Ascertaining the lithological boundaries of the Yoldia Sea of the Baltic Sea – a geochemical approach

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Dissertations in Geology at Lund University,
Master's thesis, no 417
(45 hp/ECTS credits)

Department of Geology
Lund University
2014

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Reiche, S., 2014: Ascertaining the lithological boundaries of the Yoldia Sea of the Baltic Sea—a geochemical approach. *Dissertations in Geology at Lund University*, No. 417, 22 pp. 45 hp (45 ECTS credits) .

Abstract: When analyzing sedimentary sequences, results which are based solely on macroscopic observations, can lead to misleading and incomplete conclusions. Therefore these observations need to be complemented by analyses on a microscopic or atomic scale, such as through biological, chemical or physical methods. This approach is especially necessary when analyzing marine sedimentary cores from the Baltic Sea. The Baltic Sea development following the deglaciation of Scandinavia has been widely studied and debated and this has concluded in the establishment of four developmental stages: the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake and the Littorina Sea. However not all of these stages have characteristics which make it easy to identify them in sedimentary sequences, especially in the case of the Yoldia Sea. Therefore, the aim of this thesis was to analyze the Yoldia Sea stage and especially its boundaries to the late Baltic Ice Lake and early Ancylus Lake, by using macroscopic observations and geochemical methods, namely X-ray fluorescence and biogenic silica analysis. These analyses were performed on three different cores originating from the Western Gotland Basin, the Eastern Gotland Basin and the Bornholm Basin. In a first step, the sedimentary cores were described, developmental stages were identified and boundaries between Baltic Ice Lake and Yoldia Sea and Yoldia Sea and Ancylus Lake were discerned. These results were then compared to the identification of developmental stages and their boundaries, established by correlating element ratios, calculated from the chemical data retrieved by XRF analysis, and magnetic susceptibility. In a further step, biogenic silica was analyzed. The macroscopic observations led to the identification of the boundaries of Baltic Ice Lake to Yoldia Sea and Yoldia Sea to Ancylus Lake, yet the marine ingression phase giving the Yoldia Sea its name, could not be identified. This stands directly in comparison to the results of the correlation of element ratios, in which the marine ingression phase could be identified confidently, however the boundaries of Baltic Ice Lake to Yoldia Sea and Yoldia Sea to Ancylus Lake only with caution. Additionally, all three cores, originating from different parts of the Baltic Sea basin, had different depositional influences and thus differed considerably. Very low amounts of silica were yielded when performing biogenic silica analysis, which is in accordance with the literature.

Keywords: Baltic Sea, Yoldia Sea, lithological descriptions. X-ray fluorescence, biogenic silica

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Subject: Quaternary Geology

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Fastställande av de litologiska gränserna för Östersjöns Yoldia stadium – en geokemisk undersökning

SOPHIE REICHE

Reiche, S., 2014: Fastställande av de litologiska gränserna för Östersjöns Yoldia stadium – en geokemisk undersökning. Examensarbeten i geologi vid Lunds universitet. Nr. 417, 22 sid. 45hp

Sammanfattning: Vid analys av sedimentära sekvenser där undersökningen enbart är baserad, på makroskopiska/okulära, observationer kan resultatet ibland vara missvisande och ofullständigt. Sådana observationer behöver därför kompletteras med analyser på mikroskopisk eller atomisk skala, till exempel genom biologiska, kemiska eller fysiska metoder. Detta är särskilt relevant när man analyserar sedimentära borrkärnor från Östersjön. Östersjöns utveckling efter deglaciationen är noggrant studerad och diskuterad, vilket har lett fram till att utvecklingen kan delas in fyra utvecklingsstadier: Baltiska issjön, Yoldiahavet, Ancylussjön och Littorinahavet. Vissa av dessa stadier saknar typiska litologiska kännetecken som skulle göra det lättare att identifiera dem i sedimentära sekvenser. Detta gäller särskilt för Östersjöns Yoldia stadium. Syftet med det här examensarbetet var därför att analysera sedimentära sekvenser från Yoldiahavet med särkilt fokus på dess gräns mot den senare delen av Baltiska issjön och inledningen av Ancylussjön. Detta utfördes genom okulär besiktning av borrkärnor i kombination med geokemiska metoder, främst XRF analyser och bestämning av biogent kisel (BioSi). Analyserna utfördes på tre olika borrkärnor från västra Gotlandsbassängen, östra Gotlandsbassängen och Bornholmsbassängen. I et första steg beskrevs litologin i de sedimentära borrkärnorna, utvecklingsstadierna identifierades okulärt och gränser mellan Baltiska issjön och Yoldiahavet samt Yoldiahavet och Ancylussjön identifierades preliminärt. Resultaten av detta jämfördes med XRF analyserna, där främst ett antal grundämneskvoter användes samt tidigare uppmätt magnetisk susceptibilitet. Därefter användes BioSi för identifiering av stadierna och gränserna men inte ens den bräckta fasen av Yoldiahavet, vilket har givit detta stadium dess namn, kunde identifieras. Detta jämföras med resultaten från korrelationen med grundämneskvoterna där brackvattenfasen med säkerhet kunde identifieras, medan gränserna mellan Baltiska issjön och Yoldiahavet och Yoldiahavet och Ancylussjön var mer osäkra.

