Sedimentological and chronological aspects of the Younger Dryas – Holocene transition record in southern Finland and northern Baltic

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Cover photo: Oivonoja clay pit in Koria, near Kouvola.

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Abstract

In this study, different types of sediments deposited in the Baltic Sea Basin in Southern Finland and the Gulf of Finland before and after the Baltic Ice Lake (BIL) drainage were examined. The aim was to gain a better understanding of changes in sedimentation in offshore, shallow water and onshore beach environments, to provide an independent age control for the drainage event, and to test the applicability of dendrochronological cross-correlation methods to varve clay data. The study consisted of acoustic sounding data from offshore, one offshore marine sediment core, six outcrops related to the BIL/Yoldia Sea transition sediments, and a digitized version of original varve measurements by Sauramo.

In the Baltic basin area, the drainage of the BIL occurred close to end of the Younger Dryas cold event. This sudden 25–28 m fall in water level had originally been chosen as the zero datum for the Finnish varve clay chronology, but the "key horizon" concept was not developed further and its chronostratigraphical connection and importance remain unclear. Since the early 20th century annually laminated, or varved, sediments have been used succesfully in constructing Late Pleistocene - Holocene ice retreat chronologies and in dating ice marginal formations. This also applies to Finland. Correlating varve chronnologies across the Salpausselkä zone is difficult, due to slow ice retreat rates and ice front oscillations during the Younger Dryas period. Therefore, the older part of the chronology, which pre-dates the drainage event, is only loosely connected to Holocene varve series.

In offshore environment (water depth > 40 m), the falling water level triggered debris flows, which eroded and redeposited older, varved sediments creating a distinct deformation unit. In the northern Baltic proper and Gulf of Finland, up to 4 m thick, discontinuous deposits of homogeneous clay bearing traces of rotational slump and deformation were deposited. In Jokela, where the original zero varve was first described by Sauramo (1923), a homogeneous clay unit containing deformed sandy pods and layers was observed. This unit corresponds to a zero varve which was formed as a consequence of a sudden water level drop in the BIL. In shallow water environment (water depth < 40 m), deposition of varved sediments ceased and, as a result of rapid regression, shore processes started to operate, during which progressive marine terraces were formed. The first signs of saline incursion into southern Finnish area were ca 100 varve years after the BIL drainage. On newly emerged land, exposed sediments were prone to wind erosion. The occurrence of massive cover sands, "Lammi loess", in the Second Salpausselkä area has traditionally been attributed to rapid dust-storm type of deposition. However, there are also indications of non-aeolian origin of these deposits.

Morphologically well-defined coastal terraces are related to the oldest Yoldia Sea level (YI), which was developed after the BIL drainage. One of these terraces within the First Salpausselkä zone was dated by optically stimulated luminescence (OSL) method. This is the first direct YI-level date in Finland and it yielded ages of

11 200–11 400 ± 2 700 years. The finding highlights the potential of shore terraces in verifying Lateglacial – early Holocene varve chronology in Finland. Another approach to strengthen the deglaciation chronology could be applying to clay varve data the statistical methods used in dendrochronology. This approach separates the local variation within sedimentary basin from the climatic signal, and enables varve correlations over longer distances.

The main findings can be summarized as following:

-The BIL drainage was a basin-wide sedimentological event, leading to the deposition of a distinct drainage varve facies expressed in the annually laminated glaciolacustrine sediment as a debris-flow unit and in the shallow water sediment as the change into non-annual deposition rhythm.

-After the BIL drainage, freshwater conditions prevailed in the early Yoldia sea phase for at least ca 100–200 years.

-The first OSL-dating of oldest Yoldia Sea terrace (YI) in Finland gave ages of 11 200 and 11 400 ± 2 700 years. This gives also a minimum age to the BIL drainage.

-Although drainage facies makes a good stratigraphic marker horizon, the erosion and redeposition related to drainage event combined with a possible hiatus in sedimentation make drainage varve facies problematic as a chronostratigraphic clay varve key horizon.

Tiivistelmä

Työssä tutkittiin sedimenttejä, jotka ovat kerrostuneet Itämeren altaaseen Etelä-Suomen ja Suomenlahden alueella Baltian jääjärven muuttuessa Yoldiamereksi noin 11 600 vuotta sitten. Tuolloin Skandinavian mannerjäätikkö peitti vielä suuria maa-alueita: jäätikön reuna oli Suomen alueella Toisen Salpausselän kohdalla. Baltian jääjärvi peitti lukuun ottamatta korkeimpia huippuja lähes kaiken jään alta paljastuneen maan, ennen kuin jääjärvestä avautui yhteys valtamereen Billingenin alueella Ruotsissa. Näin jääjärven pinta laski 25–28 m muutaman vuoden aikana, kunnes vakiintui senhetkisen valtameren pinnan tasoon. Tämä paljasti uusia maa-alueita veden alta ja myös mahdollisti satunnaisten suolapulssien tulon Itämeren altaan keskiosiin. Jotkut suolapulsseista päätyivät Suomen rannikolle saakka. Baltian jääjärven pinnan lasku liittyy ajallisesti kylmän ilmastovaiheen, Nuoremman Dryaksen, loppumiseen ja lämpimän jakson, Holoseenin, alkuun.

Etelä-Suomen ja Suomenlahden alueella Baltian jääjärvivaihetta ja Yoldiameren alkua luonnehtivat niinsanotut lustosavet, joissa muutokset mineraaliaineksen raekoossa kuvastavat vuodenaikojen vaihtelua. Vertaamalla raekoon muutoksia eri alueilla toisiinsa voidaan saada selville jopa vuoden tarkkuudella, kuinka kauan jään reunalla on kestänyt vetäytyä paikasta toiseen. Tähän Gerard De Geerin Ruotsissa 1900-luvun alussa kehittämään metodiin ja Matti Sauramon laajaan kenttätyöhön perustuu suurelta osin käsitys viimeisimmän jääkauden loppuvaiheista Etelä-Suomen alueella. Sauramon lustosavikronologian nollavuotena on pidetty juuri edellä mainittua Baltian jääjärven purkautumista, joka näkyy epätavallisen paksuna vuosikerrostumana.

Työn tavoitteena oli ymmärtää veden pinnan laskun aiheuttamia muutoksia altaan kerrostumisolosuhteissa sekä saada lustosavikronologiasta riippumaton ikä erityyppisille pinnanlaskuun liittyville sedimenttimuodostumille optisesti stimuloidulla luminesenssimenetelmällä (OSL). OSL perustuu sedimenttirakeiden "nollautumiseen" auringonvalossa. Mittaamalla rakeista kuumennettaessa vapautuvan signaalin voimakkuus voidaan arvioida milloin rae on viimeksi altistunut auringon säteilylle ennen kerrostumistaan eli hautautumistaan. Lisäksi Sauramon lustokronologiaan haluttiin kokeilla puulustotutkimuksessa rutiininomaisesti käytettyjä tilastollisia menetelmiä, joilla pyritään vähentämään paikallisten vaihtelujen merkitystä kronologiassa.

Tilastollisten menetelmien soveltaminen lustoaineistoon osoittautui lupaavaksi, niiden avulla pystytään mahdollisesti kytkemään entistä kauempana sijaitsevia kerrostumispaikkoja toisiinsa. Erityisen ongelmallinen jakso Suomen lustokronologiassa on Baltian jääjärven purkautumista edeltävän ja seuraavan ajanjakson kytkeminen toisiinsa. Tämä liittyy muutoksiin sedimentaatiossa.

Syvässä vedessä pinnanlasku todennäköisesti laukaisi rinteillä massaliikuntoja, veden ja sedimentin tiheitä seoksia, jotka alas vyöryessään kuluttivat ja uudelleen kerrostivat vanhempia lustosedimenttejä. Myös pienempiä aineksen romahduksia esiintyi. Tämän jälkeen olosuhteet altaassa rauhoittuivat ja lustokerrostumia alkoi taas syntyä. Tutkimusaineiston perusteella ei voida ottaa kantaa siihen, kuinka kauan altaan kerrostumisolosuhteiden rauhoittuminen kesti, ja näin ollen lustokronologian eri osien kytkeminen toisiinsa on edelleen varmentamatta. Suolaisen veden pulssien saapuminen tutki-

musalueelle kesti lustokerrostumien perusteella vähintään 100 vuotta, suolaisuuden lisääntyminen näkyy selkeänä muutoksena lustojen rakenteessa. Edellä mainitun kaltainen kerrostumishistoria on havaittavissa muun muassa Tuusulan Jokelassa, josta Sauramo kuvasi nollalustonsa.

Matalammassa vedessä lustosedimenttien kerrostuminen loppui veden pinnan laskun myötä, ja rantavoimat alkoivat vaikuttaa kerrostumiseen voimakkaasti. Tähän liittyy muun muassa rantaterassien syntyä ja aineksen raekoon yleistä karkenemista. Matalamman veden kerrostumat antoivat vaihtelevia OSL-ikiä. Lahden Renkomäestä saatu Suomen ensimmäinen OSL-ikä Yoldiavaiheen rantaterassille oli 11 200–11 400 ± 2 700 vuotta. Tämä viittaisi siihen, että rantaterassien järjestelmällinen OSL-ajoittaminen voisi tuoda uutta tietoa Itämeren altaan historiasta. Toisaalta osa matalammankaan veden kerrostumista ei ollut saanut riittävästi auringonvaloa sedimenttirakeiden nollautumiseen.

Veden alta paljastunut maa-aines joutui voimakkaan tuulieroosion kohteeksi. Ensimmäisen ja Toisen Salpausselän välisellä alueella on tavattu laajalti hienojakoista hiekka- ja silttivaltaista ainesta, joka ohuena kerroksena verhoaa maanpintaa. Tämä ns. lössi tai peittohiekka on tulkittu tähän intensiivisen tuulivaikutuksen jaksoon liittyväksi kerrostumaksi. Lähtökohtaisesti tällaisen aineksen pitäisi olla hyvin nollautunutta ja antaa luotettavia ikämäärityksiä. OSL-ajoituksen toimimattomuus tässä kerrostumassa kyseenalaistaa Salpausselkien välisten hiekkakerrostumien pelkän eolisen luonteen.

