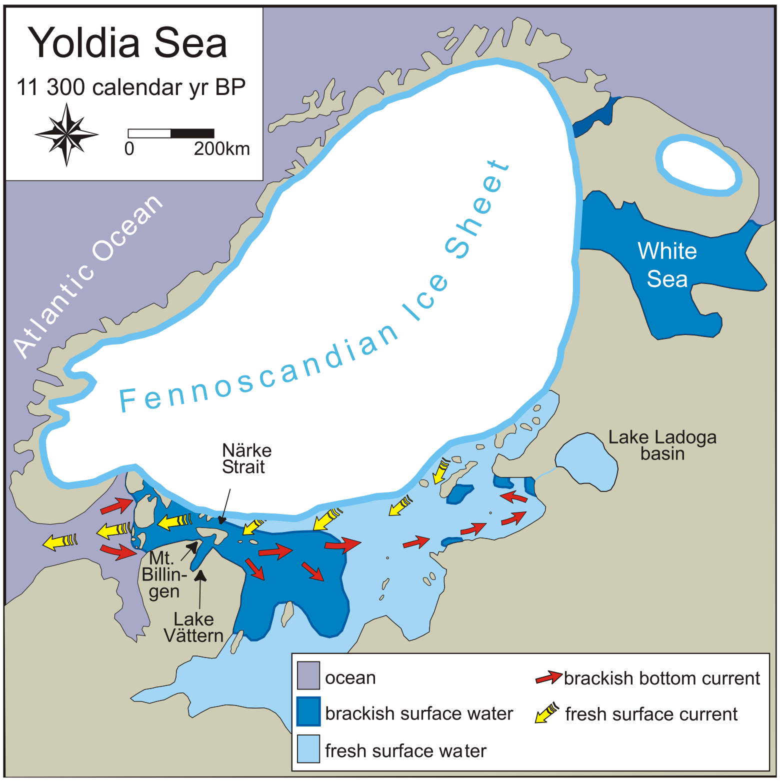

Fig. 9. Palaeogeography and palaeohydrology of the brackish Yoldia Sea phase around 11 300 years BP

In contrast with the other sub-basins of the Baltic Sea, the Gulf of Finland is a direct continuation of the Baltic Sea proper without any notable sill. Even if the cascade of sub-basins is a serious obstacle for the spread of saline water into the marginal downstream basins, a major saline inflow through the Danish Straits in winter 1993 was detected in the Gulf of Finland already some 18 months after the pulse (Alenius *et al*., 1998). The present general circulation pattern in the Gulf of Finland is governed by density differences and the Coriolis effect leading to the mean cyclonic (anti-clockwise) water circulation (Mälkki and Tamsalu, 1985) and we may assume that similar basic hydrodynamic processes played a significant role in the past. Thus the penetration of salt water during the Yoldia Sea took probably place mainly along the south coast of the Gulf of Finland and the saline water pulse would flow as a near-bottom current, whereas at the same time the outflow of meltwater flux discharging from the ice sheet occurred along the north coast. So far, no evidence of the brackish surface water layer has been revealed in the offshore settings of the Gulf of Finland during the Yoldia Sea. Instead, a stratified water column with brackish water at the bottom and turbid freshwater in the surface most likely existed at the entrance of the Gulf of Finland (Heinsalu *et al*., 2000*a*). Perhaps the permanent halocline was deep enough and suppressed efficient vertical mixing of the water column up to the surface.

The end of the brackish phase of the Yoldia Sea is dated to 10 315 varved clay years BP, which corresponds to an age of 11 190 GRIP ice core years BP (Björck, 1999). Diatom assemblages from the littoral pre-isolation sediment sequences of Maardu and Ülemiste lakes indicate freshwater conditions during the final phase of the Yoldia Sea. Similar environmental conditions have been registered on the Suursaari Island in the Gulf of Finland (Heinsalu *et al*., 2000*b*). The offshore sediments from the Baltic Sea proper (Andrén *et al*., 2002) and the Gulf of Finland (Heinsalu *et al*., 2000*a*) display also freshwater conditions for the surface waters and a very low absolute abundance of diatoms. The abrupt decline and disappearance of *Thalassiosira baltica* suggests a rapid freshening of the surface waters in the Baltic Sea Basin (Lepland *et al*., 1999) presumably due to emerging and narrowing sills (Björck, 1995) as well as a consequence of increased meltwater discharge following the Early Preboreal cooling (Björck *et al*., 1997).

