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A sub-millennial sediment record of ice-stream retreat and meltwater storage in the Baltic Ice Lake during the Bølling-Allerød interstadial

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Abstract

The rapid retreat of the Baltic Ice Stream and the development of the Baltic Ice Lake is assessed using data from sediment cores retrieved from three sub-basins in the southern Baltic Sea. Hydraulic piston coring by the International Ocean Discovery Program (IODP) recovered for the first time intact glacial lake sequences overlying diamictons and other ice-contact deposits at Sites M0063, M0064 and M0065. Based on the particle size and bulk sediment chemical composition the glacial lake sediments were subdivided into a proximal and a distal varve sequence. The origin of a dark, lithologically distinct horizon between the proximal and distal varves is attributed to a lake drainage event following the opening of a spillway in central Sweden. Available age constraints suggest that the Baltic Ice Lake developed during the Bølling-Allerød interstadial and reached its maximum size at ~13 ka. Ice retreat was forced by surface melt, and amplified by calving in the upstream deepening lake environment. Furthermore, rapid ice retreat and glacio-isostatic processes allowed for the storage of substantial amounts of meltwater in the Baltic Ice Lake during the Allerød warm period. Subsequent lake drainage into the North Atlantic took place through a conduit at higher latitude than previous drainage pathways. The pronounced changes in meltwater storage and routing caused by the rapid retreat of the Baltic Ice Stream may have contributed to abrupt climate change through the effects of changing freshwater supply on Atlantic overturning circulation.

Keywords

Pleistocene; Glaciation; Scandinavia; Baltic; Sedimentology-marine cores; XRF

Highlights

- Deglaciation of the southern Baltic Sea during the Bølling-Allerød from drillcores
- Varve records document retreat of the Baltic Ice Stream on the order of km/yr
- Deglaciation in an overdeepened basin affected freshwater storage and routing

1. INTRODUCTION

An accurate prediction of the response of the current terrestrial ice sheets, such as the Greenland Ice Sheet, to anthropogenic warming relies on our ability to characterize the mechanisms of ice retreat (Carlson and Winsor, 2012). Furthermore, determining the location and timing of meltwater release and storage is critical in assessing the role of ice sheets in other earth system processes (Condron and Winsor, 2012). The Eurasian ice sheets began to retreat rapidly during the Bølling-Allerød interstadial (~14.7–12.7 ka) with the development of large proglacial lakes (Björck, 1995). Ice streams developed during the deglaciation of the Baltic and the Bothnian Sea (Ringberg, 1988; Greenwood et al., 2017). Ages of erosional landforms in central Sweden document the important role of surface melt and subglacial meltwater discharge in driving the rapid deglaciation of Fennoscandia (Jansen et al., 2014). The Baltic intracontinental basin harbors a continuous Late Pleistocene-Holocene archive of ice retreat and melt supply from a mid-latitude ice sheet with similar vulnerabilities to the modern Greenland Ice Sheet. Glacial sediments and varve paleorecords drilled by Integrated Ocean Drilling Program Expedition 347 in the southern Baltic Sea basin are used here to explore the mechanisms of fast ice retreat and meltwater processes on annual to centennial time scales. With the new data we also document the long-term periodicities and effects of melt supply, such as meltwater storage in ice-contact reservoirs and diminished outflow to the ocean.

1.1 Objectives

Recent findings implicate complex interactions between ocean heat storage, atmospheric warming and freshwater discharge from ice sheet melt in the abrupt climate oscillations that characterize the last deglaciation (Clark et al., 2012; Condron and Winsor, 2012; Cronin et al., 2012; Thiagarajan et al., 2014, Toucanne, et al., 2015). Freshwater outbursts from ice melt into the North Atlantic slowed the Atlantic Meridional Overturning Circulation (AMOC), disrupting the Earth's climate system and causing abrupt cooling events (Björck et al., 1996; Ganopolski & Rahmstorf, 2001; Toucanne et al., 2015). Prior to ~15 ka, Scandinavian Ice Sheet (SIS) fluctuations drove freshwater discharge events routed through the Fleuve-Manche/Channel River system (Toucanne et al., 2015; Patton et al., 2017). Outflow through this conduit, however, ceased around 15 ka (Toucanne et al., 2015), coincident with the rapid expansion of a Baltic proglacial lake during the Bølling-Allerød interstadial (Björck, 1995; Patton et al., 2017). We investigate the development of the Baltic Ice Lake and its meltwater storage capacity after 15 ka using sediment cores from deep basins in the southern Baltic Sea.

The deglaciation of the Baltic basin following the Younger Dryas cold-reversal and the demise of the large proglacial lake, known as the Baltic Ice Lake (BIL), is extremely well-known from studies of varve thickness and composition at more than a 1000 localities in eastern Sweden (Wohlfarth et al., 1998; Andrén et al., 1999, 2002; Muschitiello et al., 2016). In contrast, the detailed early retreat history of the SIS from the southern Baltic Sea and the initial development of a large Baltic proglacial lake during the Bølling-Allerød warming has not received as much attention (Björck et al., 1990). Across Western Europe, abrupt temperature increases of 3 – 5 °C were reconstructed at the onset of the Bølling-Allerød warming (Clark et al., 2012). In Greenland ice core records the Bølling-Allerød (14.7-12.7 ka) is positioned to overlap Greenland Interstadial 1, which is characterized internally by several centennial scale climate oscillations (Rasmussen et al., 2014). Here we examine, for the first time, sub-millennial sediment records from basins in the southern Baltic Sea and shed light on the mechanisms of fast ice retreat and meltwater storage of the Scandinavian Ice sheet during the Bølling-Allerød interstadial. The retreat history of the Baltic Ice Stream within the southern Baltic Sea was previously poorly constrained (Hughes et al., 2016), primarily due to a lack of recovery of well-preserved sedimentary records during earlier coring efforts (Björck et al., 1990).

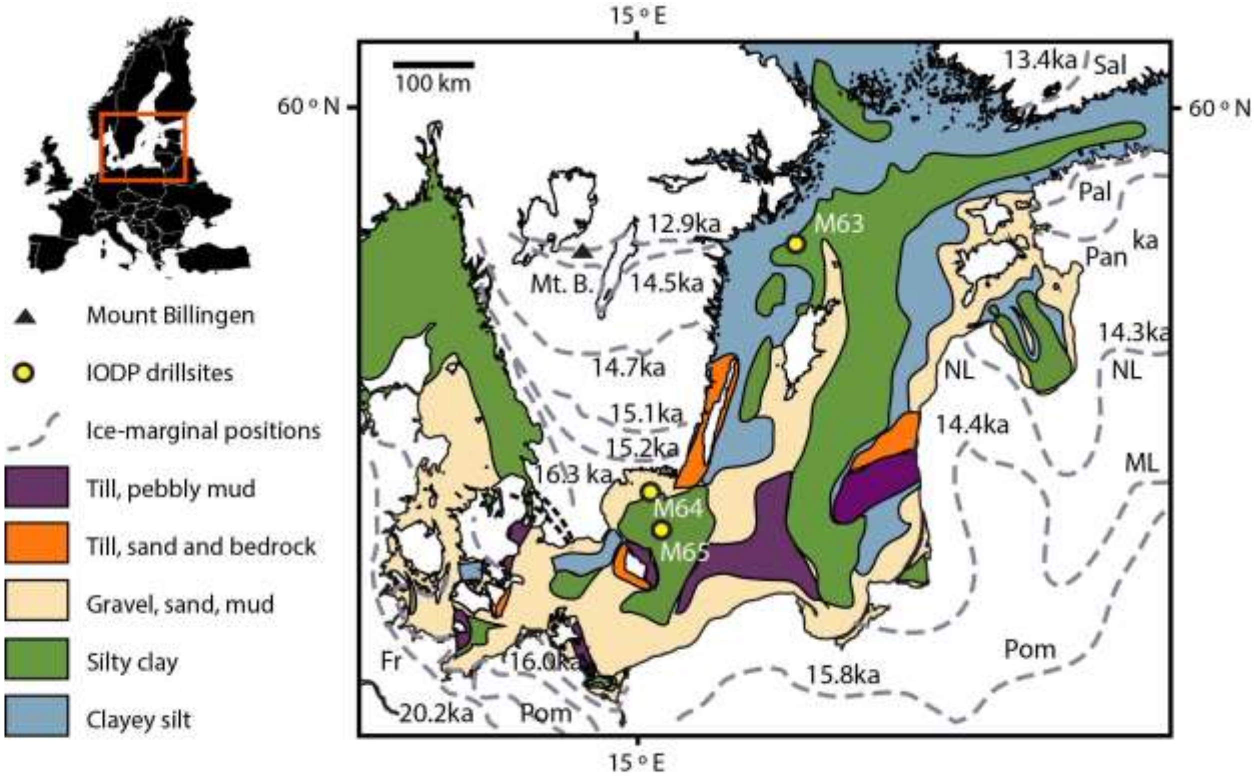


Figure 1. *Map with locations of drillsites of IODP Expedition 347 and sub-seafloor sediment distributions in the southern Baltic Sea based on data from Winterhalter et al. (1981), Emeljanov et al. (1993), Gelumbauskaite et al. (1999), and Hermansen and Jensen (2000), and glacial limits on land with approximate ages based on cosmogenic nuclide surface exposure, radiocarbon dating, and varve counts from Rinterknecht et al. (2006, 2012, 2014), Heine et al. (2009), Anjar et al. (2014), Stroeven et al. (2016), Muschitiello et al. (2016), and Cuzzone et al. (2016). Absolute ages between the reconstructions vary due to differences in processing of the raw data, but retreat rates are similar. The calculated surface exposure ages of Cuzzone et al. (2016) are adopted here. Abbreviations for glacial limits are defined as Pom: Pomeranian, ML: Middle Lithuanian, NL: North Lithuanian, Pan: Pandivere, Pal: Palivere, Sal: Salpausselkä*

(Rinterknecht et al., 2006). Mt. B. refers to Mount Billingen where the spillway is located for the 12.9 ka and post-Younger Dryas lake drainage events (Muschitiello et al., 2016).