Yhteenvetona voidaan sanoa, että Baltian jääjärven purkautuminen jätti jälkeensä tunnusomaisen joukon sedimenttikerrostumia, jotka voidaan löytää koko altaan alueelta. Näin ollen tapahtuma on jättänyt jälkeensä hyvin ajoitetun merkkihorisontin. Tämä horisontti sopii kuitenkin huonosti lustosavikronologian pohjaksi, sillä tapahtumaan liittyy laajalti eroosiota, uudelleenkerrostumista ja ajanjakso, jolloin kerrostumista ei ole tapahtunut.

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Contents

List of original publications

This thesis is based on the following publications:

I **Hyttinen, O.**, Kotilainen, A. & Salonen, V.-P. (2011). Acoustic evidence of a Baltic Ice lake drainage debrite in the northern Baltic Sea. Marine Geology 284, 139–148.

II **Hyttinen, O.**, Salonen, V.-P. & Kaakinen, A. (2011). Depositional evidence of water-level changes of the Baltic Ice Lake in southern Finland during the Younger Dryas/Holocene transition. GFF 133, 77–88.

III Helama, S., **Hyttinen, O.** & Salonen, V.-P. (2012). Varve archives re-explored to assess Late Weichselian proglacial sedimentary chronologies. Progress in Physical Geography. 36, 187–208.

IV **Hyttinen, O.**, Eskola, K., Kaakinen, A. & Salonen, V.-P. Exploring the applicability of OSL-age determinations to sediments related to drainage of the Baltic Ice Lake in southern Finland. Manuscript.

The publications are referred to in the text by their roman numerals.

Author´s contribution to the publications:

I The study was planned by A. Kotilainen and V.-P. Salonen. The data classification and interpretation was conducted by O. Hyttinen. The manuscript was prepared by O.Hyttinen and article jointly written by all authors.

II The study was planned by V.-P. Salonen and O. Hyttinen. The fieldwork was conducted and data interpreted by O. Hyttinen and V.-P. Salonen. The manuscript was prepared by O. Hyttinen and article jointly written by all authors.

III The study was planned and conducted and manuscript written and by S. Helama. The article was commented and contributed by O. Hyttinen and V.-P. Salonen.

IV The study was planned by O. Hyttinen and V.-P. Salonen. Field work and sampling was contributed by all authors. The laboratory work and age determination was done by K. Eskola. The data interpretation and manuscript preparation was done by O. Hyttinen, V.-P. Salonen and K. Eskola, article was jointly written by all authors.

Abbreviations

AMS	Accelerated mass spectrometry
BIL	Baltic Ice Lake
BP	Before present
BSB	Baltic Sea Basin
GSSP	Global Stratotype Section and Point
OSL	Optically Stimulated Luminescence
psu	practical salinity unit
SIS	Scandinavian Ice Sheet
TOC	Total organic carbon

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1. Introduction

Annually laminated sediments or varved sediments are important archives of seasonally changing sedimentation conditions. These rhythmic changes produce horizontally bedded layers, or laminae, with alternating composition and texture, such as clastic varves composed mainly of silt and clay, or organoclastic varves with organic and clastic layers. Clastic varves form couplets, where coarser or more minerogenic sediment is deposited during the spring and summer, and finer or more biogenic material in the wintertime. As changes in grain size and total organic carbon (TOC) are strongly related to climate by temperature and evaporation, varved sediments may yield valuable climatic information. In the early 20th century a Swedish geologist, Gerard De Geer, proposed a theory of the annual origin of clastic, laminated sediments and he managed to correlate varve series taken from different sites on the basis of trends in varve thickness variations (De Geer, 1912). His clay varve chronology and its application as - at its best- a precise dating method has shown its applicability e.g. in studying Late Pleistocene and Early Holocene ice sheet retreat and ice margin positions in Sweden (De Geer, 1912, 1940; Cato, 1987; Strömberg, 1994), Finland (Sauramo, 1918, 1923; Niemelä 1971; Strömberg, 1990, 2005) and Estonia (Hang, 2003; Kalm, 2006). In North America, the New England varve chronology (Antevs, 1922, 1928; Verbosub, 1979a,b; Ridge, 2004) has been used to trace movements of the Laurentide Ice Sheet. Varved sediments have also been used as a calibration aid for radiocarbon datings, especially when crossing radiocarbon age plateaux (e.g. Goslar et al., 1995; Litt et al., 2003). An indicator of the importance of certain varve series as palaeoclimatic archives, is that varved lake sediments in Germany (Brauer et al., 1999; Litt et al., 2001) have been suggested as European auxiliary stratotype of the Pleistocene - Holocene boundary Global Stratotype Section and Point (GSSP) (Walker et al. 2009).

The varve counting method itself has remained remarkably similar to that used by De Geer. Like in dendrochronology, thickness variations of varves are often measured directly from the wall of the clay pit, or from the fresh surface of a sediment core (Fig. 1). The thickness of one clastic varve is the distance from the bottom of coarser lamina to the upper contact of the associated clay lamina. Thickness variations between sites are visually compared and different localities are connected based on similar trends in the variability. Also image processing programs, which utilize digitized grayscale tone variations to quantify varve thicknesses, have been used especially in studies of organic varves, often combined with magnetic susceptibility measurements or geochemical data (e.g. Lindeberg & Ringberg, 1999; Ojala & Francus, 2002).

Besides providing useful material for dating and reconstructing ice-margin positions, varved sediments have the potential to record past changes in lake water-levels. So-called drainage varves, or varves related to water-level fall in the basin, may preserve sediment structures typical of debrites or turbidites, or they can be homogeneous, clay-rich units, often containing eroded and/or redeposited older material. Numerous examples from glacial lakes in Scandinavia (e.g. De Geer, 1912; Sauramo, 1923; Nilsson, 1968), Europe (e.g. Hang, 2003; Gruszka, 2007; Murton et al., 2009; Putkinen et al., 2011) and North America (e.g. Johnson et al., 1999; Breckenridge, 2007; Lajeunesse & StOnge, 2008; Roy et al., 2011) have shown the importance of varved lake sediment records in reconstructing water-level changes. In the Baltic Sea Basin (BSB) area, the drainage of the Baltic Ice Lake (BIL), which occurred close to the Younger Dryas -

Fig. 1 An example of Sauramo´s varve thickness measuremets (left). Pencil marks indicate varve boundaries. A metal box filled with varved clay sediment (right). Sauramo used these boxes to take samples to be later measured in the lab.

Holocene transition, is an excellent example of a basin-wide event depositing a drainage varve. This event horizon was originally chosen as the zero varve of Finnish varve chronology, as well as a boundary between the Gotiglacial, and the Finiglacial: the former meaning an intermediate stage after the maximum extent of the Scandinavian Ice Sheet (SIS) when ice retreated from central Scania to the Fennoscandian moraines, and the latter meaning the final deglaciation in the Early Holocene in Sweden (De Geer, 1912, 1940).

A major problem in the study of glacial varved deposits in Finland is the lack of precise age control. The Finnish varve chronology can be considered a floating one. It is based on Sauramo´s extensive work in southern Finland (Sauramo, 1918, 1923) and the core part of the chronology covers ca 2 100 varve years. Revisions of the chronology have suggested an earlier formation of the Salpausselkä ridges and a longer interval between the formation of the 1st and 2nd Salpausselkäs (Niemelä, 1971), or an estimation of 75 missing varve years from the postglacial part of the chronology (Strömberg, 1990, 2005). The Finnish varve chronology has tentatively been connected to its Swedish counterpart by correlating measurements from both sides of the Baltic Sea and strengthening the correlation with the help of a stratigraphical marker sequence consisting of varves with limestone fragments (Strömberg, 1990). The Swedish varve chronology covers over 14 000 varve years, and it has been connected to calendar years: varves from Ångermanälv river valley have been connected both to the present time and to De Geer´s chronology (Lidén, 1938; Cato, 1987). Later it has been revised multiple times (e.g. Strömberg, 1985; Cato, 1987; Strömberg, 1989, 1994; Ringberg, 1991; Brunnberg, 1995), but radiocarbon datings and local revisions indicate that there are still errors in it (e.g. Björck et al., 1996; Wohlfarth, 1996; Wohlfarth et al., 1997, 1998; Andrén et al., 1999; Wohlfarth & Possnert, 2000). Altogether 875 years seem to be missing from the postglacial part of the Swedish varve chronology (Andrén et al., 2002). In comparison, the New England varve chronology is floating: it consists of two parts which cover ca 4 000 and ca 1 900 years, and it is calibrated based on radiocarbon ages (e.g. Ridge et al., 1999; Ridge & Larsen, 1990; Ridge 2004) and cosmogenic isotopes (Balco & Schaefer, 2006).

The applicability of micropaleontology is typically limited when determining the age of sediments deposited soon after the ice sheet retreat because they are practically barren of micro- and macrofossils and have a very low content of organic matter, both of which also restrict the use of the AMS ^{14}C method (Ignatius et al., 1981). The reservoir effect, i.e. the redeposition of older carbon and delay in mixing of surface and deep waters, in the BSB area is problematic because it has most likely varied over time (Hedenström & Possnert, 2001), bringing thus additional uncertainty in bulk sediment datings. There is little study on this particular aspect. The palaeomagnetic secular variation record in southern Finland does not yet cover the time period in question (Ojala & Alenius, 2005). Therefore, the lateglacial deglaciation chronology in Finland is based largely on geomorphology and varve chronology. It is suggested that between 12 800 and 11 590 yr BP, the ice margin retreated from northern Estonia to the 2nd Salpausselkä, which also resulted the formation of the Salpausselkäs (Saarnisto & Saarinen, 2001; Kalm, 2006). In Sweden, the BIL drainage has been dated to 11 550 cal yr BP (e.g. Andrén et al., 2002), as well as the end of the Younger Dryas at 11 500 cal yr BP (e.g. Wohlfarth et al., 2008, Donner 2010). This places the drainage of the BIL and the transition to the early Yoldia Sea in a chronological context.

1.1. Aims of the study

There is a demand for targeted sedimentological and chronological studies on Baltic Sea sediments, because the strata are chronostratigraphically important. They relate to the most dramatic event in the recent geological history of the Baltic Sea area and have an important connection to the Younger Dryas – Holocene transition. Despite its significance, the sedimentological evidence of the BIL drainage in southern Finland area has not been adequately studied.