TIMING OF THE BRACKISH YOLDIA SEA PHASE IN THE EASTERN BALTIC SEA

AMS ^{14}C dates on aquatic plant seeds from the sediments of Northern Estonia indicate that the reservoir age for the Yoldia Sea was considerably higher, 1000–1500 years, than the estimate for modern marine and brackish-water reservoir effect *ca*. 400 years (Stuvier *et al*., 1998). A reservoir effect of more than 1000 years has also been detected by AMS ^{14}C dates of marine benthic fauna from varved clays in Sweden (Wastegård and Schoning, 1997; Björck *et al*., 2001). The considerable variability in atmospheric ^{14}C content during the Early Preboreal (Björck *et al*., 1996) must be taken into account. Björck *et al*. (2003) have suggested that similarly high marine reservoir ages during the Younger Dryas cold period in the Norwegian Sea have been caused by changing atmospheric ^{14}C content.

The problems associated with the establishment of the Yoldia Sea radiocarbon chronology for the eastern Baltic Sea Basin can be solved by correlating the environmental and climatic changes during the Yoldia Sea with alternative chronologies. Glacial varved clays with their light silty summer and dark clayey winter layer forming within one year deposited in front of the receding ice margin in south-central Sweden during the Yoldia Sea stage. Measurement and correlation of the varve sequences has allowed Swedish geologist to produce the Swedish Time Scale (STS), a continuous calendar year record covering the last 13 200 varve years BP (e.g. Wohlfarth *et al*., 1995). However, the comparison of dendrochronological and GRIP ice core records with the STS shows that 800–900 years are missing from the Holocene part of the Swedish Time Scale (e.g. Wohlfarth *et al*., 1997). The Younger Dryas/Preboreal climate shift and climatic deterioration associated with the Preboreal oscillation and recorded in the pollen spectra and varve thickness proxy in the northwestern Baltic Sea proper made it possible to link the STS with chronology from the GRIP ice core (Andrén *et al*., 1999). The Preboreal oscillation occurred in between 11 315 and 11 195 GRIP ice core years BP (Björck, 1999) and is identified in numerous pollen records in Northern Europe (Björck *et al*., 1997; Andrén *et al*., 1999).

On the basis of pollen stratigraphy of four cores from Northern Estonia the floristic response to the Preboreal oscillation was fairly distinct, despite the area was only recently emerged. There is a decrease in TPC in combination with some increase in herb pollen (*Artemisia*, Chenopodiaceae, *Rumex acetosa/acetosella*-type, *Rubus chamaemorus* and spores of *Selaginella*), *Betula nana*-type, *Juniperus* and *Salix* and also in the dwarf shrubs. A decline in the thermophilous *Filipendula* occurs at the same time. The pollen composition suggests a deterioration of the climate at that time. In Pääsküla, Rae and Saha basins (Kihno, 1996) these changes in the vegetation occur simultaneously with the appearance of littoral brackish-water diatoms in pre-isolation sediments. In the Rummu Basin, which was isolated prior to the spread of brackish water to the coast of Northern Estonia, the changes in vegetation displaying climatic deterioration are observed after the isolation of the lake.

The coincidence of the proxies showing climatic cooling during the Early Preboreal with those indicating brackish-water conditions during the Yoldia Sea in Northern Estonia is good. Moreover, shoreline displacement curve for the Tallinn area indicates that brackish-water conditions persisted for a period about 100 years (Fig. 8). Consequently, that evidence leaves no room for the assumption that a delay of some 80–90 years occurred in saline water penetration from eastern central Sweden to Southern Finland (Donner, 1969; Strömberg, 1990). It seems fairly reasonable to conclude that the brackish-water flow from the inflow area reached the Gulf of Finland within a very short time.

CONCLUSIONS

1. The history of the Yoldia Sea stage in Northern Estonia can be divided into three phases. The initial and final phases were characterized by freshwater conditions, while brackish-water conditions prevailed for a short period in between. The results of new diatom studies correlate with the notion of a well-constrained development of the Yoldia Sea extending from the inflow area in south-central Sweden into the Baltic Sea proper, but they do not support the hypothesis that the saline water failed to reach the Gulf of Finland.
2. The littoral diatom assemblages in Northern Estonia indicate that brackish water reached the Gulf of Finland during the Yoldia Sea stage. Coastal upwelling caused mixing of the water column and the circulation of brackish water up to the surface in certain near-shore areas in the Gulf of Finland. Salinity was probably lower in these coastal areas than it is today.
3. The pollen stratigraphy of the cores from Northern Estonia points to a fairly distinct floristic response to the Preboreal oscillation that occurred simultaneously with the appearance of littoral brackish-water diatoms. Thus the short-lived brackish phase of the Yoldia Sea existed *ca*. 11.300–11.200 calendar years BP. AMS dates obtained for aquatic macrofossils suggest reservoir ages of 700–1500 years for the brackish Yoldia Sea phase.

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