Det skall dock påpekas att de tre borrkörnorna vilka härstammar fran olika områden av Östersjöbassängen, har haft mycket olika depositionsmijöer. Sedimentsammansättningen skiljer sig således mycket åt, vilket kan förklara en del av de stora skillnaderna som XRF analyserna uppvisar.

Nyckelord: Österjön, Yoldiahavet, litologiska beskrivningar, XRF analyser, analys av biogent kisel

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1 Introduction

1.1 Background and Aim

Geological observations made on a macroscopic scale do not always reveal the history or true driving factors behind the development of a rock or sedimentary sequence. This leads to false or incomplete interpretations and conclusions. In order to prevent the latter, visual/ macroscopic observations need to be complemented by analyses on a microscopic or atomic scale, through biological, chemical or physical methods.

This principle of scientific work also applies directly to sediment sequences obtained from the Baltic Sea Basin, which were deposited at the end of the Pleistocene and in the Holocene. These sediment sequences were deposited following the deglaciation of the Scandinavian Ice Sheet and are studied to acquire information about the development of the Baltic Sea. This development was largely governed by the glacio-isostatic uplift of Scandinavia, the eustatic sea level rise of the Baltic Sea and the deglaciation and subsequent erosion of thresholds (Björck, 1995) and has resulted in the occurrence of different lithostratigraphical units (Andrén et al., 2000). The latter have been classified into four different successional stages, according to their either brackish or freshwater character, their connection to the North Atlantic and the circumstances affecting the depositional environments, respectably. These stages are: the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake and the Littorina Sea. Although in theory, differences in the depositional environment leads to differences in the sediment record and therefore should be recognizable in a sedimentary sequence by eye; this is in reality not always the case. When analyzing the sedimentary records from the Baltic Sea, some of the depositional phases can be identified easier than others. While the Baltic Ice Lake is easily recognizable by its largely varved character and the brownish clay, the Ancylus Lake and the Littorina Sea are identifiable by the occurrence of iron sulphide layers and the latter especially by its high organic content of the sediment. The Yoldia Sea stage however, located between the Baltic Ice Lake and Ancylus stages, does not have such convenient characteristics. The glacial influence during the Yoldia Sea stage is still large and this phase often also features varves in the beginning, similar to the preceding Baltic Ice Lake and no abrupt color changes or other characteristics. These characteristic features are often easily identifiable to ascertain boundaries leading into this stage or out of it. This has led to some confusion among scientists and therefore to false identifications in the sedimentary records or has simply not been dealt with in great depth.

The aim of this thesis therefore is to analyze the Yoldia Sea stage and especially its boundaries to the Baltic Ice Lake and the Ancylus Lake. Macroscopic observations will be compared to geochemical methods, namely X-ray fluorescence and biogenic silica, e.g. the Si in diatoms. These analyses were performed on three different cores which were taken from the Eastern and Western Gotland Basin and the Bornholm Basin.

1.2 Study area

The Baltic Sea is a marginal sea of the North Atlantic with estuarine and brackish characteristics, positioned between approximately 54°N to 66°N latitude and 10°E to 30°E longitude. Its only connections to the North Atlantic are through the Belt Seas of Denmark and the Öresund Strait between Denmark and Sweden, leading to its semi-enclosed character. Water exchanges are mainly driven by differences in sea level of the Kattegat and the Baltic Sea (Wulff et al., 1990). The topography of the Baltic Sea features the irregular topography of the crystalline Precambrian bedrock in the northern and western parts as well as the smoother topography of the sedimentary bedrock in the southern parts. This is largely the result of glacial influences on the Baltic Sea basin (Martinsson, 1979).