The focus of this study was on the drainage of the BIL and the beginning of the early Yoldia Sea phase. The study of this event is important because the weakest points of the Finnish varve chronology are found in the parts covering the perioid of drainage, and the varve chronology is the best tool available for developing a time scale for deglaciation sediments. The aim of this study was threefold: (i) to acquire a more detailed picture on how the BIL/Yoldia Sea transition can be observed in terms of sedimentology both in clay exposures representing shallow water deposition and in deep water submerged sediments, i.e. what type of sediment was deposited after the drainage, what controlled the deposition and how traceable those sediments are over longer distances, (ii) to obtain an age for the drainage event which would be independent of the varve chronology and would clarify the Finnish varve chronology, and (iii) to use cross-correlation methods and statistically validate their applicability to Sauramo's varve chronology, and to give additional knowledge of the limitations and possibilities related to varve correlations.

2. Geological background

2.1. Geology of the study area

The study area is situated at southern Finland and the Gulf of Finland (Fig. 2). It belongs to the Fennoscandian shield, which consists mostly of Paleoproterozoic rocks (shales, migmatites, volcanic rocks and granitoids) formed 1.82–1.93 Ga ago during the Svecofennian orogeny, Mesoproterozoic (1.65-1.2 Ga old) rapakivi granites, anortosites and diabases, as well as Jotnian (1.4–1.2 Ga) sandstones on the western coast extending further into the Gulf of Bothnia (Winterhalter et al., 1981; Koistinen et al., 2001). Additionally, small provinces of Paleozoic mudstones, sandstones, conglomerates and carbonates can be found on the western coast. The Gulf of Finland lies at the southern margin of the Fennoscandian shield, which dips under Palaeozoic sedimentary rocks. Major tectonic features in the area include faults, fractures and lineaments, like the Teissure-Tornquist Zone, a major fracture zone on the southwestern border of the East European Platform, or the Kökar–Hanko–Helsinki shear zone and the Åland–Paldiski–Pskov shear zone (Koistinen et al., 2001). Some tectonic zones have been active several times since the Archean. At present seismicity in the area is relatively low: according to the North-European earthquake database (http://www.helsinki.fi/geo/seismo/bulletiinit/index.html), ca 50 earthquakes, with magnitudes mostly of <3, have been observed in the study area, while, e.g., the northern half of Swedish eastcoast has undergone much more of seismic activity. Isostatic land uplift in the study area is 2-4 mm/y (Ekman, 1996).

Extensive intrusions of rapakivi granites and associated igneous rocks between 1.67 and 1.45 Ga (Haapala & Rämö, 1992) reactivated the crust. The BSB was developed at 1.4–1.2 Ga (Korja et al., 2001). During the Late Ediacaran-Early Cambrian sub-periods, the break-up of the supercontinent Rodinia established a passive continental margin basin and there was a marine transgression, resulting in the deposition of quartzitic sandstones, siltstones and shales, such as the blue Cambrian clays in Estonia. During the Palaeozoic era, sedimentation was rather continuous and the area was subsiding, the Mesozoic and Cenozoic eras being dominated by non-deposition, which was partly interrupted by recurrent marine transgressions (Šliaupa & Hoth, 2011).

A relatively thin layer of glacial Quaternary sediments covers the bedrock in southern Finland. The crystalline bedrock in Fennoscandia has been relatively resistant against glacial erosion and the landscape is typically dominated by mega-scale scouring features. The average thickness of minerogenic sediments is estimated as ca 8 m, which was interpreted to equal a 7-m lowering of bedrock by glacial erosion during the Quaternary (Okko, 1964). Since the last glaciation, the rate of bedrock weathering in southern Finland has been estimated to have been 1–3 cm (Tanner, 1938).

In the area south of the 1st Salpausselkä, the bedrock is usually covered by a till layer deposited by the Late Weichselian ice sheet. This layer varies in thickness and is missing in places. The till can be of consolidated lodgement-type or more loose melt-out type. In many places the uppermost part of the till layer was later modi-

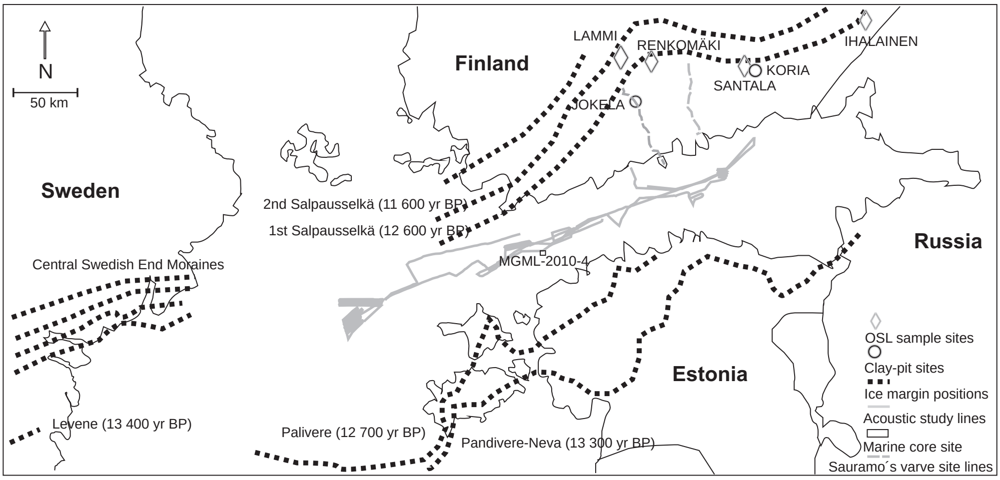

Fig. 2 Deglaciation lines and study sites. The ice margin positions are based on Lundqvist & Wohlfarth (2001), Saarnisto & Saarinen (2001) and Vassiljev et al. (2011).

fied by littoral processes, which transported fine sediments further away and thus enriched the gravel and sand content in sediment. The till is overlaid by glaciofluvial sand and gravel, which was usually deposited as eskers, deltas, subaquatic fans or beach sands. The Salpausselkä end moraines dominate the landscape in southern Finland. They were deposited during Younger Dryas and consist of till, gravel and sand. The area south of the Salpausselkäs was subaquatic after deglaciation, until dry land was exposed by isostatic land uplift. Therefore, a veneer of fine sediments deposited during various stages of the Baltic Sea covers all but the highest hills.

2.2. Deglaciation chronology from Alleröd to Holocene (13 900–11 500 yr BP)

After 16 000 cal yr BP a rapid deglaciation of SIS started in the southern BSB. In Sweden, the retreat was relatively slow along the west coast, while large areas in the central highland and on the southeastern and eastern coast were rapidly deglaciated between 15 000 and 14 400 cal yr BP, with stagnant ice remaining in the higher elevated areas until 13 900 cal yr BP (Lundqvist & Wohlfarth, 2001; Houmark-Nielsen & Kjær, 2003). Around 13 400 cal yr BP the ice had retreated to the Levene end moraine area (Lundqvist & Wohlfarth, 2001; see Fig. 2 for location), while the northern Baltic proper, the Gulf of Finland and southern Finland were still covered by SIS. The Younger Dryas cold event (12 650 - 11 500 cal yr BP) slowed down the retreat of SIS. The Younger Dryas end moraines around Fennoscandia in Finland, Sweden and Norway and in northwest Russia stand witness to a marked cooling of the climate, re-advances and stillstands of the ice margin. The moraines consist of till and glaciofluvial material, and are deposited in the ice marginal zone on land or in a marine or glaciolacustrine basin.

In southwestern Sweden, more or less continuous Younger Dryas moraines form a 100-km wide zone. These end moraine ridges were mostly formed within marine environments and consist of sorted sediments and diamictons. Towards the southeast the morphology of the deposits changes: continuous ridges become divided into multiple ridges and finally into hummocky moraine landscape in south-central Sweden. In southeastern Sweden there are only a few topographically visible ice-marginal ridges south of the Younger Dryas end moraine zone (Lundqvist & Wohlfarth, 2001).

In Finland, deglaciated areas were immediately covered with the waters of the BIL and the topographically well-defined 1st and 2nd Salpausselkä end moraines were deposited during the Younger Dryas. The Palivere ice marginal moraine system (12 675 varve years BP; Hang & Sandgren, 1996, see Fig. 2 for location) in northern Estonia is the closest well-developed ice terminal position predating the deposition of the 1st Salpausselkä. According to Kalm (2006), the formation of Palivere end moraine zone, the deglaciation of the Gulf of Finland and the formation of the1st Salpausselkä end moraine zone took 400–425 years at the most. Hang (1997) suggests that the deglaciation of the western part of the Karelian Isthmus, below the level of the BIL, took ca 450 varve years. Saarnisto & Saarinen (2001) give an age of ca 12 250 cal yr BP for the 1st Salpausselkä and ca 11 600 cal yr BP for the 2nd Salpausselkä, based on the varve clay measurements and paleomagnetism. Using the ^{10}Be-method, Tschudi et al. (2000) dated the 1st Salpausselkä to 11 930±950 yr BP (with consideration of erosion) and Rinterknecht et al. (2004) gave an error-weighted mean age of 12 400±700 yr BP for the 1st Salpausselkä.

At the end of the Younger Dryas the mean July temperature rose by 4–10°C (Renssen & Isarin, 2001; Wohlfarth et al., 2004) and the SIS started to retreat rapidly. In southern Sweden the ice recession rate was 75-100 m/year (Ringberg, 1991) before the Younger Dryas, from 20-50 m/year to 0 m/year (stillstand) during the Younger Dryas (Brunnberg, 1995), and 200 m/year during the Early Holocene (Brunnberg, 1995). In Finland, the recession rates have been of similar magnitudes (Sauramo, 1923; Niemelä, 1971).

2.3. Characteristics of the present Baltic Sea

The Baltic Sea is a brackish epeiric (or inland) sea, a semi-enclosed water body consisting of a few deeper basins separated by bedrock sills. The main sub-basins are the Bothnian Bay, the Bothnian Sea, the Gulf of Finland, the Gulf of Riga and the Baltic proper. The average depth is 52 m, and the maximum depth 459 m (Seifert & Kayser, 1995). Dense, saline water flows in from the southwest, from Skagerrak/Kattegat, and fresh water is supplied by large rivers in the north. This creates a south-north salinity gradient in the basin. The surface salinity is ca 8–10 practical salinity units (psu) in the southern Baltic, ca 7–8 psu in the Baltic proper and ca 3–5 psu in the Gulf of Finland and the Bothnian Sea (Matthäus, 2006).

