The Behavior of the Baltic Sea Ice Stream during the Deglaciation of the Baltic Ice Lake, Recorded in the Particle Size and Geochemistry within Bornholm Basin, IODP Site M0065

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Abstract

IODP 347 Site M0065 was drilled to assess the last deglaciation of the Scandinavian Ice Sheet (SIS) within the southern Baltic Sea Basin (BSB) from ~20 ka BP. Site M0065 was drilled in the Baltic Sea within the Bornholm Basin in a water depth of 87m. It provided the opportunity to study the development of the Baltic Ice Lake (BIL), which occupied the southern BSB between ~17 and 11 ka. Previous studies in this area looking at glacial till and surface exposure dates have dated the deglaciation of Bornholm Island, and consequently Site M0065, at ~16.3 ka BP. A visual inspection of the high-resolution images of cores from site M0065B indicates clay size fraction sediment was deposited from Core 1H down to Core 12H, 36 mbsf, where glacial sand/silt and clay varves are introduced. Within the clay sections color variations are observed indicating a compositional or chemical change. Glacial varve counting determined that the site was influenced directly by seasonal glacial melting for approximately 50 years. Sixty-seven samples were taken from core M0065B (3.2 to 49.1 mbsf) to analyze particle size distributions from 0.02μm to 2mm, and 23 of them were analyzed as part of this study. Grain size and geochemical XRF and ICP-MS data was used to indicate the cause of color variation and determine whether site M0065 was influenced by proximal seasonal ice sheet melting within the BIL, followed by sediment deposition within a stagnant, non-circulating, BIL with changing provenance and lake anoxic conditions. The succession of the rapid retreat of the SIS and transition from a proximal to distal glaciolacustrine environment to the drainage events of the BIL is seen within Bornholm Basin and is marked with changes in grain size and geochemistry of the sediment deposited. Al/Ti and Mn/Al ratios do not indicate a provenance or bottom water oxidation change, but Zr/Al ratios do indicate an increase in meltwater strength. Br/Al and a dramatic increase in sulfur, both proxies for organic content, further indicate reworking of previously deposited sediment due to the BIL drainage event at 12.9 ka BP. The marine incursion into deep lacustrine depositional environment of the BIL Yoldia Sea (YS) at 10.5 ka BP and
transition to the freshwater stage of the (YS) is seen with an increase in Mn/Al ratios and the change in grain size along with the emerging presence of brackish-freshwater diatoms.
The Behavior of the Baltic Sea Ice Stream during the Deglaciation of the Baltic Ice Lake, recorded in the Particle Size and Geochemistry within Bornholm Basin, IODP Site M0065

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1. INTRODUCTION

1.1 Baltic Sea deglaciation

The Baltic Sea Basin (BSB) (Figure 1) is the world’s largest intracontinental basin at approximately 373,000 km² with an average depth of about 54 meters. Its location in a glaciation-sensitive high northern latitude has allowed the BSB to have a dynamic depositional environment for over the last hundred thousand years (Andrén et al., 2011, Rosentau et al., 2017). Drilling has allowed for high-resolution recovery of sediments detailing the paleoenvironment regionally and globally.

The BSB is in between the North Atlantic Ocean and Asia and represents a link that preserves the response to oceanic forcings from the North Atlantic Ocean circulation (Andrén et al., 2015). During the Last Glacial Maximum (LGM) most of the northern hemisphere was covered with ice, and deglaciation occurred between 19 and 11 ka (Andrén et al., 2015, Anjar et al., 2014, Clark et al., 2012, Toucanne et al., 2015). This time period of global change was triggered by changes in global insolation, associated changes in ice sheets, changes in greenhouse gas (GHG) concentrations, and other feedbacks that produced regional and global responses (Clark et al., 2012).

The Baltic Ice Stream (BIS), the largest of the Fennoscandian Ice Sheet (FIS) ice streams, was active during the deglaciation and reached terminus in Germany, Poland, and the East Jutland ice margin in central Denmark during the LGM (Anjar et al., 2014, Boswell et al., 2018). The deglaciation of the southern BSB between 22 and 16 ka BP is characterized as a complex and dynamic system that has experienced ice sheet waning and waxing of the Scandinavian Ice Sheet (SIS), large fluxes in sedimentation patterns, and responses to sea level change (Andrén et al., 2015, Anjar et al., 2014).
Previous onshore studies looking at glacial till, surface exposure dates, and geochemical wetland data in the Baltic have marked the deglaciation of the SIS ~20 - 12 ka BP. Cosmogenically dating the Halland coastal moraines shows that the SIS had retreated north and east exposing southwestern Sweden, along with Bornholm Island at 16.3 ka BP (Anjar et al., 2014, Clark et al., 2012, Cuzzzone et al., 2016, Toucanne et al., 2015).

During early stages of the deglaciation (Figure 2) large amounts of freshwater, dammed in front of a retreating ice front, created the Baltic Ice Lake (BIL), which released freshwater into the North Atlantic through the Oresund Strait and through south central Sweden. It is approximated that about 8000 km$^3$ of freshwater was released into the North Atlantic during the catastrophic final drainage of the BIL at ~11.7ka (Andrén et al., 2015).

The onset of the Holocene, 11.7 ka, marked the start of a shift within the Baltic Sea with rapid warming and the start of the Baltic Sea stage the Yoldia Sea (YS) (Figure 2). The YS lasted from 11.7 to 10.7 ka and is characterized as a mix of freshwater and weakly brackish water periods. During this time period rapid deglaciation of the SIS occurred, releasing large amounts of freshwater into the Baltic Sea and at the same time increasing the sedimentation rate in the southern Baltic Sea. After ~300 yrs from the start of the YS narrow straits emerged in the south-central Swedish lowlands allowing the introduction of saline water into the Baltic Sea. This weakly brackish period of the YS, estimated to have lasted 350 yrs, turned again into a freshwater basin because of high isostatic rebound rates and large amounts of outflow of meltwater, from the deglaciation of the SIS, in the south-central Sweden region (Andrén et al., 2015).

The onset of the Ancylus Lake (AL), the next stage of the Baltic Sea (Figure 2), lasted from 10.7 to 9.8 ka and experienced shoreline regression in southern Sweden because of the closure of the southern straits and large influx of freshwater causing sea level to rise within the Baltic Sea. The final inflow of freshwater into the AL from the final deglaciation of the SIS contained little
organic material because of young developing soils within the SIS drainage areas. With low nutrient input this caused the AL to have low productivity but led to a well-mixed oxygenated water body (Andrén et al., 2007, Andrén et al., 2015).

Bornholm basin Site M0065, drilled into Pleistocene-Holocene basin fill, was chosen to investigate and study the development of the BIL in a deep lake environment. The color variations and transitions through the time period recorded within the core samples retrieved, tell an interesting and complex history of the BSB and its connection to global events.
2. SITE LOCATION AND GEOLOGY

2.1 Pre-Quaternary geological basement

The Baltic Sea is known for its highly complex geology and is divided geologically into three sections. The northern part is situated within the Precambrian Baltic Shield and the southern half situated primarily on the Precambrian East European Platform, with a small southwestern portion of the Baltic Sea situated on the Paleozoic West European Platform.