1.2 Geological setting

The Baltic Sea is currently a microtidal brackish sea with a relatively shallow connection to the North Sea and the Atlantic Ocean in the Danish straits at ~20 meters below mean sea level (mbsl). The modern Baltic Sea basin was formed in the Cenozoic, likely due to a combination of tectonic and erosional processes. Quaternary sediments directly overlying Mesozoic and Paleozoic basement rocks (Šliaupa and Hoth, 2011) contain high-resolution sediment records of climate and relative sea level change that document the retreat history of the Scandinavian Ice Sheet (SIS) in the Late Pleistocene to Holocene Epochs (Kögler and Larsen, 1979; Björck et al., 1990). The BIL began to form ~ 16 ka BP as the SIS retreated to the north and east (Jakobsson et al, 2007; Larsen et al., 2009). By ~16 ka BP, the western margin of the SIS had retreated to southwest Sweden, depositing the Halland coastal moraines, cosmogenically dated to 16.3 ka BP (Anjar et al., 2014; Houmark-Nielsen and Kjaer, 2003; Cuzzone et al., 2016). Bornholm Island in the southwestern Baltic was deglaciated by about the same time as southern Sweden (Anjar et al., 2014). The retreat of the ice-sheet margin, however, experienced a stillstand between ~16 and 14.4 ka (Figure 1). Extensive deposits of till, pebbly mud and sand suggest that an ice lobe terminated in southern Baltic basin at this time (Figure 1). Analysis of Quaternary stratigraphy on land in southern Sweden showed that a Baltic Ice Stream developed during the deglaciation of this region (Ringberg, 1988). Geomorphological evidence combined with varve chronologies and surface exposure ages show a consistent pattern of ice sheet retreat between ~15 and 12.9 ka in Sweden, but higher rates of retreat to the east of the Baltic Sea (Figure 1).

Three basins, the Hanö Bay, the Bornholm Basin and the Landsort Deep together comprise a sedimentary archive of ice retreat and base level changes dated younger than 15 kyr BP, as indicated by the distribution of surface exposure ages (Figure 1). High sedimentation rates due to sediment focusing into deep basins, which may have been hypoxic, allowed for preservation of relatively undisturbed stratigraphic records with annual to millennial resolution. Hydraulic piston-coring during Integrated Ocean Drilling Program Expedition 347 allowed for the recovery of more or less complete lateglacial stratigraphic records at Sites M0064, M0065 and M0063 respectively (Figure 1) in October 2013 (Andrén et al., 2015a).

2. MATERIALS AND METHODS

2.1 Drill sites and stratigraphy

At Site M0063, coring penetrated the upper portion of a semi-horizontally stratified succession that fills the deepest part of the Landsort Deep, a 437 m deep basin within the Baltic proper

(Expedition 347 Scientists, 2015a, their Figure 29). The lithostratigraphy was subdivided into seven units (Figure 2). Here we present data from Units III-VII at ~34 to 95 mbsf at Site M0063 (Expedition 347 Scientists, 2015a). Lithostratigraphic Unit III consists of convoluted clay with sand laminae and dispersed clasts (Figure 3a). Unit IV is greenish gray clay with a marine imprint and iron sulfide banding, gradually becoming more intensely color-banded (*sensu* Turner, 1971) and laminated downward. Based on the lithological characteristics and stratigraphic position, Unit III is interpreted as the Ancylus Lake stage clay and Unit IV as Yoldia Sea stage clay (Expedition 347 Scientists, 2015a; Obrochta et al., 2017). Units V and VI are rhythmically banded glacial lake deposits (Figures 3c-3e) and coring at the site terminated in a diamicton (Unit VII)(Figure 3f). Ten pebble-sized rock clasts were recovered from the diamicton, and 7 out of them were facetted. Clast shapes were mostly subangular to subrounded and clast lithologies included a red sandstone, dark fine-grained amphibolite and diorite/biotite gneiss.

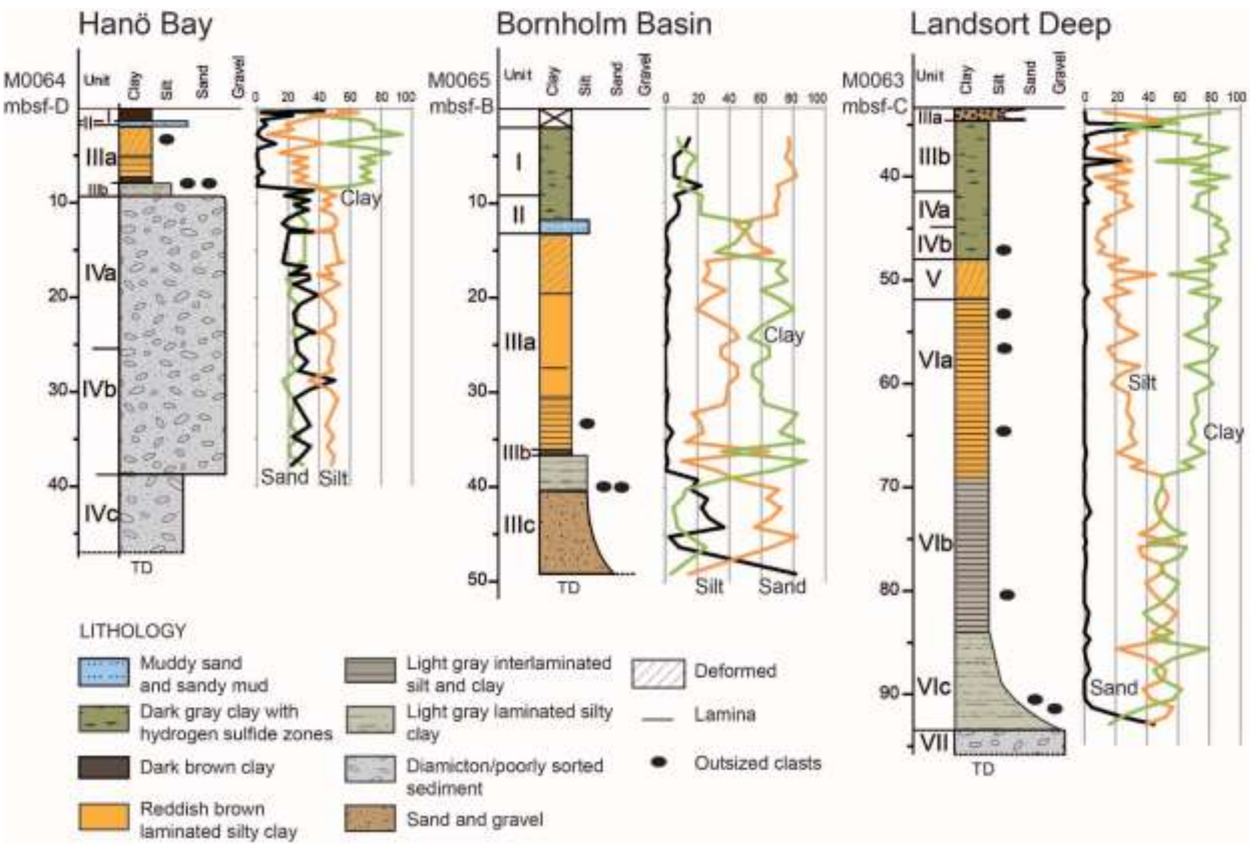


Figure 2. *Lithological logs and grain-size distributions for the deglacial sections of IODP Sites M0063, M0064, and M0065. The lithological logs are for the stratigraphy recovered in Holes M0064D, M0065B and M0063C and the particle size data is plotted on the depth scale for each of those Holes. TD=total depth.*

The cores at Site M0064 were drilled in a shallow, ~60-m deep offshore basin within Hanö Bay overlying bedrock characterized by Cretaceous chalk and clayey carbonates (Expedition 347 Scientists, 2015b). The average recovery was 79% at Site M0064 and four holes (A-D) were drilled to develop a complete stratigraphic recovery with at least three overlapping sediment copies. This study focuses on Hole M0064D (Figure 2), but also uses correlating samples from Hole M0064A. The drilled sequence is divided into four major lithostratigraphic units (Units I - IV) based on their sedimentology (Figure 2). The late glacial Units III and IV and their subdivisions are the main focus of this study. Unit III is a dark grayish brown laminated clay and silty clay with randomly distributed clasts, ~8.5m thick (Figure 4a-4c). Unit III is subdivided into two subunits, where Unit IIIa (1.75 – 7.87 mbsf of M0064D) is red-brown (Figures 4a-4b), with a dark brown layer at its base and Unit IIIb (7.87 – 9.3 mbsf of M0064D) is gray in color (Figure 4c) (Figure 2). Unit IV is subdivided into three subunits of moderately to poorly sorted, matrix-rich diamicton (Figure 4d). Unit IVa is a stratified muddy diamicton with sandy gravel (9.3 – 25.4 mbsf of M0064D) while Unit IVb is a massive gray diamicton with possible shear fabrics (25.4 – 41.2 mbsf of M0064D). In interpretations of seismic data Unit IVa appears to be deposited in a trough incised into Unit IVb (Expedition 347 Scientists, 2015b). Unit IVc, only recovered in Holes M0064A and C, is a ~7m thick stratified diamicton and sandy clayey silt with dispersed clasts that directly overlies Cretaceous limestone bedrock.