The Baltic Sea, excluding the Bothnian bay and Bothnian Sea, features a series of deeper basins, namely the Arkona Basin, the Bornholm Basin, the Gulf of Gdansk, the Western Gotland Basin and the Eastern Gotland Basin (IOW, 2009). The cores (Fig. 2) studied in this thesis derived from the Western Gotland Basin, the Eastern Gotland Basin and the Bornholm Basin.

1.3. The Baltic Sea development after the deglaciation

The Baltic Sea, located in fairly high northern latitudes, has been especially sensitive for glacial influences during the Quaternary. The recurring glaciations and deglaciations and the accompanying influences have formed the current structure and appearance of the Baltic Sea and its surrounding areas and can thus be studied by a variety of methods. While the events of the last glaciation remain only fragmentarily known and are highly discussed, the last deglaciation of the Scandinavian continent has been better understood and well studied in parts. A four stage model has been proposed, taking into account connections of the Baltic Sea with the Northern Atlantic through different outlets and inlets, reoccurring freshwater and brackish phases as well as the interplay of glacial rebound and eustatic sea level rise (Björck, 1995). These stages are: the Baltic Ice Lake (15 to 11.6 cal ka BP), the Yoldia Sea (11.6 to 10.7 cal ka BP), the Ancylus Lake (10.7 to 10.1 cal ka BP) and the Littorina Sea (10.1 cal ka BP until present); ages according to Björck (1995, 2008), Yu et al. (2003) and Berglund et al. (2005). In accordance with the aims and objectives of this thesis, the development of the late Baltic Ice Lake, Yoldia Sea and Early Ancylus Lake and the respective boundaries from one stage into another shall be described in the next paragraphs.