The Baltic Shield to the north is comprised of Archean and Proterozoic crystalline rocks and found in the Bothnian Bay, off the northern coasts of the Gulf of Finland, and the eastern coasts of Sweden. The Archean crystalline rocks are composed of plutonic and volcanic rocks, granitoids, and ophiolite rocks. Proterozoic sandstone can also be found in depressions of the Baltic Shield overlying Proterozoic magmatic rocks (Rosentau et al., 2017).

The East European Platform’s foundation is comprised of Precambrian Archaean and Proterozoic crystalline rocks and Phanerozoic sedimentary rocks extending south. In the central part of the Baltic Sea, Cambrian sedimentary rocks underlie Quaternary sediments while Neogene sediments are seen below Quaternary sediments in the south (Rosentau et al., 2017).

The West European Paleozoic Platform is comprised of Precambrian crystalline basement rocks overlain with folded early Paleozoic (Cambrian, Ordovician, and Silurian) sedimentary rocks. These early Paleozoic sedimentary rocks are overlain by Paleozoic, Mesozoic, and locally Paleogene strata comprised of a Carboniferous-Devonian complex and a Permo-Mesozoic complex (Rosentau et al., 2017). Within the Mesozoic complex, and important to this study Site, are the Cretaceous sections that reach and outcrop about 400 m along the southern coast of the Baltic Sea. The early Cretaceous deposits are composed of glauconitic sandstones and siltstones.
while the late Cretaceous deposits are composed of chalk, marlstones, and siltstones (Šliaupa and Hoth, 2011).

2.2 Pleistocene and Holocene basin fill

The Early and Middle Pleistocene deposits in the Baltic Sea consist of glacial, glacio-fluvial, and lacustrine sediments. These deposits vary in thicknesses throughout the Baltic where thinner deposited areas are due to glacial erosion while thicker deposited areas are due to deep tunnel valleys incised in the pre-Quaternary bedrock. Throughout the entire Baltic Sea area, the Early and Middle Pleistocene glacial sediments are represented by a single layer of till from the last glaciation (Rosentau et al., 2017).

The Late Pleistocene and Holocene (postglacial) deposits are generally the same throughout the entire Baltic Sea. The postglacial sediments of silt and clay form three very distinct lithostratigraphic units: the brown clay of glacio-lacustrine sediments (Baltic Ice Lake), the gray clay of brackish-water and lacustrine sediments (Yoldia Sea and Ancylus Sea), and the olive-gray mud of marine and brackish-water sediments (Littorina and Post-Littorina Sea) (Rosentau et al., 2017).

2.3 Site M0065, Bornholm Basin

Site M0065 (55°28.09′N, 15°28.63′E) is situated within the Baltic Sea northeast of Bornholm Island and lies within the deep waters (87m water depth), of the Bornholm Basin. The high sedimentation rate on the order of meters per thousand years gives a unique depositional environment in which to study and reconstruct the development of the Baltic Ice Lake (BIL) (Andrén et al., 2015, Anjar et al., 2014).

Coring started at Site M0065 with Hole M0065A on October 23rd, 2013 with Hole M0065A and was finished on October 26th, 2013 with Hole M0065C. M0065A was drilled to a depth of 73.9m below sea floor (BSF) where Cretaceous limestone bedrock was encountered. M0065B
was drilled to a depth of 49.3 mbsf and M0065C was drilled to a depth of 47.9 mbsf. Correlation and splicing were possible within a 0.1 m of error margin to 47.5 meters composite depth (MCD). Deeper correlation was not possible due to poor core sample recovery during drilling.

Site M0065 is divided into three lithostratigraphic units (Figure 3) (Andren et al., 2015). Seismic correlations for the site were calculated from two-way travel time values to identify lithostratigraphic unit boundaries along with other physical and geochemical properties. Seismic survey of the site (Figure 4) indicated pockets of sediments deposited in the former lake that occupied the southern Baltic Basin.

The top Section, Unit I (65A 2H-1 to 4H-1; 65B 2H-1 to 3H-3), is comprised of dark greenish, organic-rich clays with weak laminations which represents an oxic marine depositional environment with anoxic phases near the bottom (Figure 5A and B). The middle Section of the core, Unit II (65A 4H-1 to 5H-1; 65B 3H-3 to 5H-1), is composed of gray to dark gray laminated clay with the lowermost part of the section gradually transitioning to brown clay which represents a lacustrine depositional environment (Figure 5C).

The bottom Section of the core, Unit III, was divided into three subsections that represent a glacial lacustrine depositional environment. Unit IIIa (65A 5H-1, 130cm, to 12H-1, 105cm; 65B 5H-1, 95cm, to 12H-1, 10cm) is composed of grayish brown clay with weak laminations (Figure 5D). Unit IIIb (65A 12H-1, 105cm, to 12H-2, 15cm; 65B 12H-1, 10cm, to 12H-1, 80cm) is composed of very well sorted dark gray homogeneous clay with weak light dark coloring (Figure 5E). Unit IIIc (65A 12H-2, 15cm, through 15H; 65B 12H-1, 80cm, through 17H) is composed of grayish brown silty clay with parallel lamination at the top and downward coarsening sand with laminated silt (Figure 5F). Unit IIib and IIIC represent a more glaciolacustrine environment with rhythmically banded clays and increased grain size. The frequency of sand laminations indicates the lower part is deposited in a more ice-proximal setting (Andrén et al., 2015).
3. MATERIALS AND METHODS

The research data for this project obtained from Site M0065, Holes A and B, was collected and analyzed at Montclair State University with the exception of the XRF data from M0065A that was collected for the purpose of this study at the University of Bremen, Germany, by April Kelly (Kelly, 2017). The data collection will be divided into two main parts; 1. Particle size analysis and 2. Geochemical analysis, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and X-Ray Fluorescence (XRF) scanning.

The initial 47 samples for Site M0065 were selected to capture the top, middle, and bottom sections of Hole M0065B by Dr. Sandra Passchier of Montclair State University. A second set of 23 samples were selected from M0065B to enhance the resolution of prominent features within Cores 5H, 7H, 12H, and 13H.

A full list of samples and methods used from Hole M0065B can be found in Table 1 and core sections scanned using XRF can be found in Table 2.