Site M0065 is situated to the south of Hanö Bay in the Bornholm Basin (Figure 1), and was drilled in ~84 m water depth. Cores were recovered in three holes at Site M0065 with an average recovery of 99% down to ~50 mbsf, where a sand was reached (Figure 2). Samples of sand were recovered down to ~68 mbsf and mud with diamicton down to ~74 mbsf, but these samples were not available for formal lithological description or sampling (Expedition 347 Scientists, 2015c). The sequence above 50 mbsf was subdivided into three lithostratigraphic units: Unit I is a laminated organic-rich clay (Figure 5a); Unit II is a homogenous sandy mud and Unit III is a color-banded reddish brown silty clay with increasing thickness of sand laminae at the bottom (Figure 2). Unit I contains so-called lake-dump freshwater diatoms in smear slide observations overlying iron sulfide–laminated clay with marine/brackish diatoms, ostracods and forams, which is consistent with Ancylus Lake deposits (Expedition 347 Scientists, 2015c). Unit II likely represents the Yoldia Sea stage, whereas Unit III shows characteristics of proximal glacial lake deposits of the Baltic Ice Lake. Unit III is subdivided into three subunits. Unit IIIa is reddish in color and faintly laminated and deformed (Figure 5b); Unit IIIb is a ~0.6-0.7 m thick dark brownish gray clay that conformably overlies Unit IIIc, which is lighter in color and rhythmically laminated (Figure 5c).The lower portions of unit IIIc contain sand laminae and dispersed pebbles (Expedition 347 Scientists, 2015c).

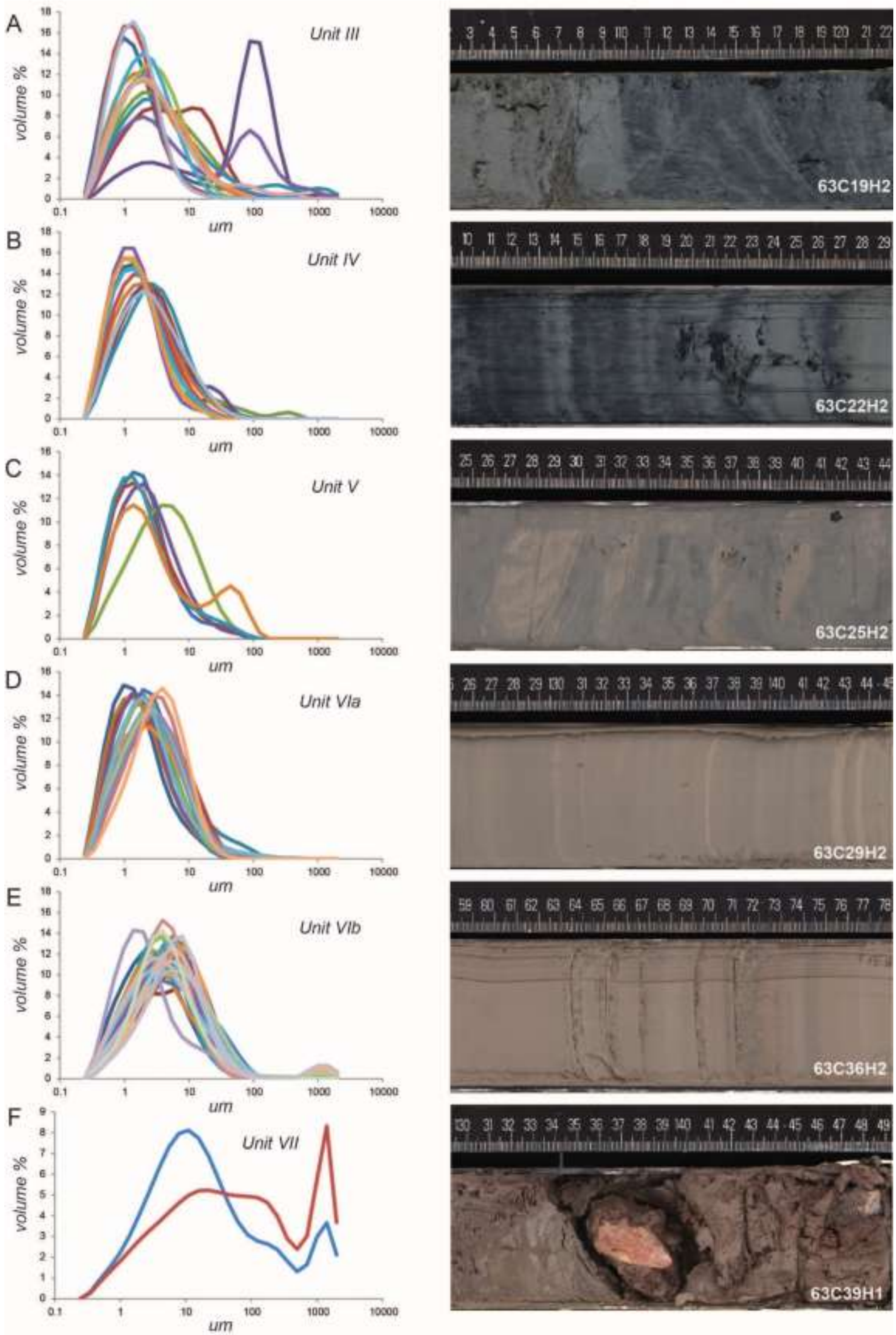
2.2 Analytical methods

Particle size analyses were carried out on samples from Holes M0064A, M0064D, M0065B and M0063C (Figure 2). Samples were manually disaggregated using a rubber policeman and chemically dispersed through heating with sodium pyrophosphate. Particle size distributions were measured using a dual light-source Malvern Mastersizer 2000 at Montclair State University, capable of analyzing grains from 0.02 to 2000 µm. Optical instrument settings were following Sperazza et al. (2004), using an absorption coefficient of 0.9 and a refractive index of 1.6 (Illite; cf. Ringberg and Erlström, 1999). Grain size classifications follow the Udden-Wentworth scale, where clay is defined as <4 µm, the silt range is 4 – 63 µm, and sand ranges from 63 to 2000 µm.

XRF core scanning of eleven core sections of Unit III of M0064D (2.21 – 13.59 mbsf) was carried out in 2017 at the MARUM-University of Bremen XRF lab adjacent to the IODP Core Repository, using the Avaatech XRF Core Scanner III (super slit). XRF scanning methods and sample preparation followed Bahr et al. (2014). Archived half core section preparation began by allowing sections to adjust to room temperature. The split-core surface was laterally smoothed over using a glass slide to remove any pore spaces. The surface was then tightly covered with a 4 µm thin SPEXCerti Prep Ultralene1 foil to avoid instrument and sediment contamination. Major, trace and rare earth elements (REE) were measured on discrete samples from Hole M0064D using an ICP-OES and ICP-MS at Montclair State University. Samples were fused with Lithium Borate in a furnace at 1050 °C and digested in 7% HNO_3 (after Murray et al., 2000). Samples were diluted with 1-2% HNO_3 before ICP instrument analyses.

For well-laminated sections, varve thickness measurements were carried out in M0064A, M0064D, and M0065A, both manually on actual size printed posters and in Corelyzer using high resolution digital core scan images. Thickness was defined as the thickness of a silt-clay couplet, measured on the cut-face of the split core as the vertical distance between the base of a "summer" silt lamina to the base of the "summer" silt lamina of the overlying couplet (Figure 4c). The preservation of multiple interannual meltwater deposits inhibited conclusive delineations of varve couplets for Site M0065. Lamina thickness counts for Site M0064A and D were standardized by dividing Ln of measurements minus average thickness by the standard deviation. Time series analysis was carried out on varve counts for Site M0064 using the PAleontological STatistics (PAST) Software ver. 2.17 (Hammer et al., 2001).

Figure 3. *(next page) Representative images of sedimentary facies (stratigraphic units) and grain-size distributions for Site M0063, Landsort Deep. (A)Disturbed Ancylus Lake deposits; (B) Yoldia Sea clay; (C) deformed Baltic Ice Lake, distal varves; (D) Baltic Ice Lake, distal varves; (E) Baltic Ice Lake, proximal varves; (F) diamicton (till).*


A
Unit III
volume %
um
63C19H2
B
Unit IV
volume %
um
63C22H2
C
Unit V
volume %
um
63C25H2
D
Unit VIa
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63C36H2
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Unit VII
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um
63C39H1