The brackish surface water is separated from more saline bottom waters by a permanent halocline which can be found at a water depth of 30–40 m in the Arkona Basin, at 40–60 m in the Bornholm Basin, and at 70–80 m in the Gotland Basin and the Landsort Deep (Kullenberg, 1981; Matthäus, 2006). The Bothnian Sea and, in particular, the Bothnian Bay have practically no haloclines and as a result of less variable inflow conditions compared to other areas the Bothnian Sea and Bay are better ventilated (Stigebrandt, 2001).

2.4. Characteristics of the Baltic Sea in the past

At the beginning of the Pleistocene, the Baltic Sea depression was occupied by the northeast-southwest running Baltic stream (Gibbard, 1988). Marine sediments related to the Holsteinian interglacial are found in the Baltic Sea area and adjacent regions (Marks & Pavlovskaya, 2003), and there are several sites known with marine deposits from the Eemian interglacial (Ikonen & Ekman, 2001; Miettinen et al., 2002).

During the Eemian interglacial (130–115 ka BP), lacustrine conditions prevailed for ca 300 years before the marine phase (Kristensen & Knudsen, 2006). After the lacustrine phase, the BSB Baltic was connected to the Barents Sea via the Karelian area during the first ca 2–2.5 ka, as the Saalian ice sheet had caused a deep glacio-isostatic crustal anomaly. The Eemian Baltic Sea had a strong west-east temperature and salinity gradient: warmer and more saline surface waters in the western BSB and lower salinity and colder bottom water in the eastern BSB, possibly creating strong salinity stratification and hypoxic bottom conditions (Andrén et al., 2011). After ca 6 ka the level of the Eemian Baltic Sea level fell and its salinity decreased (Eiríksson et al., 2006; Kristensen & Knudsen, 2006).

It is likely that the early Weichselian glaciations did not affect the central and southern Baltic Sea area during the Weichselian stage (Robertsson et al., 2005). The first Baltic glacial event occurred during the Mid-Weichselian (Svendsen et al., 2004; Houmark-Nielsen, 2007; Salonen et al., 2008; Larsen et al., 2009), and freshwater lakes covered the central and southern BSB (Andrén et al., 2011). Before the Last Glacial Maximum ice extent ca 18 000–17 000 cal yr BP in the southeastern sector of SIS (Lunkka et al., 2001) and ca 22 000 cal yr BP in the west (Mangerud, 2004), there might have been two major ice advances reaching southwest Baltic (Houmark-Nielsen & Kjær, 2003). The present state of the basin is linked closely to the retreat of the Late Weichselian SIS. A thorough review of the recent history of the Baltic was compiled by Björck (1995) and updated by Björck (2008) and Andrén et al. (2011). In the following, the main emphasis is given on describing the BIL and Yoldia Sea phases with only a short overview of the Ancylus Lake and Litorina Sea stages.

2.4.1. The BIL (14 000–11 550 cal yrs BP)

It has been assumed that the level of meltwaters in the ice free areas of the BSB equalled the contemporary sea level at around 16 000 cal yr BP. The BIL started to dam up at ca 14 000 cal yr BP (Andrén et al., 2011) as the uplift of the threshold in the Öresund area lifted the Baltic Basin above sea level.. At ca 13 000 cal yr BP, the ice margin was in south-central Sweden. Due to the glacioisostatic depression, the altitude of this area was considerably lower than the threshold in the Öresund region. Therefore water was dammed up 5–10 m above the ocean level. The deglaciation of the area around Mt. Billingen led to the first, poorly documented, drainage of the BIL. After the drainage, the new pathway for the waters was towards the west and this continued for 300–400 years (Björck, 1995). Around 12 800 cal yr BP, at the beginning of the Younger Dryas cold period, the re-advancing ice front finally closed the connection between the sea in the west and the Baltic in the east (Andrén et al., 2011). Meanwhile, the former threshold in the Öresund had risen even higher above sea level so the BIL level started to dam up until it was 25 m above ocean level.

The deep basins of the freshwater BIL were characterized by oxic conditions and low organic productivity (Andrén et al., 2002). During this period, glacial varved and non-varved clays were deposited. As the climate started to get warmer at the end of the Younger Dryas, the retreat of the ice margin accelerated. This led to a rapid drainage of the BIL at Mt. Billingen at around 11 550 cal yr BP (Björck & Digerfeldt, 1984; Strömberg, 1992; Andrén et al., 2002). The water level in the BIL dropped 25 m in Sweden (Svensson, 1991; Björck, 1995, Jakobsson et al. 2007) and 27–28 m in Finland (Donner, 1951, 1978) within only 1–2 years, and 7 000–8 000 km^3 of water were released into the ocean (Jakobsson et al., 2007). This outburst of water created large drainage sediment fans west of Mt. Billingen (e.g. Strömberg, 1992; Johnson et al., 2010). On the Swedish west coast the outburst sediments have been detected in marine cores (e.g. Cato et al., 1982; Bergsten, 1994; Bodén et al., 1997). The rapidly melting ice sheet in south-central Sweden and the isostatically depressed areas in south central Sweden later allowed the incursion of marine waters towards the east.

Shorelines formed during the BIL in southern Finland are named as BI, BII and BIII. BI is the oldest, BII occurs 5 m below BI, while BIII, the youngest shoreline recognized in the Salpausselkä zone occurs ca 5 m below BII. BIII is interpreted to represent the conditions just prior the BIL/Y drainage. In the older literature, a certain "g-level" predating the BI level is mentioned (e.g. Donner, 1978; Glückert 1995). This g-level consisted of glaciofluvial plateaus situated at 25 m lower altitudes than BI. The interpretation was that a gradual transgression had prevailed during the early BIL phase. The concept of g-level was generally abandoned after Fyfe (1990) proved that these sediment formations were deposited subaqueously and therefore do not indicate actual water level. Due to different land uplift rates and ice retreat patterns, the BI and BIII shorelines formed in the 1st and 2nd Salpausselkä zone are currently between ca 160 m and 100 m asl (Donner, 1978; Eronen & Haila, 1990). The highest shorelines are found in the Lahti region and their altitude decreases towards the east. In Estonia, five BIL levels are thought to have been formed between 13 300 and 11 500 cal yr BP (Vassiliev et al. 2011). They indicate a gradual regression between 13 300 and 12 700 cal yr BP (levels A1 and A2), small changes in water depth but considerable rearrangements of proglacial lake drainage systems around 12 200 cal yr BP (level BI) and water level regression until 11 500 cal yr BP (levels BII and BIII) (Vassiljev et al., 2011). In Sweden, the highest BIL shorelines prior to the drainage are currently between ca 160 m and 10 m asl (Svensson, 1989), the highest altitudes are found in the Stockholm region and decrease towards the south.

2.4.2. The Yoldia Sea (11 550–10 700 cal yrs BP)

The Yoldia Sea phase of the BSB was established after the drainage of the BIL to the contemporary sea level. The Yoldia Sea phase can be divided into three sub-phases (Svensson, 1989).The first and third sub-phases characterized by a very low salinity were interrupted by a sub-phase characterized by brackish conditions which lasted 200-300 years (Wastegård et al., 1995; Andrén et al., 2002). Saline water reached as far as the southern Baltic (Björck et al., 1990; Andrén et al., 2000a; Andrén et al., 2007) and Finland (Heinsalu, 2001; Strömberg, 2005; Heinsalu & Veski, 2007). The highest salinity values existed in low-lying areas between Lake Vänern and Stockholm in central Sweden (Schoning, 2001). The dominant sedimentary deposits from the Yoldia Sea phase consist of organic-poor (silty) clays, often varved in and north of the Gotland Basin (Andrén et al., 2002). Rapid land uplift in south-central Sweden led to the shallowing of the connecting sounds and the Yoldia Sea phase came to an end. During the retreat of the ice sheet in the Baltic Basin, varved clays were deposited in front of the receding ice margin, while non-varved clays were formed in more distal positions (Ignatius, 1958). In southern Finland, the oldest YI shoreline between ca 120 and 145 m asl marks the highest water level of the Yoldia Sea (Donner, 1978; Eronen & Haila, 1990).

2.4.3. The Ancylus Lake (10 700–ca 9 800 cal yr BP)

Glacioisostatic land uplift was rapid in south central Sweden and the gradual shallowing of outlets forced the outflow to the straits in the Vänern area. This eventually led to the Ancylus Lake phase of the BSB. Transgression occurred in the area south of the outlets (Björck, 1995) in the Vänern area while regression took place in the area north of the outlets. Homogeneous or laminated, grey clayey sediment, poor in organic material, was deposited during this freshwater phase. Laminated fine sand and clay-rich rhythmites together with dropstone structures were deposited in a proximal glaciolacustrine setting next to the ice margin.

2.4.4. The Litorina Sea (ca 9 800 cal yr BP –present)

The early Litorina Sea was practically nonsaline, until around 8 500 cal yr BPa strong and rapid spread of saline influence occurred throughout the BSB. This is seen in the sediment record as a change in sediment type and as an increasing amount of marine diatoms. As a result, the organic content increased and greenish grey gyttja and gyttja clay started to deposit. The highest salinity in the Baltic Sea was reached 6 000 years ago (Andrén et al., 2011). The reason for the decreasing salinity since then can be related to increased precipitation, lower summer temperatures and/or restricted inflow of Atlantic water into the BSB (Björck, 2008).

3. Material and methods

3.1. Acoustic sounding data *(Paper I)*

The acoustic sounding was targeted to collect systematic and up-to-date information on offshore-marine sequences representing the transition from ice proximal varved clays to homogeneous postglacial clays (Ignatius et al., 1981; Åker et al., 1988). Acoustic records from the northern Baltic proper and the Gulf of Finland were collected onboard R/V Aranda during 2006–2007 by the Marine Geology Group of the Geological Survey of Finland (GTK) (Fig. 2). A MD DSS sonar system (Meridata Finland Ltd), operating in the pinger mode at the frequency of 12 KHz was used. Approximately 1 200 km of high-resolution acoustic data were analysed and interpreted as a desktop study, using the Meridata MDPS postprocessing system. the data were examined in detail and soft-sediment structures were classified by their appearance and occurrence of erosion and disturbance structures. This information was combined with the bathymetric data.