3.1 Particle Size Analysis

3.1.1 Laser Particle Size Analysis

Particle size analysis was performed on 67 core samples from M0065B using Montclair State University’s Malvern Mastersizer 2000. Sample preparation and instrumentation setup followed the procedures outlined in Sperazza et al. (2004). Changes in depositional environment was determined from the particle size data obtained from the M0065B samples. Each sample was prepared in the lab to disaggregate the sample before running the sample through the laser particle sizer. This was performed to ensure that no grains were stuck together. A small amount of sample was taken from each core sample section, placed in a glass beaker, and 50mL of Millipore water was added. The addition of Millipore water and using a soft rubber tipped glass stirrer was
used to softly manually disaggregate each sample. Samples that did not disaggregate completely were placed in a sonic bath for two minutes. After disaggregation, a small amount (small scoop) of sodium pyrophosphate was added to each sample and was brought to a boil on a hot plate. Each sample was left to cool for approximately 30 minutes before analyzing the sample with the laser particle sizer.

The Mastersizer 2000 laser diffractometer with Hydro 2000MU pump accessory using two light sources, a red He-Ne laser and a blue LED, measures diffracting light off each individual grain by 52 sensors. Grain-size distribution as volume percent is reported by the utilization of Mie theory, converting the scatter of light energy to grain size (Sperazza et al., 2004). Grain size distribution is recorded from 0.02 µm to 2000 µm and the Mastersizer 2000 takes three measurements of each population of grains to produce an average. Each sample was analyzed using a “marine sediment” protocol that uses a refractive index of 1.6 (illite) and an absorption coefficient of 0.9. The dispersion rotary pump speed was set to 2000 rpm, due to our samples being very fine-grained sediments. If the laser obscuration for each sample was lower than 8% or greater than 40%, then that sample was re-prepared and re-analyzed to reduce the possibility of artifacts.

3.2 Geochemical Analysis

Major and trace element abundances within each sample were analyzed using Montclair State University’s Thermo Scientific iCap Q Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and MARUM – University of Bremen’s Avaatech X-ray Fluorescence (XRF) Core Scanner III (super slit).

3.2.1 ICP-MS

Twenty samples from M0065B were prepared for ICP-MS analysis (Table 1). Each sample was crushed using a mortar and pestle using between 0.0995 – 0.1005 grams and mixed with
0.3980 – 0.4020 grams of lithium metaborate flux, following Murray et al. (2000). The prepared sample and flux mixture were poured into a graphite crucible and placed in a 1050° furnace for 30 minutes to produce a molten sample bead. At 25 minutes the crucible was temporarily removed from the furnace and swirled in a circular motion to produce a molten bead and capture any powder on the side walls of the crucible. Once the bead was formed the crucible was reinserted into the furnace for the remaining 5 minutes. After 30 minutes the crucible with the molten bead was removed and poured into a Teflon beaker with 50mL of 7% nitric acid (HNO₃) solution and a stir rod for dissolution. Each beaker was then placed on a magnetic stirring plate until all of the remaining sample was completely dissolved. Once dissolution was complete, each sample was filtered through Whatman 540 filter paper into a Nalgene bottle.

The 500x sample solution was diluted to 10,000x to prepare samples for ICP-MS analysis. 0.5mL of the 500x solution and 9.5 mL of 2% nitric acid was pipetted into test tubes. These test tubes contained the final sample to be analyzed by the ICP-MS. During each step mass was recorded and a new pipette was used for each sample to avoid cross contamination between samples.

ICP-MS was used to determine major (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and P) and select trace and rare earth elements (REE) (Sc, V, Cr, Co, Ni, Ga, Rb, Sr, Y, Zr, Nb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Pb, Th, and U). USGS rock standards (DNC-1, BHVO-2, W-2, AGV-2, MAG-1, SCO-1, BIR-1, GSP-2, G-2, BCR-2, QLO-1, RGM-1, Ba 1ppb, Ce 1ppb, Pr 1ppb, Nd 1ppb, and Sm 1ppb) were prepared along with M0065B.

### 3.2.2 XRF Scanning

XRF scanning of M0065A Core Sections 21H-1 through 12H-CC (35.63 – 39.1 MCD) (Table 2) took place at the MARUM-University of Bremen, Germany by Montclair State University.
Earth and Environmental Masters’ student April L. Kelly who was concurrently researching sediment cores from Expedition 347 Site M0064.

The methods and sample preparation followed the procedures outlined in Bahr et al. (2014) using the Avaatech XRF Core Scanner III. Major and trace element concentrations were collected every 1 cm down-core with a down-core slit size of 10 by 12 mm using a 10 kV (Mg, Al, Si, P, S, Cl, K, Ca, Ti, Cr, Mn, Fe, and Rh), 30 kV (Ni, Cu, Zn, Ga, Br, Rb, Sr, Zr, Nb, Mo, Ru, Rh, Pb, and Bi) and 50 kV (Br, Rb, Sr, Zr, Mo, Ag, Cd, Sn, Te, Ba, and Pb) generator setting (Kelly, 2017). Raw data files were received and processed within spreadsheets for the purpose of this study.

Elemental normalization was performed to correct for sensor sensitive variations from porosity and density. Since XRF scanning measures element intensities on a volumetric basis, layers containing coarse-grained material can cause problems because of higher porosity and bad surface contact of the scanner. Element intensities were derived from area counts normalized by dividing each elemental area count by the total area counts.
4. RESULTS

4.1 Particle Size Analysis – M0065B

The original data of the 44 samples collected by S. Passchier is published in Kelly and Passchier (2018). The additional 23 samples collected and analyzed in this study were chosen to enhance our resolution of the top part of Unit IIIc, Unit IIIb, and the transition from Unit IIIa to Unit II. In this chapter the new particle grain-size results from the 23 samples are presented together with the existing data from Kelly and Passchier (2018).

M0065B grain size distributions of all 67 samples, plotted on a sand-silt-clay ternary diagram (Figure 6), show that sediments deposited were mostly silt with some sand and mud but also sandy silt and mud sediments.

Unit I, 3 – 9.63 mbsf, particle size analysis from six samples, is composed of poorly sorted very fine sandy coarse silt sediment. The majority of the samples are characterized as sandy silt sediment with one sample characterized as silt sediment (Figure 7). Over 65% of the cumulative mass is composed of silt sediment with the remaining 35% that of sand. Individual particle size distribution curves from the six samples resulted in unimodal distributions with peaks between the medium silt and coarse silt fraction (16 um and 31 um) (Figure 8).

Unit II, 9.63 – 13.85 mbsf, particle size analysis for six samples, is composed of silt sediments with one sample characterized as sandy silt sediment (Figure 9), with over 90% of the samples composed of medium silt. Individual grain size distribution curves from the six samples resulted in poorly sorted unimodal distributions with peaks between the very fine silt and medium silt fraction (4 um and 16 um) (Figure 10).

Unit IIIa, 13.85 – 36.10 mbsf, particle size analysis for 31 samples, is composed of silt and mud sediments (Figure 11), with over 90% of the samples composed of very fine silt. Individual
grain size distribution curves from the 31 samples resulted in poorly sorted unimodal distribution curves with peaks between the very fine clay to fine silt fraction (1 um and 8um) (Figure 12).