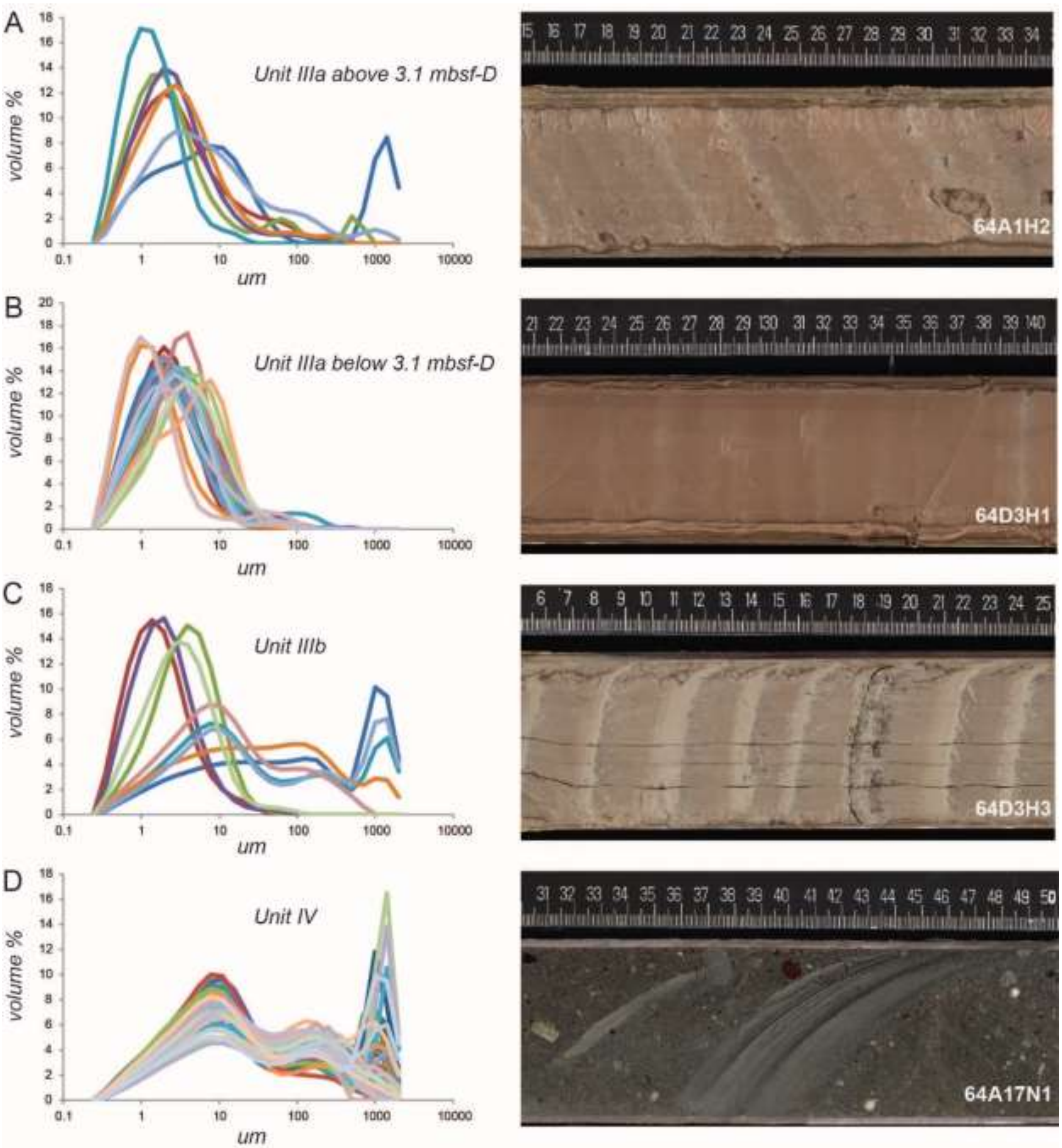


Figure 4. *Representative images of sedimentary facies (stratigraphic units) and grain-size distributions for Site M0064, Hanö Bay. (A) deformed Baltic Ice Lake, distal varves; (B) Baltic Ice Lake, distal varves; (C) Baltic Ice Lake, proximal varves; (D) diamicton (till).*

3. RESULTS

3.1 Sedimentary facies distribution and interpretation

The diamictons at the base of Sites M0063 (Unit VII) and M0064 (Unit IV) have a silt-rich matrix with variable amounts of coarse sand and gravel (Figures 3 and 4). The massive diamictons are consistent with deposition of till in an ice-contact depositional environment. At Site M0064 a sand and gravel rich unit (Unit IIIc) is present between the diamicton and the overlying varves (Figure 6). This facies probably marks episodes of meltwater discharge immediately following glacial retreat. The sand and interlaminated sand and mud (Unit IIIc) at the base of Site M0065 in the Bornholm Basin are also typical of ice-contact meltwater discharge (Gustavson et al., 1975; Gustavson and Boothroyd, 1987; Pearce et al., 2003). Laminae are well-sorted, but show a large variability in particle size modes (Figure 5d).

Rhythmically laminated silt and clay overlying ice-contact facies represent seasonal fluctuations in meltwater discharge in an ice-contact lake (Gustavson, 1975; Ashley, 1975; Ridge et al., 2012). This facies is present at all three Sites with differences in laminae thickness and particle size. At Site M0064 varve couplets have uniform thickness with thicker clay layers than silt layers (Figure 4c). There is significant variability in particle size distributions of individual laminae at Site M0064, but laminae grain-size characteristics are replicated in different individual laminae, consistent with rhythmic sedimentation. At Sites M0065 (Unit IIIc) and Site M0063 (Unit VIb) couplets are generally more complex, show greater variability in thickness, and contain sharp-based sand laminae indicative of underflows (Figures 3e and 5c). Waters with high sediment loads enter a lake via both hyperpycnal flows and surface plumes (Gustavson, 1975; Østrem, 1975). Due to the physical properties of water, which has its highest density at 4°C, cold glacial meltwater can rise to the top of a lake, dilute via sedimentation of coarser particles, with the finer grained component spreading as a surface plume. The more expanded proximal varve successions of Sites M0063 and M0065 contain varves that represent multiple summer melt events and episodic underflows. Thus, at these Sites delineation of annual couplets is more challenging and additional work will be necessary to accomplish unambiguous reconstruction of annual meltwater discharge. The total number of varves counted between the top of the diamict and the top of the grey varve sequence at Site M0064 in Hanö Bay is ~60. We interpret these rhythmites as annual couplets (Figure 4c), and suggest that the varved sequence represents 60 years of deposition.

At all three sites the proximal varves are overlain by considerably finer laminated silty clays with uniform grain-size distributions: Unit IIIa at Sites M0064 and M0065 (Figures 4b, 5b) and Unit VIa at Site M0063 (Figure 3d). The abrupt upward lithological change from silt-rich proximal varves to clay-rich varves is most prominent in the particle size record of the stratigraphically expanded sedimentary succession of Site M0063 in Landsort Deep (Figure 2). The clay-rich varves are more typically diffuse and were likely deposited from distal meltwater suspension

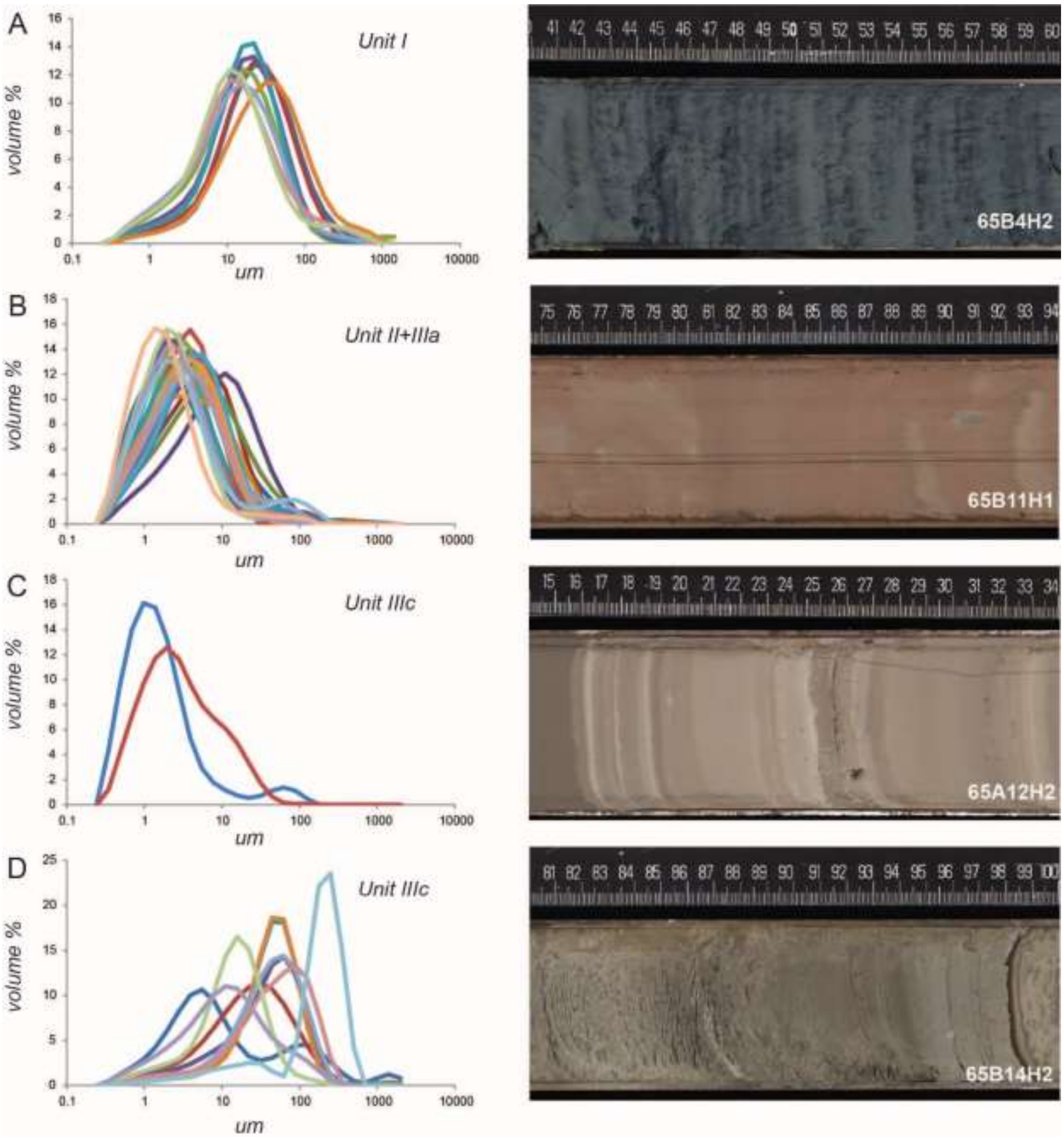


Figure 5. *Representative images of sedimentary facies (stratigraphic units) and grain-size distributions for Site M0065, Bornholm Basin. (A) Ancylus lake deposits; (B) deformed Baltic Ice Lake, distal varves; (C) Baltic Ice Lake, proximal varves; (D) stratified sand.*