1.3.1 Baltic Ice Lake

The Baltic Ice Lake was created when the ice

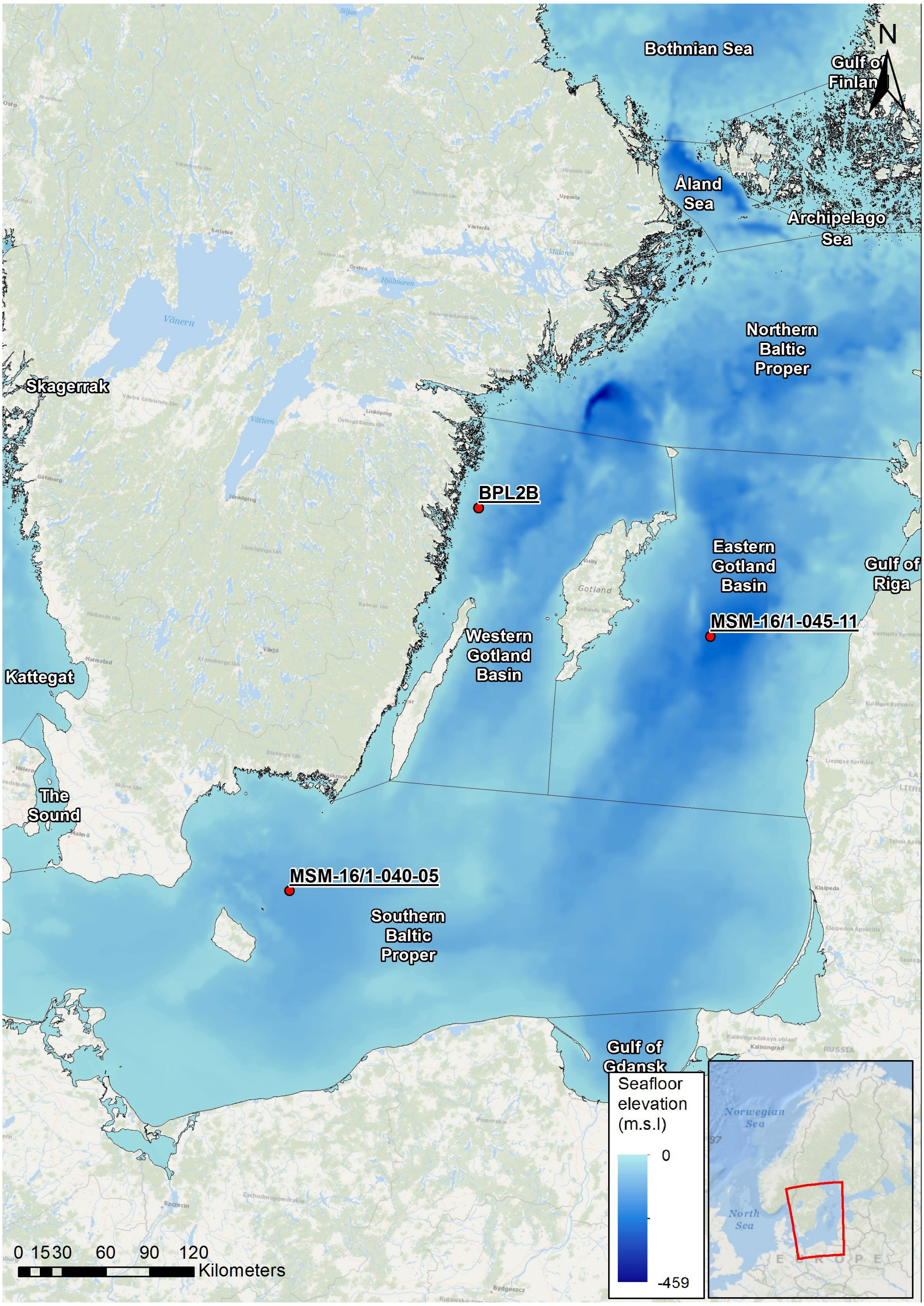

Fig. 1. core locations, map modified from HELCOM, IOW Warnemünde

sheet, covering Scandinavia, began to retreat from the Baltic Basin and was thereafter filled by meltwater at around 16 ka (Houmark-Nielsen & Kjaer (2003). Subsequently glaciolacustrine varved clays were deposited at the retreating ice margin (Andrén et al. 1999). Initially connected to the North Atlantic by the Öresund, resulting in the erosion of the area to the present bedrock, the Baltic Ice Lake level started to rise above the sea level of the North Atlantic at around 14 cal ka BP, due to isostatic rebound. This damming, depicted in

Fig. 2A, lasted for the rest of the Baltic Ice Lake stage, thus creating a large glacial freshwater lake in which mainly varved and homogenous clays were deposited, depending on their position to the receding ice margin. Further characteristics of this freshwater lake were the very low abundance of biogenic strata interlinked with a very low organic productivity (Andrén et al. 2011, Björck 1995). However it has been hypothesized that at about 13cal ka BP a connection to the North Atlantic was opened up, when the ice retreated north of the south Swedish Lowlands and Mount Billingen and subsequently opened up a new drainage route (Björck & Digerfeldt 1984). However no evidence has been found, that this connection allowed for an inflow of marine sea water into the basin, as discussed by Björck (1995). This connection through south central Sweden lasted until the Younger Dryas, during which the ice sheet readvanced, damming up the Baltic Ice Lake for a second time. At 11.6 cal ka BP (Fig. 2B), the Baltic Ice Lake drained suddenly, when the ice retreated north of Mount Billingen. This caused a water level drop of 25m in 1 to 2 years (Björck 1995). Although