Unit IIIb, 36.10 – 36.80 mbsf, particle size analysis for five samples, is composed of silt sediments (Figure 13), with over 80% of the samples composed of fine silt. Individual grain size distribution curves from the 5 samples resulted in poorly sorted unimodal distribution curves with peaks in the fine silt fraction (4 um and 8 um) (Figure 14).

Unit IIIc, 36.80 – 40.20 mbsf, particle size analysis for nine samples, is composed primarily of silt and sandy silt sediments with a few samples characterized as mud, sandy mud, and silty sand (Figure 17). With over 80% of the samples composed of fine silt. Individual grain size distribution curves from the nine samples resulted in six of the nine samples being poorly sorted unimodal distribution curves with peaks between the clay and medium silt fractions (1 um and 16 um) (Figure 18). Two samples had very poorly sorted bimodal distribution curves with major peaks between the fine silt and medium silt fraction and minor peaks at the fine sand fraction, and one poorly sorted unimodal sample with a peak at the fine sand fraction (125 um).

Unit IIIc, 40.20 – 49.10 mbsf, particle size analysis for ten samples, is composed primarily of sandy silt sediments with a few samples characterized as silt and silty sand (Figure 19). Individual grain size distribution curves from the ten samples resulted in poorly sorted unimodal distribution curves with nine of the ten samples with peaks between the fine silt and fine sand fractions (8 um and 125 um) and one sample with a peak at the medium sand fraction (250 um) (Figure 20).

Percent sand, silt, and clay particle size data from all 67 samples analyzed plotted downcore (Figure 21) indicate abrupt changes in particle size at Unit boundaries. The top section of Unit IIIc at 38.51 mbsf switches from being sand and silt dominated to silt and clay dominated, which continues upward until Unit IIIb, with another change to being silt dominated. Unit IIIb, at 36.71
mbsf, changes from silt to clay and back to silt again at the boundary of Unit IIIa. The boundary between Unit IIIb and Unit IIIa is clay dominated lithology until just below, 15.2 mbsf, the lower boundary of Unit II where silt and clay narrow the range between and oscillate from silt to clay and vice versa and continue up core until 11.2 mbsf where clay decreases, and silt increases dramatically. This trend continues up core to the boundary of Unit I with a further decrease of clay and an increase of sand, while silt remaining in abundance.

4.2 Geochemical Results

4.2.1 M0065B ICP-MS

The data was collected and used from all 20 samples to determine the ratios of Mn/Al, Al/Ti, and Zr/Al from each sample and plotted downcore (Figure 22). Mn/Al ratios were used to determine if any changes occurred in the bottom-water oxygenation status during sediment deposition (Calvert and Pedersen, 1993). Al/Ti ratios were used to determine if any change in provenance occurred of sediments that were deposited (Young and Nesbitt, 1998). Zr/Al ratios were used to determine changes in bottom water or glacial meltwater current strength (Bahr et al, 2014). Interstitial pore water geochemistry, total organic carbon (TOC) in wt. % collected shipboard during the expedition (Andrén et al., 2015) was also brought in and compared to the ICP-MS samples analyzed at Montclair State University from M0065B (Figure 22).

The raw ICP-MS data from the samples analyzed were normalized to 100% total weight oxide percent and converted from weight oxide percent to weight element percent using the conversion table from Murray et al., 2000 (Table 3). To account for any grain size bias with the geochemistry and the detrital fraction within the samples each element was normalized with Aluminum (McLennan et al., 1993).

Al/Ti ratios throughout the entire core range from 22.2 to 15.7. Within Unit IIIc the six samples range from 22.2 to 16.6 and have an average of 19.7. The lowest value within this
section of 16.9 is located at the top of the section at 37.18 MCD. The Al/Ti ratios for three
samples from Unit IIIb range from 19.1 to 17.6 and have an average of 18.2. The nine samples
from Unit IIIa range from 20.8 to 16.3 with an average of 18.7. The two samples from the top of
the core at the base of Unit II ranges from 17.5 to 15.8 with an average of 16.6.

Mn/Al ratios throughout the entire core stayed relatively constant ranging from 2.408 to 0.613
with only two data points > 1.0 located within the top of Unit IIIa at 14.98 MCD with 1.089 and
the bottom of Unit II at 12.985 MCD with 2.408. Unit IIIc samples ranged from 0.697 to 0.844
with an average of 0.775 and Unit IIIb samples ranged from 0.716 to 0.812 with an average of
0.770. Unit IIIa samples ranged from 0.6137 to 1.090 with an average of 0.717. The two samples
within Unit II range from 0.947 to 2.408 and average 1.677.

Zr/Al ratios throughout the entire core range from 0.038 to 0.0016. Unit IIIc samples ranges
from 0.0038 to 0.0017 with an average of 0.0023. Within Unit IIIb and Unit IIIa the Zr/Al ratios
decreased as a whole relative to Unit IIIc and Unit II. Unit IIIb samples range from 0.0019 to
0.0023 with an average of 0.00205 and Unit IIIa samples ranged from 0.0016 to 0.0032 with an
average of 0.00203. Both samples from Unit II had the same Zr/Al ratio of 0.0022.

4.2.2 M0065A XRF Core Scanning Results

A total of 3.5 meters of core was scanned from Sections 65A-12H-1 to 65A-12H-4 (35.63 –
39.13 MCD), covering the lower part of Unit IIIa, IIIb, and top part of IIIc. This section will also
compare the results from the 65B-12H-1 to 65B-12H-3 ICP-MS samples to the corresponding
XRF results.

The overview of the XRF data within this section and following will be referring to the
normalized XRF area counts instead of the raw, unnormalized area counts. Some normalized
element counts were exaggerated by 100 or 1000 times for purposes of comparison to other
elements.
To test the normalization of the XRF data collected, raw and normalized Ca and Fe intensities were plotted against each other (Figure 24). Due to Ca and Fe connection to different main sediment phases in hemipelagic sediment, biogenic carbonate and terrigenous silt and clay, Ca and Fe usually anticorrelate (Bahr et al., 2014). For the most part, the XRF raw intensities for Ca and Fe anticorrelate but after normalization a stronger anticorrelation can be seen. Fe throughout the entire scanned sections stayed relatively within the same range but with some minor trends. Unit IIIc doesn’t exhibit any discernable trends while Unit IIIb and IIIa show increasing trends with sharp decreasing rebounds followed by increasing trends. Ca follows the same trends as Fe but inverse as mentioned earlier within this section.

Mn counts stay relatively the same throughout Units IIIa, IIIb, and IIIc, averaging 1.71, with a spike within Unit IIIc, between 37.46 – 37.50 MCD, to 4.89 (Figure 23). S counts within Unit IIIc stay relatively the same ranging from 0.34 to 2.19. Unit IIIb experienced a relative increase ranging from 1.82 to 4.71, averaging 2.74, with a decreasing trend from the bottom of the section to the top. Unit IIIa experienced a narrower range in counts, 0.58 to 2.12, similar to Unit IIIc but continues the decreasing trend starting within Unit IIIb with a rebound spike at 35.91 MCD (Figure 23).