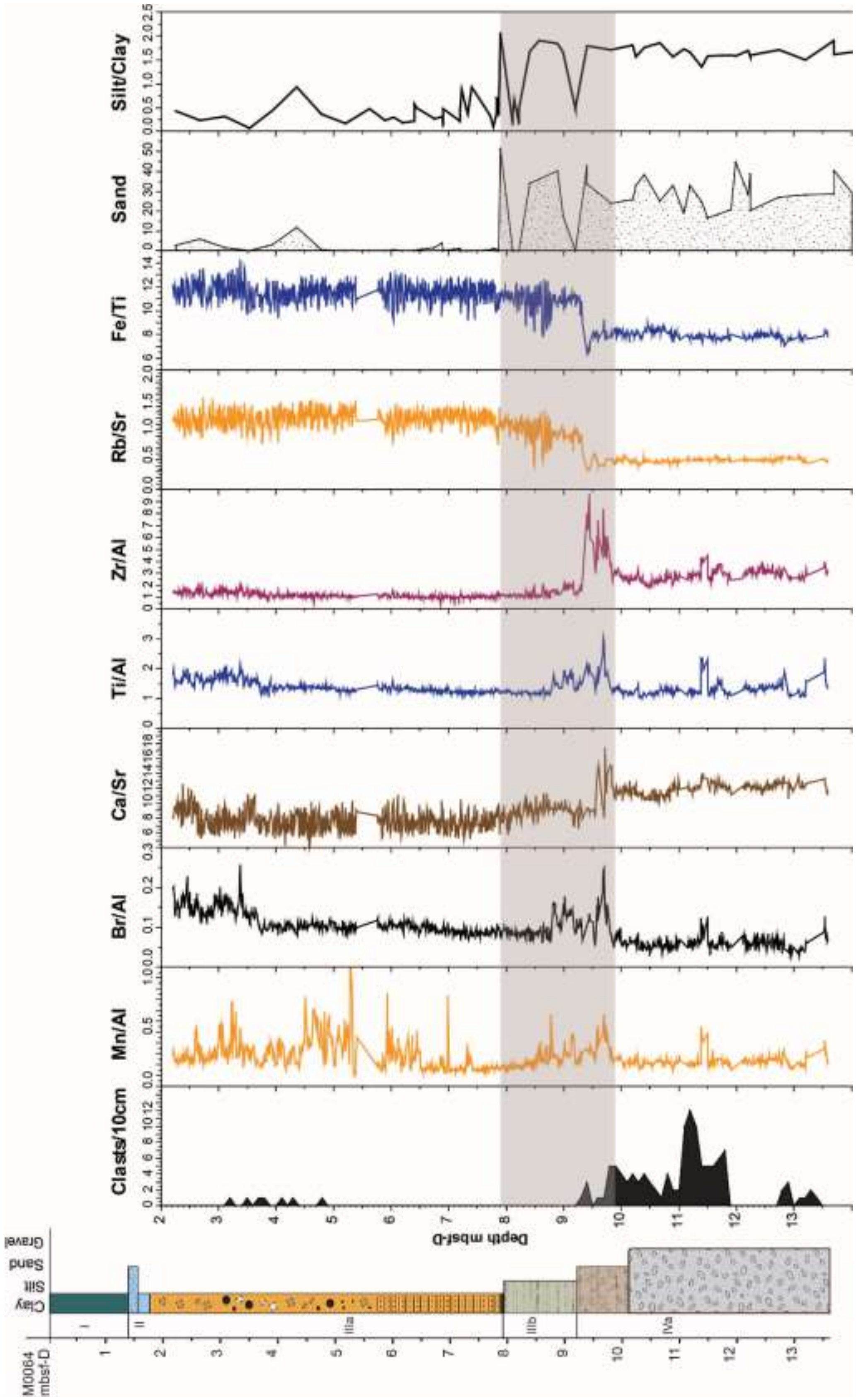
plumes and not in an ice-contact glacial lake environment (cf. Pickrill and Irwin, 1983; Ringberg and Erlström, 1999; Ridge et al., 2012). At Sites M0063 and M0065 and above 3.1 mbsf in Hole M0064D (Figure 4a), however, these sediments transition upward into deformed laminated silty clays with outsized clasts in the sand and gravel grade, suggesting renewed ice rafting from ice grounded in the lake. Approximately 50 distal varves were counted in upward sequence at Site M0064 until varves were too diffuse.

Holocene units of the Yoldia Sea and Ancylus Lake phases were sampled and analyzed at Sites M0063 and M0065. Units III and IV at Site M0063 (Figures 3a,b) probably represent the Yoldia Sea stage (Obrochta et al., 2017). At Site M0065 the Yoldia Sea clay is a thin clay-rich bed in Unit II. The overlying Unit I (Figure 5a) is extremely uniform in particle size distribution with a prominent fine silt mode, which is consistent with deposition in a non-glacial intracontinental basin with restricted circulation, as inferred for the Ancylus Lake sequence (Andrén et al., 2011). The Yoldia Sea and Ancylus lake sequences represent successive early Holocene brackish and freshwater stages between ~11.7 and 9.8 ka that coincided with freshwater discharge from the rapid demise of the land-based Fennoscandian ice sheet (Jansen et al., 2014). A detailed discussion of these ice-distal deposits, however, is beyond the scope of this paper.

3.2 Geochemical data for site M0064, Hanö Bay

XRF data for M0064 is plotted as elemental ratios. The most prominent changes in composition occur in the transition from subglacial to proglacial facies at the base of Unit III (Figure 6). The upper part of Unit IV, which overlies the till has elevated concentrations of Zr and Ti, which are elements that are enriched in mechanically and chemically resistant mineral phases, such as iron oxides, zircon and other accessory minerals, and phyllosilicates. This unit could be interpreted as a lag deposit after dissolvable and easily suspended mineral phases were flushed out. The transition from Unit IV to Unit IIIb is sharp in all compositional data sets (Figure 6). Upward, there is an abrupt termination of gravel, and Ca/Sr, Zr/Al, Rb/Sr and Fe/Ti ratios show shifts as well. These shifts are likely associated with a change in provenance. ICP-MS data show that Unit IIIb has exceptionally high Th values compared to those of the diamict and the overlying unit (Figure 7). Th and Sc are immobile elements in the surface environment that can be used to track provenance changes in fine-grained sediments (McLennan et al., 1993). Interestingly the abrupt shift in particle size between subunits IIIb and IIIa is only minimally expressed in the XRF data. This suggests that changes in chemical composition were decoupled from changes in the energy of the depositional environment.

Figure 6. *(next page) Detailed lithological log of the Baltic Ice Lake section of Hole M0064D and downcore distributions of gravel clasts (>2mm), XRF elemental ratios, and particle size data. The upper stratified part of Unit IV has a lower boundary marked by abruptly increasing Zr/Al and Ti/Al ratios, indicating substantial winnowing and preservation of mechanically resistant mineral phases, such as Zircon and Ilmenite. The grey section represents the sequence of proximal varves (Unit IIIb), and the upper boundary of Unit IIIb is marked by an abrupt decrease in sand % and silt/clay ratios, indicating a transition into much finer, clay-rich distal varves (Unit IIIa).*


Silt/Clay
Sand
Fe/Ti
Rb/Sr
Zr/Al
Ti/Al
Ca/Sr
Br/Al
Mn/Al
Clasts/10cm
Depth mbsf-D
Clay
Silt
Sand
Gravel
M0064
mbsf-D
I
II
IIIa
IIIb
IVa

4. DISCUSSION

4.1 Ice retreat

The style of ice retreat and the composition and architecture of glacial facies assemblages in glacio-aquatic environments depends heavily on the physiographic boundary conditions (Ashley, 2002; Fyfe, 1990; Dowdeswell et al., 2008). Sediments and bedrock mapped by others at shallow depth beneath the southern Baltic Sea bed show till deposits coinciding with bedrock exposures, such as Bornholm Island (Figure 1). The restricted geographic distribution of till deposits and the more than 35 m thickness of succession of the diamicton with shear fabrics recovered at Site M00064 in Hanö Bay (Unit IV, Figure 2) suggests that the margin of the Baltic Ice Stream was at a stillstand for some time with minor readvances of limited extent. The winnowed top of the diamicton in Hanö Bay (Unit IV) suggests that the onset of ice retreat was associated with episodes of high-volume meltwater discharge, followed by deposition of well-developed varves through seasonal meltwater discharge (Unit IIIb in Figure 6).