To validate the acoustic profile interpretation, a 535-cm-long sediment core MGML-2010-4 (Fig. 2) was retrieved in June 2010 on R/V Aranda using a 90 mm diameter piston-corer. The core was cut into sections onboard, and kept refrigerated before sediment description, subsampling and analysis. The halved and trimmed sediment core was described in the laboratory, and the sediment surface was measured at intervals of 0.5 cm for magnetic susceptibility, using a Bartington MS2E1. Plastic containers were used in subsampling for microtomography X-ray images of the core. The X-ray samples were scanned with a μCT scanner nanotom® in the Department of Physics, University of Helsinki.

3.2. Sedimentology *(Paper II)*

Two open-face clay exposures in southern Finland, south of the 1st Salpausselkä end moraine (Fig. 2), were chosen for sedimentological analyses to study lithological indications of the drainage event in the selected sections. The site in Jokela had been previously examined by Sauramo (1918, 1923), Niemelä (1971) and Donner (1995) and was therefore known to represent the BIL/Yoldia Sea transition in an accessible section. Furthermore, it provided a possibility to compare varve thickness measurements with the older data. The section in Koria presented in this study was chosen after preliminary field studies on lithological characteristics of the varves. The sections were logged in the summers of 2009 and 2010 by describing sediment properties like grain size, structures, contacts between laminae, beds and units, and finally dividing the series into lithostratigraphical units. Colour was defined in the field on natural moist sediment using Munsell ColorTM soil charts. In the Koria section, a foil corer (Strömberg, 1989) was used to extend the profile downwards from the base of the pit. The varve record was measured in the field by marking the varve limits on a paper tape directly from the cleaned outcrop or core surface. Rhythmites were measured as distances from the top of one clay lamina to the top of the next lamina above to an accuracy of 1 mm. This was repeated using digital photographs (Jokela) and an additional sediment profile (Koria).

3.3. Application of dendrochronological cross correlation methods in a clay varve study *(Paper III)*

To construct a varve chronology, several varve thickness measurements from separate locations are correlated. Correlation is based on visual comparison of variations in thickness, like in dendrochronological studies. In addition to that, statistical methods used routinely in dendrochronology to remove noise - non-climatic signal or local variations - from the dataset were applied. This approach was tested on an existing clay-varve dataset. The varve measurements by Sauramo (1918) were digitized by measuring the varve thicknesses published and transferring the results in a database. The digitized series were all located south of the 1st Salpausselkä (Fig. 2), and the material consists of 47 individual varve series with lengths between 16 and 291 increments, covering a total time period of 867 varve years.

The data series of individual varve diagrams were processed by detrending, pre-whitening and averaging methods adopted from tree-ring studies. The original varve dates (Sauramo, 1918, 1923) were re-examined using the treated, dimensionless series. First, each series was correlated with all other series in their suggested temporal positions; additionally, each sample was lagged forward and backward in time to determine whether offsetting the time-series would yield higher visual and statistical correlation. In the case of higher correlation in a new position, the number of years lagged was taken as an indication of the number of offsetting varve years. As an additional step, the varve series were divided into overlapping segments before the lag analysis. Identification of the segment in which a correlation substantially drops was used to locate the year of a dating error. Subsequently, the t-value was calculated between the individual series and the average of all other series.

3.4. OSL datings *(Paper IV)*

Optically stimulated luminescence (OSL) is a dating method which under favorable conditions can give an absolute age of the deposition and burial of mineral grains. OSL years correspond directly to calendar years. In this respect, the OSL dating method and OSL ages differ from ^{14}C ages, which give an age of organic material in sediment and need to be calibrated for a corresponding age in calendar years. However, to obtain correct OSL ages, the grains must have been exposed to sunlight long enough before deposition (i.e. to bleach well). Examples of sediments potentially datable in glacial environments are shallow water glacial-lake beach sediments (e.g. Mangerud et al., 2001; Murray & Olley, 2002; Fuchs & Owen, 2008) or subaerially transported aeolian sediments (e.g. Koster, 2005; Roberts, 2008). To calculate the age in optical dating the dose rate, i.e. the background radiation per unit of time, needs to be calculated. This factor is caused by natural radioactive elements in the soil and by cosmic radiation. The other factor needed in the optical dating age equation is the equivalent dose, i.e. the estimate of the amount of radiation a grain has been exposed to since it was last bleached.

The BIL drainage created and deposited a series of well-defined sediment units containing sand. Four sites, Santala, Lammi, Ihalainen and Renkomäki (Fig. 2), were selected for studying sediments and sampling for OSL-age determinations. The chosen deposits had been interpreted to be connected either with the BIL drainage, like in Ihalainen (Rainio, 1993), or to have been deposited soon after it, as in Santala, Lammi (Gibbard, 1977; Rainio, 1997), Ihalainen (Rainio, 1993) and Renkomäki (Okko, 1962). The selected sites form a transect through the basin: from 30-m deep water (Santala) to ca 10-m deep water (Ihalainen), and further to littoral (Renkomäki and Ihalainen) and aeolian (Lammi) sedimentary environments.

On the study sites, sedimentological observations included grain-size, fabric, structure and colour of the sediment. After description, OSL-samples were collected from freshly cleaned vertical sediment surfaces in clay- and sand pits. Opaque copper tubes, 28 mm in diameter and 30 cm in length, were hammered into the selected bed, sealed and stored in the dark. Site coordinates and altitudes were measured with a GPS, and the altitudes were checked against topographic maps (1:20 000). The gamma dose rate was measured in sample locations using a portable spectrometer. Quartz grains from the samples were analysed at the Laboratory of Chronology of the Finnish Museum of Natural History, University of Helsinki using the SAR protocol.

4. Results

4.1. Acoustic sounding data reflecting properties of BIL/Yoldia Sea transition sediments *(Paper I)*

Based on the acoustic data, five acoustic units (I-V) and three deformation horizons (i, ii and iii) were defined. The examination of the gravity core lithologies confirmed the interpretations of acoustic units II and III. Acoustic unit I was substratum, acoustic unit II represented ice-proximal BIL varves, and acoustic unit III recorded the transition into and the actual Yoldia Sea phase. Unit IV represented the lacustrine sulphidic clay-gyttja of the Ancylus Lake (Ignatius, 1958) and unit V organic-rich Litorina Sea and/or the modern Baltic Sea sediments (Ignatius, 1958).

The oldest deformation horizon (i) was identified in the lower part of acoustic unit II and indicated horizontal sliding and compacting of sediment, possibly relating to early diagenesis and consolidation of the sediment (Virtasalo et al., 2007) or readvances and stillstands of ice sheet (St-Onge et al., 2008). Faulting, rip-up mud clasts and complete or partial mixing of the strata (deformation horizon ii) in the upper part of acoustic unit II and the lower part of acoustic unit III were seen in the studied core. This was interpreted as a high-energy flow event, corresponding with the BIL drainage event and gravity flow deposits triggered by the base-level fall. The deformations were stratigraphically related to BIL and Yoldia Sea clays, occurring throughout the study area. The process generating debrites was destructive, controlled mostly by sea-floor topography and redeposited older sediment. The distance to the glacier margin has not controlled the type i and type ii deformations. Deformations in unit III (iii) closely resemble the gravity-flow deposits described in the Archipelago Sea and the Bothnian Sea as described by Kotilainen & Hutri (2004) and Virtasalo et al. (2007), or in proglacial sedimentary basins elsewhere (e.g. St-Onge et al., 2004). These deformations were possibly triggered by neotectonics, but this cannot be associated with a single event throughout the basin.

4.2. Sedimentological properties of BIL/Yoldia Sea transition sediments *(Paper II)*

Two sections studied for sedimentological purposes represented a continuous varve record, with a total of 447 (Koria) and 450 (Jokela) rhythmic laminae deposited in the water depth of ca 40–70 m. The studied series record a distal glaciolacustrine environment during the Younger Dryas cold event when the ice margin was about 20–30 km away. Measured varve thickness varied between 1 and 69 mm. Two pronounced clay colour changes were observed in sections. The first change was sharp, from reddish clay laminae to grey clay laminae, while red-hued clay being a typical feature for rhythmites associated with the BIL in Finland and Sweden. The red colour is caused by redox-variations (e.g. Johnson & Ståhl 2010). Another pronounced colour change in the varve series is the sharp transition from thin, grey varves to thick, clay-rich brown varves, marking the arrival of saline water and the beginning of the saline Yoldia Sea phase, as already interpreted by Sauramo (1918). The current strata could therefore be correlated with sediment facies previously described in Finland (Sauramo 1918, 1923; Niemelä 1971; Rainio 1993; Strömberg 2005) and Sweden (e.g. Strömberg, 1992; Brunnberg, 1995; Andrén et al., 2002).

The lithology in the both sequences studied was divided into 6 units starting from the lowermost unit 1. Units 1, 3, 5 and 6 were laminated, 2 and 4 were deformation beds. Starting from the lowermost unit 1 and continuing in unit 3, the reddish-clay clastic varve series in Jokela (315 varves) and Koria (275 varves) reflect stable annual sedimentation in a distal BIL glaciolacustrine environment. Sedimentation resulted mainly from suspension, interrupted by meltwater-derived pulses of coarser material (Brunnberg, 1995; Ringberg & Erlström, 1999). Two deformation horizons, units 2 and 4, interrupt the varved sediment series. Both can be associated with a water level fall, or the older one (unit 2) could be a local slumping event. This unit was deposited ca 120 varve years before the assumed BIL drainage. It is worth noting that neither Sauramo (1918, 1923) nor Niemelä (1971) do report such a unit/bed. It is possible that before the BIL drainage, the water level was gradually lowering as a result of isostatic change, rather than dropping in steps. This, too, points more towards unit 2 originating from local slumping.