Zr/Al ratios in Unit IIIc range from 0.48 to 5.32 with an average across the section of 1.33. Oscillating peaks and troughs are present throughout the entire section with two major peaks occurring at 38.32 and 38.27 MCD and a noticeable dip occurring at 38.13 MCD. These oscillating peaks and troughs coincide with the glacial varves present within the section. Unit IIIb experiences a change in signal type with the signal increasing to 2.10 at the bottom of the section (38.06 MCD) and fluctuates from 2.10 to 1.66 until 37.18 MCD. This part of section IIIb experiences an upward increase in the silt concentration and a decrease in the clay concentration. From 37.02 to 36.72 MCD the signal decreases sharply to 1.26 (37.02 MCD) and fluctuates from 1.16 to 1.51 until 36.72 MCD. This relative decrease in intensity coincides with a shift in grain
size of majority clay within silt. Unit IIIa ranges from 0.91 to 1.75 with an average across the section of 1.23. The beginning of the section (36.67 to 36.51 MCD) fluctuates between 0.98 to 1.75 showing an oscillating pattern of peaks and troughs. At 36.49 MCD a relatively linear downward trend continues until 35.92 MCD with a starting signal strength of 1.49 and ending with 0.95 respectively. This downward trend ends with a sharp signal increase to 1.43 (35.90 MCD) and relatively continuing to 35.81 MCD. The ICP-MS data points within these sections can be matched with the XRF data with the exception of one data point at 37.07 MCD (Figure 27).

Mn/Al ratios in Unit IIIc display in similar results as Zr/Al ratios, as mentioned above. Unit IIIc range from 0.16 to 0.61 with an average across the section of 0.22. A major spike occurs at 37.49 MCD with in intensity of 0.61. This spike corresponds to a thicker than average glacial varve sequence within the section. Unit IIIb ranges from 0.18 to 0.26 with an average of 0.22 showing a potential weak oscillating pattern with peaks and troughs. Unit IIIa ranges from 0.14 to 0.26 with an average of 0.19 and displays a similar trend as Zr/Al ratios once again with a decreasing trend and a rebound at 35.90 The ICP-MS data points within these sections plot relatively the same as the XRF data with the exception of one data point at 37.18 MCD (Figure 26).

Al/Ti ratios (Figure 25) within Unit IIIc display once again similarly as Zr/Al (Figure 27) and Mn/Al (Figure 26) ratios with oscillating peaks and troughs ranging from 0.58 to 0.99 with an average of 0.86. A major spike is present at 38.95 MCD to 0.58, which corresponds with a change in grain size from a sand dominated section to clay. In Unit IIIb the values are relatively lower than Unit IIIc, ranging from 0.68 to 0.85 with an average of 0.79. Another major fall is present at 37.13 MCD to 0.68 corresponding to another major shift in grain size from clay dominated to silt dominated (Figure 25).
A major change in grain size occurs at the beginning of Unit IIIa with another increase in silt and decrease in clay content (Figure 21). This bottom most section of Unit IIIa, 36.67 – 36.50 MCD, corresponds to this change in grain size with an increase in Al/Ti ratios ranging from 0.74 to 0.2. At 36.50 MCD the ratios drop to 0.74 and proceed in a step-up trend to 0.90 until 35.92 MCD where a color transition occurs, from reddish to grayish sediment, and ratios drop to 0.74. The ICP-MS data points within these sections plot relatively the same as the XRF data (Figure 25).

Rb/Sr ratios within Unit IIIc display the same oscillating peaks and troughs (Figure 28) as Zr/Al (Figure 27), Mn/Al (Figure 26), and Al/Ti (Figure 25) and within Unit IIIb and Unit IIIc further trends, similar to Al/Ti ratios (Figure 25), continue to occur, as previously mentioned. Br/Al ratios within Unit IIIc show minor oscillating trends with major peaks at 38.32, 38.27, and 38.13 MCD (Figure 29) similar to Al/Ti. Within Unit IIIb an overall average increase occurs with a major peak at 36.81 MCD. The Br/Al ratios across the Unit IIIb and Unit IIIa transition show a decreasing trend to ~36.14 MCD where the decreasing trend ceases and another major peak occurs at 36.02 MCD.

4.3 M0065 Varve Counting

Varve counting on high-resolution imagery of core sections was performed by four graduate students at Montclair State University as part of a glacial deposits class. Glacial marine varves record annual and, in some cases, sub-annual resolution of glacial events. Varves can be used to determine rates of terrestrial ice recession and timing of glacial readvances, as well as non-climatic events. During the summer months, meltwater fluxes and more turbid waters would bring sands and silts while the winter months, where ice might have frozen over the BIL, would only allow for clay particles to be deposited (Ridge et al., 2012). This oscillation of sediments deposited at site M0065B are visible within Unit IIIc.
Varve counting (Table 4) for core M0065A-12H-2 through M0065A-12H-4 (37.27 - 38.6 mbsf) resulted with an average varve couplet count of 35.5 sequences. Varve counting (Table 4) for core M0065B-12H-1 through M0065B-12H-2 (36.8 - 38.5 mbsf) resulted with an average count of 32 sequences. Varve couplets from cores M0065A-13H and M0065B-12H-3 through M0065B-13H-2 could not be visually distinguished through the majority of these sections due to the sediment being moderately disturbed.

Rb/Sr ratios from core M0065A-12H-2 through M0065A-12H-4 (37.27 – 39.13 MCD) were used as a proxy to determine varve couplets (Figure 28). Approximately 27 varve couplets were identified within these sections resulting in an average sedimentation rate of approximately 7.04 cm/yr of ice distal sedimentation. Minor or less prominent ratio couplets were considered sub-annual oscillations and were not counted.
5. Discussion

5.1 Glaciolacustrine to Deep Lacustrine Transition

The sedimentary sequence within the Unit IIIc represents a transition from a proximal to distal glaciolacustrine depositional environment represented with annual varve sequences. The lower, thicker, ice proximal varves contain higher sand and silt content while the top section, thinner distal varves, contains mostly silts and clays. This sedimentary sequence represents the retreat of the SIS with the upward transition of higher sand concentrations to more silt and clay dominated (Ridge et al., 2012). Rb is preferentially retained in clay minerals during weathering compared to Sr (McLennan et al., 1993, p. 24), so higher Rb/Sr values are indicative of higher clay content of winter laminae in varve couplets. Using the Rb/Sr ratios from Unit IIIc as a proxy to determine varve couplets (Figure 28), approximately 27 ice distal varve couplets were identified within the sections and further resulting in a sedimentation rate during this time period of 7.04 cm/yr.

Extrapolating downcore to M0065A-13H-2 (40.52 MCD), the base of the clay/silt varve sequences, assuming the same sedimentation rate would result in a maximum of approximately 23 years of ice proximal sedimentation below the interval with 27 couplets. With this extrapolation and ignoring the possible increase in sedimentation, would mean that the Bornholm Basin was influenced directly by proximal and distal glacial meltwater for approximately 50 years.