The Th enrichments of the oldest varves at Site M0064 above average upper crustal compositions (Figure 7) point to glacial erosion of Th-rich bedrock. The most likely candidates are the 1.8 Ga granitoids in the southern part of the Proterozoic late Svecofennian domain, which runs from east-central Sweden via the Åland archipelago to southern Finland (Gáal and Gorbatschew, 1987; Andersson et al., 2006). The highest Th enrichments were observed in the eastern part of this granitoid belt in southern Finland near the Baltic Coast (Andersson et al., 2006). The Th-enrichment of the older proximal varves suggests that bedrock erosion and melt supply by an active Baltic Ice Stream were concentrated in the bedrock underlying the central and eastern Baltic basin. The younger distal varves, however, appear to have a different provenance from the proximal varves based on the much reduced Th enrichments (Figure 7). We suggest that the distal varves were deposited following ice retreat to the north of the Th-enriched south Svecofennian granitoids, which coincides with the position of the Salpausselkä I Moraine system in southern Finland (Figure 1). The end of deposition of the proximal varves, thus, corresponds to an age of around 13.4-12.5 ka, which is the most recent estimate for the Salpausselkä I Moraines (Rinterknecht et al., 2006; Stroeven et al., 2016; Cuzzone et al., 2016).

Chronological studies confirm that the Baltic Ice Stream retreated rapidly from the southern Baltic region during the Allerød warm period (Figure 1; Anjar et al. 2014; Rinterknecht et al., 2006; 2012; 2014; Heine et al., 2009; Wohlfarth et al., 1998; Lundqvist and Wohlfahrt, 2001; Cuzzone et al., 2016). Surface exposure ages suggest that ice retreat was faster in the eastern Baltic region than in Sweden (Cuzzone et al., 2016; Figure 1). Based on the surface exposure ages and published varve chronologies, the deglaciation of the southern Baltic is constrained to a time span of no more than a few hundred years sometime between ~15 and 13 ka (Ringberg, 1988; Björck, 1995; Wohlfarth et al., 1998; Lundqvist and Wohlfahrt, 2001; Muschitiello et al, 2016; Cuzzone et al., 2016). As detailed below, our analyses based on a completely recovered sequence of varves from Hanö Bay, however, suggests that retreat of the Baltic Ice Stream during the initial phase of the Baltic Ice Lake possibly took just ~60 years.

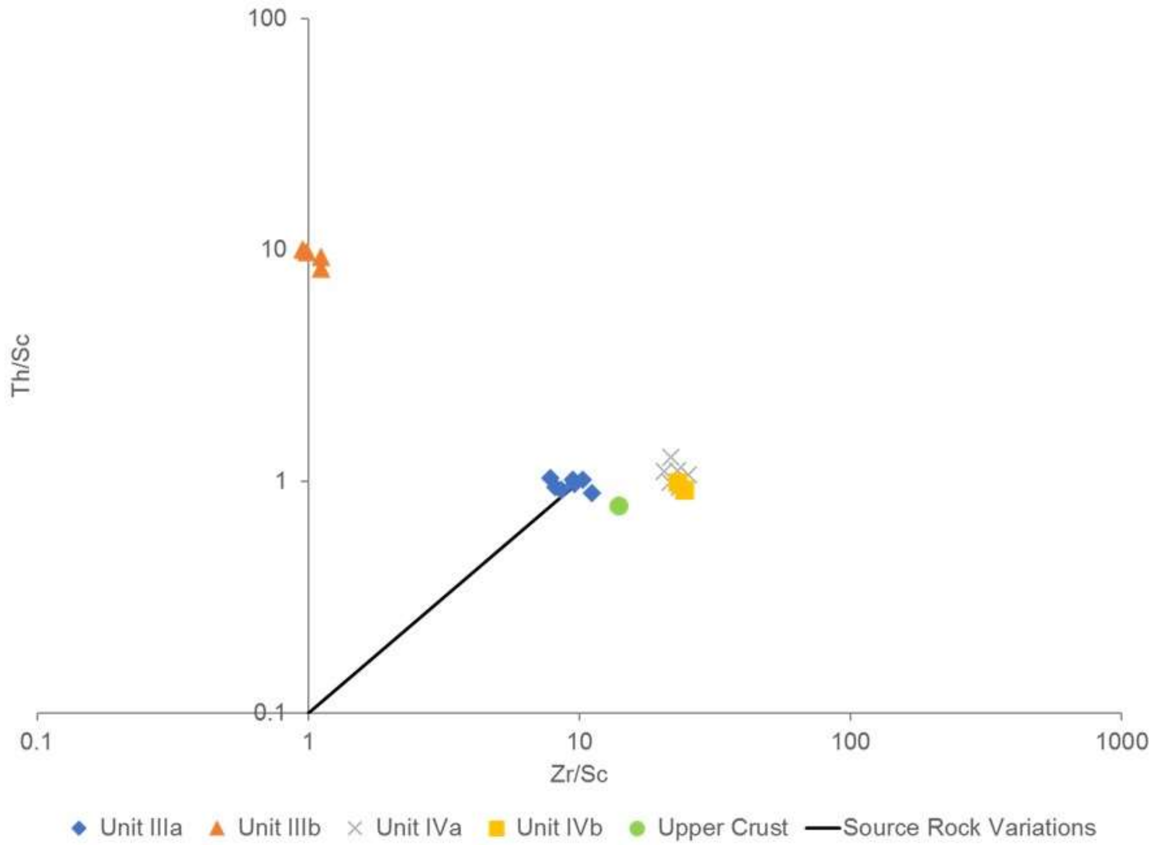


Figure 7. *Bi-plot of Th/Sc ratios vs. Zr/Sc ratios, showing enrichment of Th for the lower proximal Baltic Ice Lake varves at Site M0064 (Unit IIIb). Diamictites of Unit IV and distal varves of Unit IIIa both have compositions near upper crustal values (McLennan, 2001) with Zr enrichment in the diamicton. The black line represents the typical compositional variability of fine-grained turbidites generated in active margin settings (from McLennan et al., 1993).*

4.2 Sedimentation in the Baltic Ice Lake

Deposition of diamicton at Site M0064 in Hanö Bay was followed by winnowing of the top of the diamict prior to deposition of well-developed varves (Figure 6), which suggests that the ice stream began to retreat abruptly within the glacial lake. Evidence of winnowing and ice rafting at both M0064 and M0065 in the southern Baltic Sea signals decoupling of the ice margin from the bed due to episodic subglacial meltwater release and the onset of rapid retreat via calving in the upstream deepening glacial lake. Our interpretation of the geographic distribution of the tills and bedrock (Figure 1) is that the ice-stream margin was grounded in the Baltic Ice Lake on shallow banks and bedrock pinning points at the downstream edge of an overdeepened trough for some time between ~16 and ~14.4 ka (Figure 1). Subsequently, between ~14 and 13 ka the Baltic Ice Lake shoreline was raised due to shoaling of the meltwater spillway to the Kattegat as erosion reached more resistant bedrock under ongoing isostatic rebound (Sandgren and Snowball, 2001; Andrén et al., 2011). The maximum Baltic Ice Lake shoreline level prior to ~13 ka ranged from ~20 m below the present sea level near the German and Danish straits (Jensen et al., 1997; Feldens & Schwarzer, 2012) to > 200 m above present sealevel in east central Sweden (Påsse and Daniels, 2015; Muschitiello et al., 2016). Surface exposure ages suggest that ice retreat from the southern Baltic Sea and, consequently, deposition on top of the diamicton at Site M0064, a subglacial deposit, commenced after ~14.4 ka (Figure 1, Cuzzone et al., 2016). Ice streams grounded in overdeepened aquatic environments typically retreat episodically due to extension and dynamic thinning of the ice margin and decoupling of the ice margin from the bed (Dowdeswell et al., 2008).

The facies assemblages recovered from the Hanö Bay and Bornholm basin are consistent with a dynamic Baltic Ice Stream during the Allerød. It is noteworthy that the role of subglacial meltwater is also highlighted in discussions of the dynamics of the Holocene Scandinavian Ice Sheet in the northernmost Baltic. Crosscutting relationships between megascale glacial lineations (MSGL) and meltwater channels in the Bothnian Sea suggest the presence of substantial basal meltwater outflow during ice streaming (Greenwood et al., 2017). Facies assemblages recovered in Hanö Bay and the Bornholm Basin are similar to those deposited during a later phase of the Baltic Ice Lake (Fyfe et al., 1990) and to those within the deep proglacial Lake Agassiz in North America (Sharpe and Cowan, 1990). Deposition in proglacial lakes > 40-100 m deep is typically mud-rich with narrow ridges of diamicton and sands that grade laterally into varves over short distances, with evidence of iceberg calving. In the deeper parts of the Baltic Ice Lake at that time meltwater and sediment were probably delivered through distributed subglacial drainage rather than flow in large widely spaced conduits (Fyfe, 1990). Deposition of the proximal varves in water depths greater than or similar to today for Sites M0064 and M0065 is corroborated by reconstruction of maximum lake levels of ~55-65m above present sea level in southern Sweden (Björck and Möller, 1987; Ringberg and Erlström, 1999).

4.3 Drainage of the Baltic Ice Lake ~12.9 ka

We interpret the ~0.6-0.7 m thick dark layer between the proximal and the distal varves (Units IIb and IIa in M0064 and Unit IIIb in M0065; Figure 2) as evidence of a lowering of the Baltic Ice Lake surface level. This layer had a higher TOC (1.75 wt. %) with respect to the proximal and distal varves (Expedition 347 Scientists, 2015b). At Site M0064, the bulk sediment of this dark layer was radio-carbon dated and yielded an age of > 44 ka (Andrén et al., 2015b). The age near the limit for radiocarbon dating combined with the relatively low TOC, however, is more consistent with the recycling of large amounts of old radiometrically "dead" carbon. Furthermore, the recycling of carbon from soils and limestone is a known impediment to the radiocarbon dating of Baltic Ice Lake sediments (Obrochta et al., 2017). We correlate the dark layer to an early Baltic Ice Lake drainage event (Björck, 1995; Bennike and Jensen, 2013) that was independently dated to 12.9 ka BP and immediately preceded the onset of the Younger Dryas (Muschitiello et al., 2016). Lake drainage was facilitated by ice retreat to central Sweden and the opening of a spillway to the Atlantic Ocean near Mount Billingen (Figure 1).