The younger deformation unit (unit 4) showed many signs of reworking and deformation. A very similar unit could be found in all Niemelä´s (1971) cores south of the 1st Salpausselkä, in eastern Finland (Rainio, 1993) and in-Lammi, between the 1st and the 2nd Salpausselkäs (Gibbard, 1977). Therefore, unit 4 was interpreted as the BIL drainage bed, i.e. as the original "zero varve" described by Sauramo (1918). The water-level drop reactivated sediments deposited previously, which generated mud flows (Vesajoki, 1982; Johnson et al., 1999).

Before the arrival of saline water to the study area, a transitional varve series (unit 5 containing 120 varves in Koria and 190 in Jokela) was deposited in the study area. Previous studies have suggested a transition interval of 240-400 years in Finland. The facies change from thin grey winter layers to thick brown winter layers in the uppermost unit 6 has been described from many places in southwest Finland and associated with the arrival of brackish water (Sauramo, 1918, 1923; Niemelä, 1971; Strömberg, 1990, 2005). It is likely that the saline water incursion was a diachronous event controlled by bottom topography, currents and the widening of the outlet in Sweden (Heinsalu, 2001; Andrén et al., 2002). This renders the event unsuitable for precise varve-chronological correlation or dating.

4.3. Applying the dendrochronological cross-correlation methods in varve clay series *(Paper III)*

The applicability of statistical methods used in dendrochronological studies was tested to varve records using Sauramo´s (1918) varve measurements from southern Finland. The data series of individual varve-thickness diagrams were detrended, prewhitened and averaged. It was assumed, that the effects of changing deposition mode, the retreating glacier margin, the circulation processes in the pro-glacial basin and the local depositional variations would thus be removed from the data. The methods used in the study indicated that Sauramo´s connections between varve series were valid. In addition to this, it was seen that the series having 80 or more varves have a higher potential to be unambiguously cross-dated than shorter series. It was possible to separate two types of varve-thickness diagrams: those having regional chronological importance due to good correlativity over a distance of more than 20 km distance and those showing sub-regional correlativity over a distance less than 20 km. The former type can be regarded as suitable material for constructing geochronology. The latter type has a low geochronological validity but a more local sedimentological importance. Dendrochronological methods provided information needed for realistic correlations to be made between two or more varve records and these methods can be considered potentially useful in constructing varve series.

4.4. Chronological aspects of the BIL/Yoldia Sea transition: testing the OSL-method to drainage sediments *(Paper IV)*

The Renkomäki shore terrace was the only material out of 4 sequences studied in southern Finland that gave an expected age (11 400 and 11 200 ±2 700 yr BP), being thus the first direct age determination for the oldest Yoldia Sea shoreline in Finland. The other samples were interpreted as only partially bleached or as representing a mixture of sediments from different age generations. The mixture of different age generations may result in a well-defined dose distribution but yielding too old an age, indicating recycling of older material. In case of Santala, this explains the clear maximum in dose measurements but > 16 000 yr BP age. The Lammi samples could have been deposited very quickly during a duststorm type of aeolian activity. During transportation, a thick cloud of suspended particles would have shielded sunlight very efficiently and inhibited proper bleaching of the grains. It is also possible, that final deposition took place in shallow water, which was very rich in suspended sediment material. This further prevented grains from bleaching. For Ihalainen area, the evidence of sedimentary environment was inconclusive, but the deposits were clearly of Mid-Holocene or younger age, indicating prevailing erosion after the BIL drainage.

It is extremely important to understand the genesis of the sandy units sampled in order to obtain potentially optimal samples cannot be overestimated. The results of this study indicate that traditional morphology- and altitude-based classifications of shoreline features or land uplift history studies could benefit from OSL-dating. The results also suggest that most of the BIL drainage-related sediments are/were unsuitable for OSL-dating. However, the single–grain method could improve the results, as many of the samples which yielded too old an age consisted of grains from several age populations.

5. Discussion

5.1. Sediment characteristics indicating the BIL/ Yoldia Sea transition

Sediments deposited in southern Finland and northern Baltic during the BIL and early Yoldia Sea phases contain little of microfossils (e.g. Åker et al, 1988; Andrén et al., 2002; Subetto et al., 2002; Veski et al., 2005). The cold and turbid water column was dark due to suspended sediment, allowing only reduced light penetration, and in consequence, the TOC values remained very low. Therefore, the use of pollen, foraminiferal or diatom assemblages is not reliable for defining the BIL/Yoldia Sea transition in the sediment record. In the study area, the climatic conditions before 11 650 yr BP were cold and dry with open vegetation ("steppe tundra") (Heikkilä & Seppä, 2003; Wohlfarth et al., 2007; Spiridonov et al. 2007; Amon et al., 2011). The proximity of the ice margin and large, cold water mass would have influenced atmospheric circulation regionally (Wohlfarth et al., 2007). East of the study area, BIL extended into the Lake Ladoga Basin (Björck, 1995; Saarnisto & Saarinen, 2001). South of the study area, on the Blekinge coast, southeastern Sweden, scarce aquatic micro- and macrofossils and very low carbon content indicate oligotrophic conditions and mosaic regional vegetation in the basin during the BIL/Yoldia Sea transition (Yu et al., 2005).

Sauramo (1923) described four different horizons from the Jokela (Jokela and Kolsa brickyards) section in southern Finland. The lowermost horizon aSs ("ante-Salpausselkä") was composed of relatively thick varves, up to 10 cm. Upwards in this series, the varves got thinner and the material finer. In the description given in *Paper II* this horizon corresponds to unit 1 in the Jokela and Koria sections: parallel laminated and ripple laminated fines with slickensides and dropstones. Sauramo´s (1923) second horizon ISs ("1st Salpausselkä"), was 1.25 m thick and the varve thickness was 1.5-0.3 cm. The sediment consisted of silt and reddish clay, and the varves were difficult to distinguish in their natural state of humidity. This was also confirmed by Niemelä (1971). This horizon ISs included an exceptionally thick varve containing sand and gravel (Sauramo, 1923; Niemelä, 1971; Donner, 1995). In the current study this horizon corresponds to units 3 and 4 in Jokela and Koria: parallel laminated and ripple laminated fines and massive clay with deformed sand layers (*Paper II*). Sauramo's third horizon, iSs ("inter-Salpausselkä"), was 1.25 m thick and the varve thickness varied between 1.5 and 0.4 cm. The varve boundaries were sharp and no mention was made of the red hue of clay. Niemelä (1971) agreed with Sauramo´s observations. This horizon is consistent with unit 5 in Jokela and Koria: ripple laminated and parallel laminated fines with occasional normal grading, and a more grey clay hue (*Paper II*). Sauramo's (1923) uppermost horizon, IISs ("2nd Salpausselkä") consisted of thick and dark varves with thin silt parts. The thickness of the unit was not given. The properties described by Sauramo are also seen in unit 6 in Jokela and Koria (*Paper II*). Niemelä (1971) mentioned thick varves and a darker hue of the sediment, but according to him the upper part of his unit (thickness ca 3.30 m) was not varved.

Based on sedimentological observations in this work and previous studies, three main features indicate a change in the sedimentary environment during the BIL/Y transition. These features are the drainage unit itself, the deposition of thick varves following the drainage, and the colour change from reddish to non-reddish clay, observed in the sediment record close to the drainage horizon. Sauramo (1923) connected the exceptionally thick varve with the drainage of the BIL, and the thick, dark grey-brown varves of the uppermost unit with the arrival of saline water to the study area. This study confirms these interpretations and widens the spatial coverage of the evidence by introducing a new locality in Koria and by connecting offshore drainage facies to onshore sites.

5.1.1. Drainage unit

Niemelä (1971) detected the drainage unit in all his sediment cores and sections south of the 1st Salpausselkä. The sediment in the drainage unit observed in his core records had slight variations in structure and grain size. As presented in *Paper I,* it was also possible to identify the drainage unit in the sediments of the offshore Baltic Sea basins. According to Nilsson (1968), the BIL drainage varve he observed in Sweden was very similar to the drainage unit described in the current study. Therefore, it seems appropriate to state that the drainage unit is widespread and exists in a variety of sedimentary records, but its physical properties depend on the local sedimentary environment.

In deep water (offshore zone), the drainage unit is discontinuous. Where present, it may be up to a few meters thick and deposited by debris flows, which eroded and deformed older laminated fine sediments (*Paper I*). The drainage unit is sharply overlaid by undeformed crudely laminated sediment. In shallow water (shoreface zone), the drainage unit is laterally relatively continuous, with rather consistent physical properties even over a distance of 100 km. It is a homogeneous clay unit with deformed sand and gravel layers some tens of centimetres thick (*Paper II*). The lower contact of the drainage unit is, at least in Koria, erosional, and the upper contact is sharp. The sediment sections in Ihalainen and Santala (*Paper IV*) represent the transition from shallow water to the shore environment and it seems that the water level drop caused post-depositional convoluted bedding just below the drainage unit. In Ihalainen and Santala, ripple and parallel laminated sand and silt were deposited after the drainage. The seasonal rhythmic cyclicity controlled no more sediment deposition, but sediment transportation and sedimentation were subject to local wave and current processes within the shallow water shore environment (*Paper IV*).

5.1.2. Varve thickness and colour

In a sequence of rhythmically laminated sediments, it is important to be able to verify the annual vs. non-annual origin of couplets. Turbidity currents can deposit rhythmites in a timescale of minutes to hours. To distinguish between varves and turbidites in glacial lakes, Smith & Ashley (1985) suggested the following criteria: a gradational transition within a couplet, variation in both silt and clay layer thickness and normal grading throughout the whole couplet are typical of turbidites. Varves exhibit a sharp contact between the layers within a couplet, clay layers whose thickness remains rather constant, more variation in silt layer thickness and, relatively often, graded clay layers but not graded silt layers. Turbidites can be triggered, e.g., by slumping of sediment or river floods. Therefore, turbidites are products of one sedimentation event and grading is associated with waning flow. In varve formation there are two separate mechanisms, suspension settling in winter and deposition from over- and interflows, underflows or surge currents in summer.