The Zr/Al ratios from the XRF and ICP-MS data across the transition from distal glacial varves, Unit IIIc, to the gray layer of Unit IIIb is marked by an overall average increase to 0.51007 that can be seen in Figure 27. This increase while only in the lower 0.25 meters of the section would suggest an increase in depositional energy, like a meltwater discharge allowing for the transportation of zirconium-bearing minerals. Following this increase within Unit IIIb, at 37.02 MCD the average Zr/Al ratios decrease to 0.29291 suggesting a decrease in depositional
energy, continuing through the gray to brown (Unit IIIa) color transition, limiting the transportation energy needed to deposit zirconium-bearing minerals within Bornholm Basin.

This increase in depositional energy can be supported based on the particle size data within Unit IIIb. The Zr/Al ratios seen within Unit IIIb corresponds to the grain size sediment fraction characteristics following the transition to from the varves within Unit IIIc to the gray layer in Unit IIIb (Figure 27). The lower ~0.25 meters of the section demonstrate an increase in the silt size sediment fraction along with a decrease in the clay size sediment fraction followed by a switch around 37.02 MCD with the lowering of the silt size fraction and an increase in the clay size fraction.

A counter argument to the Zr/Al ratios indicating an increase in depositional energy following the glacial varves in Unit IIIc could be a result from merely an increase in grain size alone due to shoreline regression. Zirconium-bearing minerals, such as zircon and monazite are transported in a variety of ways, including within the coarser terrigenous fraction, with the medium to coarse size silt fraction, with other heavy minerals, and with fine-medium size quartz grains making Zr more readily available for transport and deposition. Zircon, like quartz, is highly chemically and physically resistant to weathering, making it easily recycled and retained in soils. This could explain the increase in Zr present within this section of Unit IIIb and corresponds to the timing of the first drainage of the BIL at 12.9 ka BP (Kelly and Passchier, 2018, Muschitiello et al., 2016). This lake drainage of glacially derived freshwater into the Atlantic through a spillway near Mount Billingen dropped the BIL levels 10 – 25 m which caused the shoreline to move basinward and previously deposited sediments along the lake floor to become exposed to surface runoff. Massive amounts of former lake floor were being reworked and resuspended and deposited below what was now the new lake level and a shallower Bornholm Basin (Kelly and Passchier, 2018).
This reworking of sediment deposited within Unit IIIb can also be supported with the dramatic spike in the sulfur content and the increase in Br/Al ratios at the transition of Unit IIIc and Unit IIIb. Bromine has been used in many studies due to the fact it preserves the most pristine climate signatures representing marine organic content (Ziegler et al., 2008) and because bromine is independent of grain size changes and current-related processes (Bahr et al., 2014).

Using Br/Al ratios and sulfur as a proxy for organic content, Br/Al ratios within Unit IIIb shows an overall increased average compared to Unit IIIc with a spike of 0.0909 at 37.28 MCD to 0.1179 at 37.27 MCD at the unit boundaries (Figure 29). This increased average in Unit IIIb continues through the silt rich, lower section of Unit IIIb, upward to the clay rich section of Unit IIIb. Sulfur over this same transition spikes to a dramatic high from 0.7817 at 37.30 MCD to 4.7076 at 37.20 MCD and steadily decreases from the bottom of Unit IIIb, through the gray and brown clay unit boundary (36.67 MCD), to ~ 36.42 MCD where it returns to comparable levels from below within Unit IIIc.

Along the transition from the glacially derived varves (Unit IIIc) to the deep lacustrine transition (Unit IIIb and lower Unit IIIa), Mn/Al XRF and ICP-MS ratios indicate minor fluctuations throughout the entire transition (Figure 26) with an average of 0.2170, 0.2222, and 0.1934 respectively. This most likely indicates no significant redox change within the water column during sedimentation. An exception does occur within Unit IIIc with a dramatically large peak of 0.6124 at 37.49 MCD compared to the average within the section of 0.2170. This peak corresponds at the point where a thicker varve is located. This peak is from the bottom waters being more oxic and for an oxidizing environment and allowing manganese to become highly insoluble (Calvert and Pendersen, 2007, Calvert and Pendersen, 1993).

At 14.96 MCD, the top of Unit IIIa, the Mn/Al ICP-MS data would suggest a potential marine incursion spikes to 1.08 and continues an overall increase to 2.407 at 12.96 MCD in the bottom of
Unit II (Figure 22), would suggest the start of the brackish phase of the YS at 10.5 ka BP where a saline ingression occurred north of Mt. Billingen (Andrén et al., 2015).

Al/Ti XRF and ICP-MS ratios across the color transition from Unit IIIc to the bottom of Unit IIIa does indicate a relative change in values that could support a provenance change within the sediment supply during this period of time (Figure 25). Unit IIIc, while the range of values are wide, contains an average of 19.6929 for ICP-MS and 0.8629 for XRF. Unit IIIb with a narrower range, contains an average of 18.291 for ICP-MS and 0.7957 for XRF, indicates an overall decrease in values and a potential change in provenance. Unit IIIa exhibits the widest of ranges of values with an increase in the amplitude of each maximum peak and trough and contains an average of 0.7780 for XRF.

The wide range of values within Unit IIIc can be explained by the individual varve couplets that alternate from silts and clays distinguishing seasonality changes. The lower values, meaning an increase in Ti content, corresponds to the clay layers within the varves and could be due to the grain-size effect of Ti (Young and Nesbitt, 1998). Ti in mafic minerals tends to preferentially break down within glaciers and separate during fluvial transport, thus causing coarser grain material being depleted of Ti (Young and Nesbitt, 1998). The major dip at 37.13 MCD in Unit IIIb to 0.6798 and at 36.62 MCD in Unit IIIa to 0.7338 (Figure 25) also confirms the grain-size effect on Ti from the particle size data (Figure 21) with a spike in the clay concentrations indicating these increases in Ti counts are grain-size dependent and not provenance changes.

The transition from the distal to proximal glacially derived varves followed by the dramatic color change of the BIL drainage event can be distinctively identified based on grain-size analysis and geochemical evidence (Figure 21, Figure 27, and Figure 29). Zr/Al ratios indicate a potential meltwater pulse or bottom water velocity increase at the bottom of the dark gray layer along with a dramatic spike in sulfur and a relative increase in Br/Al ratios indicating evidence
for the BIL drainage event and the reworking of previously deposited, newly exposed shoreline, now being re-deposited within Bornholm Basin. The grain size analysis at the bottom of the gray layer also supports this with the presence of a silt to clay depositional pattern.