After this initial Baltic Ice Lake drainage, the shoreline moved basinward and large areas of clay-rich former lake floor sediments became exposed to surface runoff. Streams likely incised the shorelines to meet the new lake level, thereby generating massive amounts of fine-grained suspended sediment. These conditions, and the fact that Sites M0064 and M0065 became situated in shallower water closer to shore, led to an increase in varve thickness (Figure 9a), a high clay content of varves (Figure 6) and a more subdued seasonal contrast in varve couplets (Figures 4b and 5b). This interpretation is in agreement with Ringberg and Erlström (1999) who found similar more diffuse, clay-rich varves overlying more uniform silt-rich varves in stratigraphic lake sequences onshore in southern Sweden. Incision and erosion of clay-rich sediments also explains the lithological transition from silt-rich proximal varves to clay-rich distal varves at ~68 mbsf in Site M0063, Landsort Deep (Figure 2). Deposition in a smaller Baltic Ice Lake resumed, but a second and final lake drainage event occurred near the end of the Younger Dryas cold period at ~11.7 ka (Jacobsson et al., 2007). After the second drainage, deposition in the shallower, rebounded, southern Baltic Sea basin ceased due to a 25-m drop in water level, which is marked by an unconformity in the seismic stratigraphy of both the Hanö Bay and the Bornholm Basin (Jensen et al., 1997; 2017). In the Landsort Deep (Site M0063), however, deposition continued (Obrochta et al., 2017).

4.4 Time series analyses of varve thickness

At Site M0064, only ~60 proximal varves separate the diamicton from the dark "lake drainage horizon" (Figure 9a,b). If we assume the lake drainage event is correlative to the 12.9 ka event of Muschitiello et al. (2016) near Mt. Billingen, the ice retreated a distance of ~300 km northwestward from the northern edge of the till mapped within the seafloor in 60 years (Figure 1), which amounts to an average retreat rate of ~5 km/yr. We realize that this retreat rate is greater than the average ~0.3 km/yr Bølling-Allerød retreat rates for both the terrestrial Laurentide Ice Sheet (Ridge et al, 2012) and SIS in Sweden (Cuzzone et al., 2016). It is noteworthy, however, that the most recent compilation of surface exposure ages of the SIS shows significantly higher retreat rates in the eastern Baltic Sea region that contrast with the relatively slow retreat rates in Sweden (Figures 1 and 8). Cuzzone et al. (2016) attribute the discrepancy in retreat rates to the presence of the Baltic Ice Lake, which affected the Finnish ice margin. As discussed above, our provenance data with Th enrichments in the proximal varves is indicative of glacial erosion and ice discharge focused in the Th-rich terrains of southern Finland and the eastern Baltic coast, which is in agreement with a more dynamic ice margin for the eastern Baltic basin (Cuzzone et al., 2016). Retreat rates would be reduced if an hiatus is assumed at some position in the proximal varve sequence in Hanö Bay (Unit IIIb; Figure 6). However, given the conformable and undisturbed nature of the varve succession above the diamicton, the only reasonable assumption would be an hiatus due to non-deposition, which would require an unrealistic disruption in the meltwater and sediment discharge to the lake during ice retreat. Noteworthy is also that the retreat rates of ~5 km/yr we report are consistent with the surface exposure ages for the eastern Baltic between 14.4 and 13.4 ka (Cuzzone et al., 2016)(Figure 8). Furthermore, the retreat rate of ~5 km/yr for the Baltic Ice Stream is comparable to retreat rates upward from ~1.2 km/yr measured today on some of the fastest retreating ice streams in West Antarctica (Rignot et al., 2014; Konrad et al., 2018). Based on this evidence we conclude that the Baltic Ice Stream retreated with a rate between ~0.3 to ~5 km/yr prior to lake drainage at ~13 ka, but with the sedimentological evidence pointing to the higher end of this range.

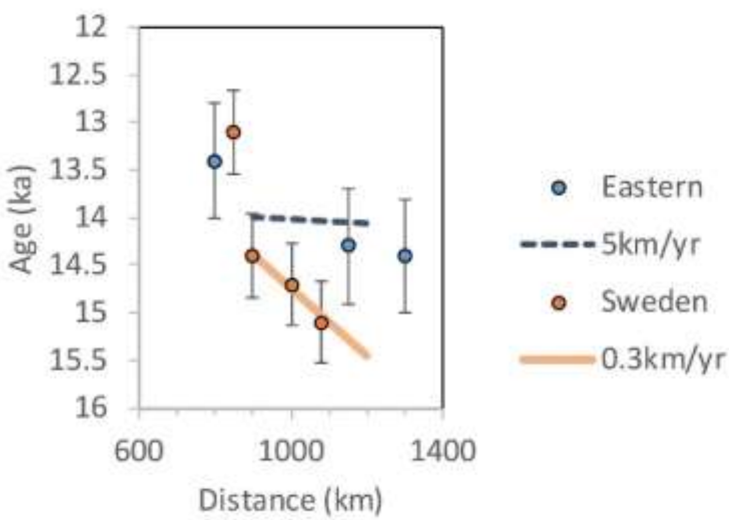


Figure 8. *Time – distance diagram for the retreat of the ice sheet from the southern Baltic Sea during the Bølling-Allerød. Surface exposure ages of ice limits are plotted with standard errors, as in Cuzzone et al. (2016). The Distance (km) is the position of the ice limit with respect to the youngest surface of exposure in northwestern Sweden. The orange solid line is a retreat rate of 0.3 km/yr along a transect in Sweden (Cuzzone et al., 2016). The dashed line represents the deglaciation rate of ~5 km/yr as determined from the varve record at Site M0064 (this study), for comparison with surface exposure ages for ice limits in the eastern Baltic (Cuzzone et al., 2016).*

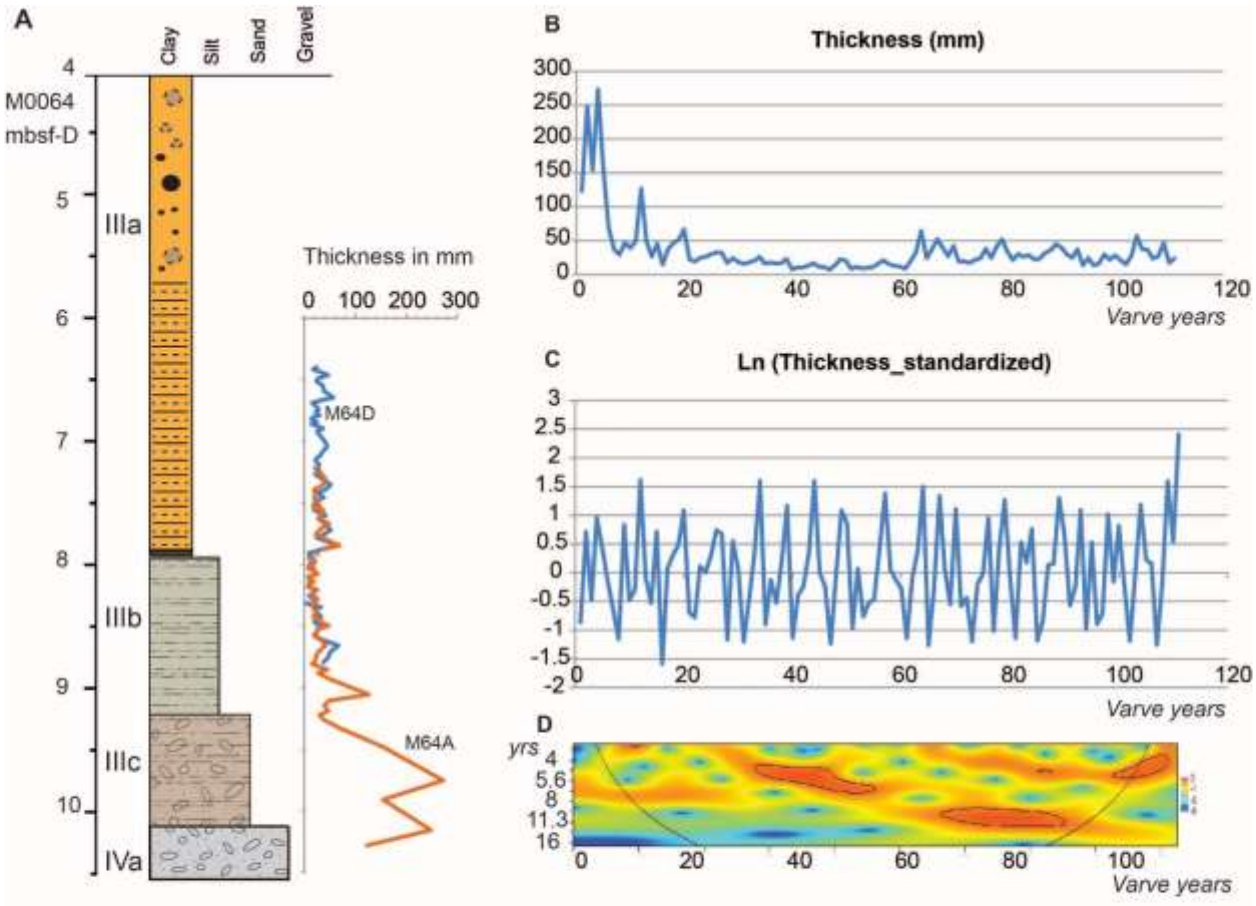


Figure 9. *Varve counts and time series analyses for Site M0064. A: Detailed lithological log of Hole M0064D with varve thickness measured in Hole M0064D (blue) and Hole M0064A (red). B: Composite varve thickness curve combining the records of Holes M0064A and D. C: Ln standardized thickness of the varves. D. Wavelet analysis of varve thickness distribution. Black envelopes designate significant results at the 95% confidence level.*