Summer deposition from inter- and overflows is often seen as a sharp contact between couplets, but the situation is more complicated in the case of underflows. Underflows can be regarded as density-driven turbidity currents, and their dispersal pattern is controlled by topography. Therefore, a summer layer deposited by an underflow may have a more diffuse or graded contact to the overlying winter layer, and thickness variations in the summer layer reflect both sediment dispersal patterns and short-term variation in sedimentation. The Coriolis effect and wind-driven currents also distribute sediment to the lake bottom, for example katabatic winds in the vicinity of glaciers drive surface water away from the ice margin. A compensational countercurrent due to underflow and surface current driven in the opposite direction by katabatic wind has been reported from glacier-fed lakes. This was seen as enhancing turbulence in the bottom zone near subaqueous sill (Chikita et al., 1996).

The laminations in the Jokela and Koria sediments, as described in *Paper II*, can be regarded as varves. Sedimentation during the BIL has been relatively regular both in winter and in summer, and slump-generated turbidity currents have been rare. The BIL/Yoldia Sea transition unit is clearly of a non-varved origin, and thus should not be considered one thick varve in varve thickness measurements. During the early Yoldia Sea phase, varves were again deposited in an environment possibly promoting stronger underflows, seen as more frequent occurrence of rippled lamination. In the beginning of the saline Yoldia Sea phase, the clay laminae of the couplets are considerably thicker than prior to that phase but still exhibit a consistent change and the couplets have sharp inner contacts. Therefore they can be regarded as varves. In general, varve thickness measurements from Jokela and Koria show a typical upwards-thinning pattern of glaciolacustrine varves, if the uppermost thicker varves deposited in saline water are excluded. This pattern is commonly associated with the increasing distance to the ice-margin (*Paper III*).

The varved BIL sediments have a reddish hue indicating oxidation of iron compounds (Sauramo, 1923; Strömberg, 2005; Johnson & Ståhl, 2010). The colour change from reddish to greyish which was described above, is not related to bedrock composition, but redox-conditions in the sediment. The oxygen-rich meltwater can keep the sediment which contains little of organic matter oxidized if there is a steady support of suspended matter The greyish transition varves bear indications of reduced conditions, for which one good explanation is the arrival of brackish water and the formation of a permanent halocline, resulting in anoxia at the bottom (Andrén et al. 2002). An increase in sedimentation rate and organic carbon content can also create a reductive environment. A similar change from red to grey or brown clay in varved sediments has been reported from e.g. Lake Agassiz (Anderson, 2011) and Lake Superior (Breckenridge, 2007). In the latter case, at least, the change is related to the bedrock source of material, rather than to redox-conditions.

5.2. Time of arrival and duration of saline water conditions in the study area during the Yoldia Sea

The study of various varve sequences from southern Sweden, southern Finland and the northern Baltic proper has made it obvious that brackish influence was neither synchronous nor instantaneous (e.g. Sauramo, 1923; Andrén & Sohlenius, 1995; Brunnberg, 1995; Heinsalu, 2001; Strömberg, 2005), but it started to influence sedimentation in different parts of the basin at different times.

The following pattern for saline water to the Yoldia Sea basin was proposed by Andrén & Sohlenius (1995). As the denser saline water flowed into the northwestern Baltic proper, it followed the bottom topography and occupied first the deepest parts of the BSB. Fresh meltwater emerging from the ice front was cool and sediment-laden, so it also moved as a bottom current. When these two flows met, saline inflow was forced to take a southward direction along the east coast of Sweden. Andrén & Sohlenius (1995) also suggested, that within the Yoldia Sea, there was a similar 15-year periodicity for the intrusion of saline water as there is in the present Baltic (Stigebrandt, 1987), estimating that each saline pulse could have reached ca 3 km further north if the ice recession rate in the area was approximately 200 m/year. More marine conditions seem to have prevailed in the Bornholm Basin than in the Gotland Basin (Andrén et al., 2000b).

The time from the final drainage of the BIL to the first marine incursion in Sweden is between ca 200 (Nilsson, 1968) and ca 300 varve years (Brunnberg, 1995), which is somewhat more than the results summarized in *Paper II* indicate. However, it is still unclear, for how long time the varve deposition was interrupted in shallower parts of the basin, like in Jokela and Koria (*Paper II*). The duration of the Yoldia Sea saline phase has been defined as having been ca 200 clay varve years (Strömberg, 1989), 150 years (diatoms; Heinsalu, 2001), 120 clay-varve years (mineral magnetic measurements; Andrén and Sohlenius, 1995) or 60 clay-varve years (fossil content; Andrén and Sohlenius, 1995). According to Raukas (1994), the study area is close to the furthermost eastern salinity limit of the Yoldia Sea. The sections studied do cover only the beginning of the saline sub-phase and therefore do not yield a new age estimation. If the variation in the duration of the saline phase is more than one hundred years, it is not unrealistic to assume that the results concerning the arrival of saline water presented in this study are reliable.

5.3. Paleoseismicity as a possible explanation for the drainage varve

One possible explanation for the clay-rich, homogeneous deposit with sandy interlayers (unit 4 or deformation type ii, as described in Jokela and Koria sections, *Paper II*, and the marine core, *Paper I*) could be a seismically triggered gravity flow. Small-scale sliding and slumping in clay rich sediments is a regular phenomenon. Kohv et al. (2009) were able to differentiate three groups of modern landslides in Estonia. The largest slides were retrogressive slide complexes developed in the glaciolacustrine clay. The second group included slides in marine sand and silt, triggered by additional shear stress generated by groundwater flow in the slope, a situation somewhat comparable to the basel-level fall in a basin. The third group consisted of small landslides at the river bank, that were actually the first stage in developing retrogressive landslide complexes, triggered by fluvial activity decreasing the stability of slopes in the varved clay. The critical slope angle to place fine grained sediment in the state of instability is rather small. In the Estonian glaciolacustrine clay it was estimated at ≥10° and in fine-grained marine sands at 20° (Kohv et al. 2009). This seems to support the idea of a linkage between the drainage debrite and topographical lows, as postulated in *Paper I*.

Several studies of lake deposits have documented sediment units which had been initiated by seismic activity, base-level changes or flooding. Oselger et al. (2009) found that the high-volume runoff of rivers was a trigger for most of the cm-scale turbidites in Lake Tahoe. Another depositing mechanism was found to be a seismic collapse of lake margins which initiated debris flows which in turn triggered distal turbidites. Osleger et al. (2009) suggested that for the latter, sediment material potentially derives from lake walls and bottom sediments, thus indicating mixing of older sediments. They also suggested that seismically induced turbidites do not necessarily cross tectonic structures in the lake basin. Guyard et al. (2011) described a Mass Wasting Deposit (MWD), consisting of folded and reworked glacigenic material from the Pingualuit crater lake. The MWD was suggested to originate either from slope instability induced by rapid drainage or a paleoseismic event . From the crater lake El´gygytgyn, several Late Quaternary mass movements were reported (Juschus et al., 2009). Mass-flow induced debrites showed lateral heterogeneity, signs of erosion and the occurrence of displaced but intact sediment fragments. Here also, either lake-level fluctuations or earthquakes were suggested as the initiators of debris flows.

Two types of rapidly deposited layers (RDL) whose thickness varied in the cm-to-m scale, were described from a fjord overdeepened by glacial erosion (St-Onge et al., 2004). The first type had fining-upward beds with a sandy base. These were interpreted as Bouma-type turbidites, which were originated from earthquake-triggered terrestrial and/or submarine slides which had transformed into a debris flow and then to a turbidity current (e.g., Piper et al., 1999). The second type had a fining-upward and then a coarsening-upward unit followed by a fining-upward unit. This group was interpreted as the result of initial earthquake shaking, followed by a hyperpycnal turbidity current generated by the flood (Mulder et al., 2002).

Palaeoseismicity has been suggested as the causing mechanism of the 4–6 m thick turbidite-like layer found in the same stratigraphical position in the Gulf of Bothnia, Archipelago Sea and in the northern Baltic proper (Virtasalo et al., 2006; Hutri et al., 2007). In the Bothnian Sea there were no observations of a similar type of layer (Hutri et al., 2007). All the observations that could be stratigraphically correlated were formed between the glacial distal varves and the “lower Ancylus Lake” sediments. They were found to become younger towards the northern parts of the study area and the thickness of the layer was also increasing towards the contemporary ice margin. It was proposed by Virtasalo et al. (2006, 2007), that the normal faulting, slumping and debris-flow deposition are time-transgressive within the direction of the ice-margin retreat and are related to the post-glacial seismic activity, resulting from the time-transgressive reactivation of old bedrock fracture zones. Possible contributors are also ice-berg scouring and/or gravitational failure of oversteepened depositional slopes.

Based on sedimentological properties, such as the absence of typical turbidite sediment structures, lack of an upward-fining character and the erosion and redeposition of older sediment, the drainage unit (deformation horizon ii and unit 4) described in *Paper I* and *Paper II* is not a turbidite, but a mass-flow induced debrite. Currently there are no unambiguous sedimentological criteria to distinguish seismically triggered debrites from debrites triggered by a base-level fall. In *Paper I*, the drainage unit was associated with basin topography and found in a fixed stratigraphic context from various sedimentological settings. This strongly favours the base-level fall hypothesis.

5.4. The possible reasons for problems in connecting Sauramo´s varve series to the absolute chronology

When different variables affecting sedimentation in the glaciolacustrine environment are considered, the list includes at least the proximity to ice, the number and direction of sediment sources, the position of melt-water inflow into the lake water column, lake stratification, the relative densities of lake water and melt water, ice rafting, the extent of ice cover, and slope stability (Ashley, 1975, 1989; Smith & Ashley, 1985).

Some factors controlling the varve thickness variations are more directly linked to climate, such as temperature (e.g., Desloges, 1994; Leonard, 1985) and precipitation (e.g., Leemann & Niessen 1994; Lotter & Birks 1997). Some factors are more likely to be related to intrabasinal processes. As stated by Ringberg (1991), Strömberg (1994) and Brunnberg (1995), based on studies in Sweden, varves are difficult to correlate when the retreat of ice margin was slow, it was stagnant or there were oscillations and readvances. This is best explained by irregular melt-water discharge, including e.g. more overland stream discharge. Varves which were deposited after the retreat rates increased at the beginning of the Holocene were easier and more reliable to correlate. A similar problem is found in Finnish varve chronology (Strömberg, 1990). This reflects a change from more transitory melt-water streams to stable drainage patterns, seen, e.g., as long eskers chains and large glaciofluvial deposits (Brunnberg, 1995).