The transition from the bottom of the BIL drainage (Unit IIIb) to the freshwater phase of the YS (Unit IIIa) cannot be distinctively determined based on this data set. Zr/Al ratio do not indicate any melt water or bottom water velocity changes. Mn/Al ratios do not indicate any bottom water oxidation changes and Al/Ti ratios do not indicate a significant provenance change. While shipboard sediment TOC data (Figure 21) (Andrén et al., 2015) does spike dramatically at one point (22.84 MCD) relative to the entire core there is no other data to conclusively say that this would be the transition from the BIL drainage event to the Preboreal warming freshwater phase of the YS.

The transition (13.56 MCD) from the brown layer of Unit IIIa to the gray layer of Unit II (the freshwater phase to the brackish phase of the YS at 10.5 ka BP) is distinguished by multiple approaches, from grain-size analysis to the geochemical changes (Figure 22). The Zr/Al and Mn/Al ICP-MS ratios indicates large dramatic spikes which means a meltwater pulse or bottom water velocity increase and an increase in the bottom water oxidation change relatively along this transition (Figure 22). Al/Ti ICP-MS ratios do not indicate a provenance change at all along with no significant shipboard sediment TOC (Andrén et al., 2015) concentration change either. A dramatic change in grain-size is present shifting from clay-dominated distributions to silt dominated and continuing up-core at a relative even distribution. Sample preparation for the particle grain-size samples from Hole M0065B were not processed to remove or eliminate diatom biogenic silica potentially within each sample. This dramatic change in grain-size characteristics can be explained by the presence of diatoms that, based on shipboard data from Hole M0065A (Andrén et al., 2015), are present above ~12 mbsf (Figure 30). The presence of freshwater and
brackish-freshwater taxa at this transition between Unit IIIa and Unit II also confirm that a saline incursion could have occurred at 10.5 ka BP, north of Mt. Billingen (Andrén et al., 2015).
6. Conclusion

Varve counting within Unit IIIc, augmented by interpretations of Rb/Sr ratios in XRF data (Figure 28) show that Bornholm Basin was influenced by distal glacial meltwater for a relatively short period before the first drainage of the BIL at 12.9 ka BP and the transition of Bornholm Basin from a glaciolacustrine to a deep lacustrine depositional environment. The lower boundary of Unit IIIb, deposited during the early phase of BIL drainage is characterized by an increase in silt and organic material concentrations with an increase in Zr/Al ratios, indicating an increase in meltwater discharge, and Mn/Al and Al/Ti ratios, indicating no provenance or bottom water oxidation changes, which means massive reworking of previously deposited sediments on newly exposed shorelines around Bornholm Basin. The upward transition to Unit II, interpreted as the onset of the freshwater stage of the Yoldia Sea, is characterized by spikes in Zr/Al and Mn/Al ratios and an increase in silt concentrations that can be explained by the presence of siliceous brackish-marine diatoms, which would mean this color change represents the brackish phase of the of the Yoldia Sea (10.5 ka BP) that lasted ~300 years before returning to a freshwater basin once again.

The deglaciation of the Baltic Sea is marked by a complex and dynamic glacial history seen within Bornholm Basin from 16 – 10 ka BP. The rapid deglaciation of the SIS led to meltwater pulses depositing large fluxes of sediments, isostatic rebound in the Baltic area, and the release of large amounts of freshwater into the Atlantic Ocean and inversely marine saline water into the BSB. These events within the Baltic Sea had global effects like potentially slowing down or weakening the AMOC from prolonged events of freshwater release and continue to strengthen our understanding of the vital link the Baltic Sea has with the world (Andrén et al., 2015, Andrén et al., 2011, Clark et al., 2012, Toucanne et al., 2015).
7. References


Kelly, A. L. (2017). Determining late Pleistocene to Early Holocene deglaciation of the Baltic Ice Lake through sedimentological and geochemical analysis of IODP Site M0064


Table 1. M0065B sample and method distribution list. Shaded and marked boxes indicate which analysis performed. Samples marked with an A indicate the additional samples analyzed that were not reported in Kelly and Passchier, 2018.

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Table 1 Cont. M0065B sample and method distribution list. Shaded and marked boxes indicate which analysis were performed. Samples marked with an A indicate the additional samples analyzed that were not reported in Kelly and Passchier, 2018.

<table>
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<tr>
<th>IODP Expedition 347 Sample Name</th>
<th>Depth (mbsf)</th>
<th>Depth (MCD)</th>
<th>Unit</th>
<th>Add. Samples</th>
<th>Particle Size</th>
<th>ICP-MS</th>
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<td></td>
</tr>
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<td>27.74</td>
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<td></td>
<td></td>
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<td>37.67</td>
<td>IIic</td>
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Table 2. List of core sections scanned using XRF by April L. Kelly in 2017.

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<th>Depth Interval (mbfs)</th>
<th>Depth Interval (MCD)</th>
<th>Unit</th>
<th>XRF Scanned</th>
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<td>M0065A-12H-1</td>
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<td>35.63 - 36.67</td>
<td>IIIa</td>
<td>X</td>
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<td>M0065A-12H-1</td>
<td>36.05 - 36.49</td>
<td>36.67 - 37.11</td>
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<td>X</td>
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<td>36.51 - 36.65</td>
<td>37.13 - 37.27</td>
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<tr>
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<td>37.27 - 38.61</td>
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<td>38.63 -38.95</td>
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<td>M0065A-12H-CC</td>
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<td>39.96 - 39.1</td>
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Table 3. Conversion table for oxide to elemental concentrations (Murray et al., 2000).

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<tr>
<td>Al₂O₃</td>
<td>0.5293</td>
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<tr>
<td>Fe₂O₃</td>
<td>0.6994</td>
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<tr>
<td>MnO</td>
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<tr>
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<tr>
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<tr>
<td>P₂O₅</td>
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Table 4. Individual and average varve counts performed on core sections from M0065A and M0065B by graduate students at Montclair State University.

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<th>IODP Expedition 347 Core Section</th>
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<th>Count Average</th>
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Table 5. Major grain size boundaries notations with corresponding grain size classification derived using the Wentworth Scale.