Time series analysis of the standardized varve thicknesses at Site M0064 (Figure 9c,d) shows a dominant 4 to 7-year periodicity, combined with an 11-year periodicity at the transition between the Allerød and the Younger Dryas (distal varves). These periodicities compare well to time series of modern Baltic sea-ice conditions with power in the 2.2–3.5, 5.7–7.8 and 12.8 year bands (Jevrejeva et al., 2003). The variations on 4 to 7 year timescales in the proximal varves can be attributed to the influence of tropical phenomena on mid-latitude atmosphere processes. A similar multi-annual periodicity in late-glacial varve records from New England in the United States was attributed to, El Niño-like, low-latitude atmospheric teleconnections (Rittenour et al., 2000). Migration of Atlantic storm tracks and variability in storm intensity likely influenced northward directed heat and moisture transport during the last deglaciation (e.g., Li and Battisti, 2008). In contrast, the 11-year frequency following Baltic Ice Lake drainage that coincides with the onset of the Younger Dryas cooling is more consistent with a connection to changes in a

North Atlantic atmospheric circulation pattern, such as the Arctic Oscillation/Northern Annular Mode (Jevrejeva et al., 2003; Moore et al., 2013).

4.5 Mechanisms of rapid ice retreat and effects of meltwater storage

Our sedimentological data demonstrate that surface melt and calving drove fast retreat of the Baltic Ice Stream during the Bølling-Allerød interstadial, amplified by the upstream deepening of the Baltic Ice Lake (Figure 10). Using 3D ice-sheet modeling with a surface melt effect parameterization, Clason et al. (2014) showed that, in agreement with field-based ice-sheet reconstructions, the Baltic Ice Stream was extremely susceptible to atmospheric warming with the fastest retreat rates recorded during the Allerød warm period immediately prior to the Younger Dryas. Further, modeling of the Eurasian ice sheet complex and its meltwater drainage networks shows that the Baltic proglacial lake grew rapidly upon retreat of the Baltic Ice Stream and stored water draining from a large area of the Fennoscandian ice sheet (Patton et al., 2017). Ice retreat outpaced glacio-isostatic adjustment leading to the development of a Baltic Ice Lake that was significantly deepening upstream. The retreat of the grounding line increased the volume of the freshwater storage as long as the ice blocked drainage of meltwater prior to ~ 12.9 ka BP (Jensen et al, 1997; Muschitiello et al., 2016).

We conclude that the Baltic Ice Lake reached its maximum depth and storage capacity at ~13 ka, and reduced outflow of freshwater to the Atlantic Ocean through the Fleuve-Manche/Channel River system (Toucanne et al., 2015). The increasing freshwater storage in such lakes as the Baltic Ice Lake and decreasing freshwater supply to the ocean may have renewed enhanced turnover and heating of deepwater in the North Atlantic Ocean (Björck et al., 1996; Cronin et al., 2012; Thiagarajan et al., 2014). Eventually, ice retreat opened a spillway in south-central Sweden with freshwater release to the ocean at 12.9 ka (Muschitiello et al., 2016). This spillway, however, is at higher latitude than the Fleuve-Manche/Channel River system, which could be important because hosing experiments with ocean circulation models demonstrate larger effects of meltwater release into the North Atlantic than for conduits located farther south (Condron and Winsor, 2012).

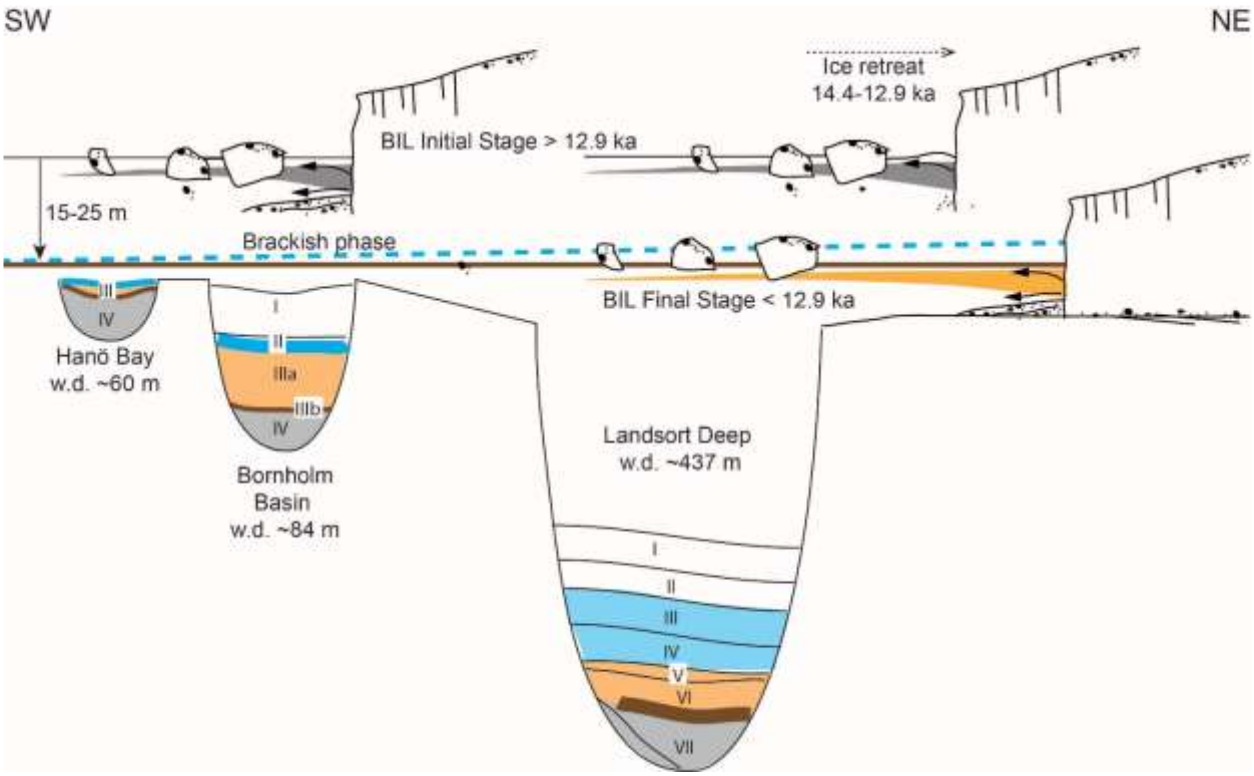


Figure 10. *Ice retreat and its impact on lake levels and sedimentary processes in the three sub-basins in the Baltic Sea. The top half illustrates ice retreat and sedimentation within a deep Baltic Ice Lake (BIL) prior to 12.9 ka and deposition of the proximal varves (grey). The bottom half illustrates the effect of lake drainage and deposition of the distal varves after 12.9 ka (orange). The blue sequence corresponds to the Yoldia Sea transgression and the white sequence the Ancylus Lake and younger sediments, which are not discussed in detail.*

5. CONCLUSIONS

Integrated Ocean Drilling Program Expedition 347 recovered sediment deposited in the Baltic Ice Lake during the Bølling-Allerød interstadial. The main volume increase of the initial lake phase took place sometime between ~15 and 13 ka as the Baltic Ice Stream disintegrated. Within this time period varves overlying diamictons and ice-proximal glaciofluvial sediments were deposited in the deeper parts of the Baltic intracontinental basin, the Hanö Bay, the Bornholm Basin and the Landsort Deep. Time-series analysis of varve thickness from core sections recovered in Hanö Bay points to atmospheric forcing of meltwater supply and ice retreat on multi-annual to decadal timescales. Ice marginal thinning probably resulted in the rapid disintegration of the Baltic Ice Stream which occupied an upstream deepening lake basin. Retreat of the ice sheet from south-central Sweden resulted in a lake drainage event dated at 12.9 ka (Muschitiello et al., 2016), which we correlate to a lithological transition recovered at three

IODP sites. Varve deposition in the Baltic Ice Lake continued following the lake drainage, but the varves became diffuse due to the basin wide migration of lake shorelines, surface runoff, and the shallower water depths of deposition.

Ice-stream instability in the upstream deepening Baltic Ice Lake probably caused ice retreat rates to substantially outpace glacio-isostatic rebound leading to the development of large freshwater storage capacity during the Allerød warm period. Storage in the pro-glacial lake halted freshwater outflow at mid-latitude into the North Atlantic (Toucanne et al., 2015) and may have diminished the freshening of the Atlantic Ocean surface, allowing renewed overturning circulation and heat storage (Cronin et al., 2012; Thiagarajan et al., 2014). We conclude that meltwater storage in large ice-contact lakes upon deglaciation could be a key element in the abrupt feedbacks between atmospheric and oceanic processes and could play a role in sub-millennial deglacial climate instability as documented in ice cores and deep-sea sediment cores.

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