The amount of sediment material present in the lake also contributes to regional thickness variations Young et al. (2000) suggested that autocorrelation in clay varve series originates from "a slow response time", meaning that if in one year a considerable amount of sediment material is present in the lake, part of that material is going to be deposited during the following winter. If only a small amount of winter material is present, its contribution to the next year’s winter layer will be minor. This could be the situation during colder climatic conditions, when there would be less melt water and the ice cover in the lake would probably be more extensive and last longer. An example of variation in melt season inflow peaks was described in the Mirror Lake sedimentary record as the frequent occurrence of two-silt-unit varves (Smith, 1978; Tomkins & Lamoureux, 2005). This suggested that past sedimentation has been characterized by distinct snow and glacial melt phases, thus potentially controlling varve thickness and structure variations. Based on the results from *Paper III*, local variations could be removed from varve thickness diagrams, thereby increasing the correlativity to regional (> 20 km distance) scale. As the tested part of chronology includes also varves which were deposited during Younger Dryas, the application of the technique might provide a tool to cross problematic periods of slow ice retreat and stillstand of the ice margin.

In many glacial subenvironments, sediment grains do not necessary bleach completely. Incomplete bleaching results in too old OSL ages, as experienced in *Paper IV* and in several studies from glacigenic sediments (e.g. Gemmell, 1999; Richards, 2000; Lukas et al., 2007, Raukas et al. 2010). Other possible sources of error are bioturbation (animal activity and roots), redeposition of sediment, changes in sediment water content and different properties of mineral grains (Murray et al., 2002; Murray & Funder, 2003, Duller, 2004). There was no evidence that these other factors would have significantly affected the age determination of the BIL/Yoldia Sea transition sediments. The fact that only a small proportion of the grains in an aliquot emit a signal, means that different stages of bleaching can contaminate the age signal (Duller et al., 2000; Alexanderson et al., 2008). One method to control the occurrence of grains of incomplete bleaching is the statistical analysis of the small-aliquot or single-grain data (Wallinga, 2002; Duller, 2006). Further OSL investigations of the BIL/Yoldia Sea transition deposits using single grain measurements might give better defined results also for studies on sites described in *Paper IV*. Sofar, the BIL/Yoldia Sea shore terraces show most potential for OSL age determination purposes.

Dating of the drainage deposits within the BSB is challenging.The maximum ice extent of the SIS during the Late Weichselian was reached later in the east, and deglaciation was more rapid and occurred earlier in the east (Saarnisto & Lunkka, 2004).This is one source of error when correlating varve records in different parts of the BSB. Also the erosion and redeposition, possible hiatuses in sedimentation and, in general, the very variable nature of sediments deposited during the BIL/Yoldia Sea transition, as depicted in Figure 3, has to be taken into account when correlating and dating the drainage deposits. This study has shown that drainage varves cannot be used as varve-chronological markers. The unknown amount of erosion and the duration of hiatus might explain why the attempts to connect varve diagrams depicting the BIL/Yoldia Sea transition in different places have not succeeded. However, as a basin-wide marker horizon drainage deposits appear to work better.

5.5. Future prospects: trace fossils

One possible means to get more detailed information on the environments and age of the BIL drainage is studying the contemporary faunal assemblages. Although a glacial lake has been a harsh environment for living organisms and microfossils are rare, it most likely was not without life. Trace fossils have been reported from several Pleistocene glacial lake deposits, closest examples being from Finland (Gibbard, 1977), Sweden (Högbom, 1893, 1915; Andersson, 1897) and Lithuania (Uchman et al., 2009). Holocene trace fossils have been studied close to the area studied here, by Virtasalo et al. (2006, 2011) and by Uchman & Kumpulainen (2011).

In older studies, there are reports of chironomid trails from Sweden (Högbom, 1893; Andersson, 1897) and Finland (Andersson, 1897), as

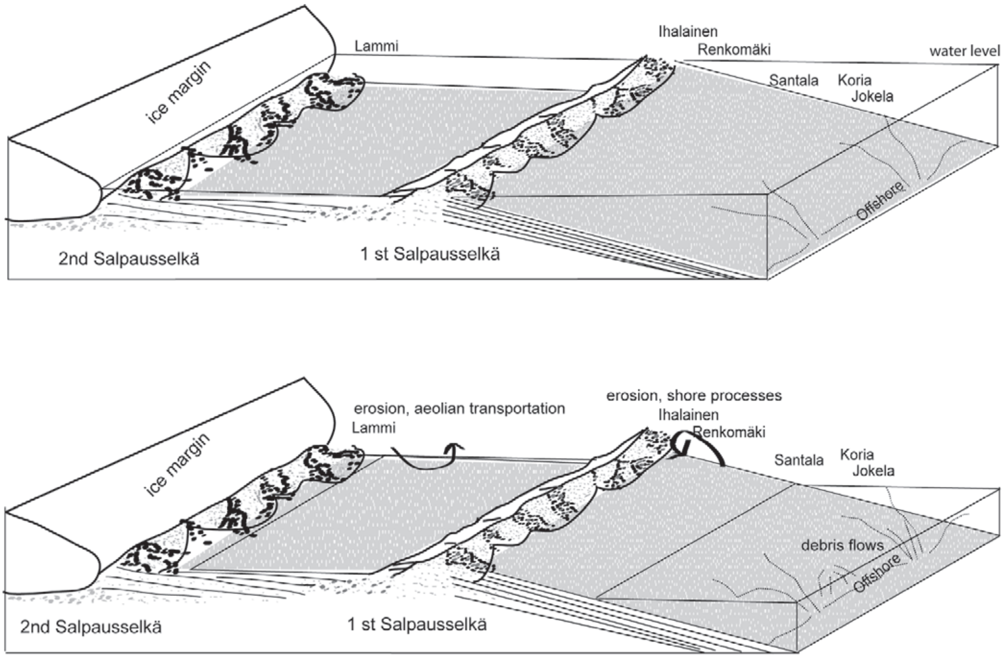

Fig. 3. Sedimentological reconstruction of depositional settings prior to and after the BIL/Y transition Upper picture: study sites depicted before BIL drainage. Lower picture: situation just after the drainage.

well as crustacean, annelid and possible fish traces from Sweden (Högbom, 1915). In addition, insect larval tracks from varved sediments related to the BIL/Yoldia Sea transition from Finland were described by Gibbard (1977). The trace fossil distribution in a Lithuanian Pleistocene proglacial lake indicated that food was distributed patchily and that summers and transitional periods were the most active times of trace making and winters were less active or inactive (Uchman et al., 2009). In studies of Holocene trace fossil assemblages from the Archipelago Sea, Virtasalo et al. (2006) noted a succession in trace fossil assemblage. Glaciolacustrine rhythmites deposited ca 11 300 cal yr BP, characterized by low organic content, were found to be barren of trace fossils. During post-glacial lacustrine conditions, P*alaeophycus* and *Arenicolites* trace assemblages reflected domicile -based activities. Later on increasing salinity, increasing sediment organic content and decreasing sea floor oxygen content were seen as a *Planolite*s-dominated assemblage. Uchman & Kumpulainen (2011) studied Early Holocene proglacial lake sediments from Sweden, which had deposited during the late Yoldia Sea phase or early Ancylus Lake phase, ca 11 000 cal yr BP. They interpreted traces as Mermia ichnofacies, and suggested that the ecosystem was strongly affected by the local sedimentation processes, arthropods and fishes living in the basin, rather than glacially derived melt water and position of the glacier margin.

Uchman et al. (2009) suggested that a relatively uniform trace fossil assemblage, fitting generally to Mermia ichnofacies (Buatois & Mángano, 1995), can be seen in Pleistocene glacial lakes in several regions. It is composed of arthropod trackways, grazing traces and fish traces. The level of oxygenation, availability of food or other factors controlled the change of ichnoassemblage rather than change in the water depth. The ecological development model for two New England glacial lakes by Benner et al. (2009) fits well in this idea. In the Benner et al. (2009) succession, stage I represented a simple benthic system with pioneer invertebrates such as nematodes, oligochaetes, ostracods and chironomids living on the lake bottom. These pioneers could have been transmitted passively by insects and birds, or actively. The initial arrival of fish was seen in stage II. To survive, fish pioneers would have needed an established benthos in the lake. The stage III trace fossils indicated crustacean and a more abundant fish population. Stage IV represented an environment with a shift from a glacial water source to a non-glacial water-source with increasing velocity of undercurrents. This meant less silt and clay in water and made it possible for fishes to breed.

It seems that there is potential to investigate trace fossils in varved sediments in southern Finland in order to gain more specific information on the facies change at the BIL/Yoldia Sea transition. Furthermore, trace fossil assemblages could provide information on small-scale saline pulses, increase -decrease in the amount of suspended sediment and bottom oxia-anoxia.

6. Conclusions

- The BIL drainage triggered topographically controlled debris flows in deep-water areas of the BSB. While drainage deposits occur more sporadically in the Gulf of Finland and northern Baltic proper, the drainage unit can be traced over long (~ 100 km) distances in the area close to the 1st Salpausselkä.
- The offshore drainage-related sediments were deposited in an environment unsuitable for OSL-dating, but they display a well-defined facies change both in relation to water-level fall and the arrival of saline water. The former can be used as a chronostratigraphical horizon, since it was formed by a single, well-dated event.
- Lag in the arrival of brackish water could be interpreted as an undefined time period because of prevailing erosion or non-deposition in the basin after the drainage.
- The early Yoldia Sea phase is characterized in the foreshore and shoreface environment by shallow water formations and well-developed shore terraces. The first YI OSL-date (11 200 and 11 400 ±2700 yrs) was obtained from Renkomäki shore terrace, thus proving the potential of the method and the material for dating the BIL/Yoldia Sea transition.
- Statistical approaches, like the methods routinely used in dendrochronology, combined with sedimentological observations were-proven to offer new possibilities in the construction and revision of varve chronologies.
- The BIL/Yoldia Sea transition represents a change in sedimentary environment which is potentially reflected in contemporary ichnofacies assemblages, thus giving new perspectives in studies of Late Weichselian proglacial environments.

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