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<th>Diameter (µm)</th>
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<td>D 2000</td>
<td>very fine granules (pebbles)</td>
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<tr>
<td>D 1000</td>
<td>very coarse sand</td>
</tr>
<tr>
<td>D 500</td>
<td>coarse sand</td>
</tr>
<tr>
<td>D 250</td>
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<tr>
<td>D 125</td>
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<td>D 62</td>
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<td>D 31</td>
<td>coarse silt</td>
</tr>
<tr>
<td>D 16</td>
<td>medium silt</td>
</tr>
<tr>
<td>D 8</td>
<td>fine silt</td>
</tr>
<tr>
<td>D 4</td>
<td>very fine silt</td>
</tr>
<tr>
<td>D 1</td>
<td>very fine clay</td>
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</table>
Figure 1. IODP Expedition 347 site location map of the Baltic Sea (Andrén et al., 2015). Site M0065 highlighted with red and Bornholm Island annotated with yellow.
Figure 2. Paleogeographic maps showing the Baltic Sea stages and glacial ice presence with Site M0065 annotated in red. Top Left map showing the Baltic Ice Lake (BIL) just before the final drainage at ~11.7 ka BP. Top right showing the Yoldia Sea (YS) at the end of the brackish phase at ~11.1 ka BP. Bottom left map showing the Ancylus Lake (AL) at maximum transgression at ~10.5 ka BP. Bottom Right map showing the Littorina Sea (LS) at ~6.5 ka BP. (Andren et al., 2014)
Figure 3. Graphic lithological log of Site M0065 (Andrén et al., 2015).
**Figure 4.** Seismic profile of Site M0065 indicating lithostratigraphic boundaries with multisensor core logger magnetic susceptibility data (Andrén et al., 2015).
Figure 5. Images of lithostratigraphic Units from Hole M0065. A. Unit I. B. Unit Ia. C. Unit II. D. Unit IIIa. E. Unit IIIb. F. Unit IIIc. (Andrén et al., 2015)
Figure 6. Ternary sand:silt:clay diagram produced using GRADISTAT software showing all 67 core samples analyzed using laser particle size from Hole M0065B. Plots below the line represent samples with 0% sand.
Figure 7. Unit I ternary sand:silt:clay diagram produced using GRADISTAT software showing all 7 core samples analyzed using laser particle size from Hole M0065B.
Figure 8. Unit I grain size distribution (µm) with volume percent. Major grain size boundaries are marked by vertical colored lines with corresponding diameter values (exp. D1). Diameter value classifications are listed in Table 5.
Figure 9. Unit II ternary sand:silt:clay diagram produced using GRADISTAT software showing all 5 core samples analyzed using laser particle size from Hole M0065B. Plots below the line represent samples with 0% sand.
Figure 10. Unit II grain size distribution (µm) with volume percent. Major grain size boundaries are marked by vertical colored lines with corresponding diameter values (exp. D1). Diameter value classifications are listed in Table 5.
Figure 11. Unit IIIa ternary sand:silt:clay diagram produced using GRADISTAT software showing all 31 core samples analyzed using laser particle size from Hole M0065B. Plots below the line represent samples with 0% sand.
Figure 12. Unit IIIa grain size distribution (µm) with volume percent. Major grain size boundaries are marked by vertical colored lines with corresponding diameter values (exp. D1). Diameter value classifications are listed in Table 5.
Figure 13. Unit IIIb ternary sand:silt:clay diagram produced using GRADISTAT software showing all 5 core samples analyzed using laser particle size from Hole M0065B. Plots below the line represent samples with 0% sand.
Figure 14. Unit IIIb grain size distribution (µm) with volume percent. Major grain size boundaries are marked by vertical colored lines with corresponding diameter values (exp. D1). Diameter value classifications are listed in Table 5.
Figure 15. Unit IIIc ternary sand:silt:clay diagram produced using GRADISTAT software showing all 19 core samples analyzed using laser particle size from Hole M0065B. Plots below the line represent samples with 0% sand.
Figure 16. Unit IIIc grain size distribution (µm) with volume percent. Major grain size boundaries are marked by vertical colored lines with corresponding diameter values (exp. D1). Diameter value classifications are listed in Table 5.
Figure 17. Unit IIIc (12H-1 through 12H-3) ternary sand:silt:clay diagram produced using GRADISTAT software showing coresamples analyzed using laser particle size from Hole M0065B. Plots below the line represent samples with 0% sand.
Figure 18. Unit IIIc (12H-1 through 12H-3) grain size distribution (µm) with volume percent. Major grain size boundaries are marked by vertical colored lines with corresponding diameter values (exp. D1). Diameter value classifications are listed in Table 5.
Figure 19. Unit IIIc (13H through 17H) ternary sand:silt:clay diagram produced using GRADISTAT software showing core samples analyzed using laser particle size from Hole M0065B.
Figure 20. Unit IIIc (13H through 17H) grain size distribution (μm) with volume percent. Major grain size boundaries are marked by vertical colored lines with corresponding diameter values (exp. D1). Diameter value classifications are listed in Table 5.
Figure 21. Percentage sand (blue), silt (yellow), and clay (red) analyzed using laser particle sizer plotted downcore (mbsf).
Figure 22. M0065B sand, silt, and clay particle size data (%) and ICP-MS Al/Ti, Mn/Al, and Zr/Al ratios plotted downcore (MCD). M0065B shipboard sediment TOC (wt. %) data plotted taken from shipboard data. Dashed blue lines indicate Unit boundaries.
**Figure 23.** Fe, S, Mn elemental XRF counts plotted downcore (35.63 – 39.14 MCD) across sections 12H-I through 12H-CC from Hole M0065A. Boundaries between Unit IIIc, Unit IIIb, and Unit IIIa are annotated with green lines at 37.27 MCD and 36.67 MCD.
Figure 24. Ca/Fe XRF ratios plotted downcore (35.63 – 39.14 MCD) across sections 12H-1 through 12H-CC from Hole M0065A. Boundaries between Unit IIIc, Unit IIIb, and Unit IIIa are annotated with green lines at 37.27 MCD and 36.67 MCD.
Figure 25. Al/Ti XRF ratios plotted downcore (35.63 – 39.14 MCD) across sections 12H-1 through 12H-CC from Hole M0065A with corresponding ICP-MS data points from Hole M0065B. Boundaries between Unit IIIc, Unit IIIb, and Unit IIIa are annotated with green lines at 37.27 MCD and 36.67 MCD.
Figure 26. Mn/Al XRF ratios plotted downcore (35.63 – 39.14 MCD) across sections 12H-1 through 12H-CC from Hole M0065A with corresponding ICP-MS data points from Hole M0065B. Boundaries between Unit IIIc, Unit IIIb, and Unit IIIa are annotated with green lines at 37.27 MCD and 36.67 MCD.
Figure 27. Zr/Al XRF ratios plotted downcore (35.63 – 39.14 MCD) across sections 12H-1 through 12H-CC from Hole M0065A with corresponding ICP-MS data points from Hole M0065B. Boundaries between Unit IIIc, Unit IIIb, and Unit IIIa are annotated with green lines at 37.27 MCD and 36.67 MCD.
**Figure 28.** Rb/Sr XRF ratios plotted downcore (35.63 – 39.14 MCD) across sections 12H-1 through 12H-CC from Hole M0065A. Boundaries between Unit IIIc, Unit IIIb, and Unit IIIa are annotated with green lines at 37.27 MCD and 36.67 MCD.
Figure 29. Br/Al XRF ratios plotted downcore (35.63 – 39.14 MCD) across sections 12H-1 through 12H-CC from Hole M0065A. Boundaries between Unit IIIc, Unit IIIb, and Unit IIIa are annotated with green lines at 37.27 MCD and 36.67 MCD.
Figure 30. Shipboard analysis of siliceous microfossils present within Hole M0065A. Diatoms are classified based on salinity tolerance which divide the taxa into: marine, brackish-marine, brackish-freshwater, and freshwater (Andrén et al., 2015).