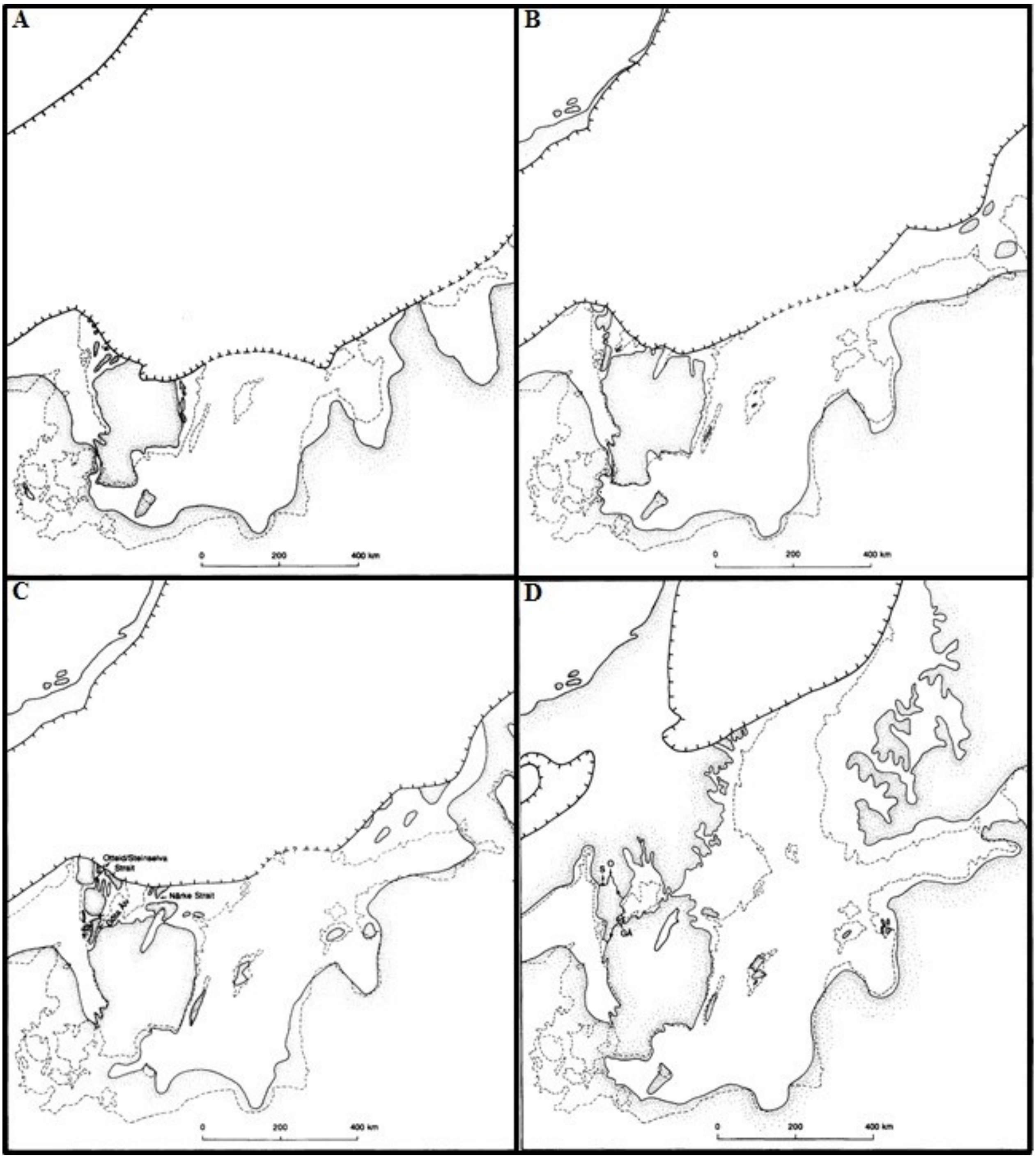

Fig. 2: Developmental stages of the Baltic Sea, modified from Björck (1995) – A: Baltic Ice Lake at 12ka, B: Baltic Ice Lake shortly before drainage, C: Yoldia Sea shortly before marine ingression, D: Ancylus Lake transgressions

the details of this drainage are debated, the altitudinal difference between the dammed up Baltic Ice Lake and the North Atlantic due to the isostatic rebound of the Öresund area, was the main factor for the catastrophic drainage. With the sudden drainage of the Baltic Ice Lake the next stage of the Baltic Sea development, the Yoldia Sea, started.

1.3.2 Yoldia Sea

The Yoldia Sea stage, which began at around 11.6 cal ka BP, coincided approximately with the onset of the Holocene and with the associated climate warming. For this reason, the first part of the Yoldia Sea, hereafter called Yoldia Sea I, was mostly characterized by the retreat of the Scandinavian Ice Sheet (Björck 1995) and a large regression. The latter was caused by the continued isostatic rebound, resulting in low shore levels in the southern Baltic Sea and a shallowing of the Baltic Sea in the northern and northwestern parts of the Baltic Proper.

The name Yoldia Sea indicates a marine influence on the Baltic Sea throughout this developmental stage, but this is largely misleading. The basin, being closed in the south due to a land bridge being formed across Denmark, South Sweden and Germany, only experienced marine influences for a short period of time when the Preboreal Oscillation resulted in a climatic deterioration (Björck et al. 1996, 1997). This deterioration most likely lead to a smaller amount of melt water being discharged from the receding ice margin, thus allowing saline marine waters entering into the Baltic Sea through the Närke Strait, a newly opened up connection with the North Atlantic (see Fig.2C). Evidence for this short marine ingression, occurring about 300 (varve) years after the catastrophic water level drop which ended the Baltic Ice Lake Stage, can be traced throughout the newly opened up strait and down to the southern parts of the Baltic Sea. This has been mostly observed by studying marine bivalves, like Portlandia (Yoldia) Arctica, benthic foraminifera or diatoms (Wastegard et al. 1995). The marine ingression phase ended, when the outlets connecting the Baltic Sea with the North Atlantic, shallowed up due to high uplift rates. This marine phase of the Yoldia Sea, lasting about 70 to 120 years according to Wastegard et al. (1995) and 240 years according to Andrén et al. (2002) is hereafter called Yoldia Sea II.

With the connection to the North Atlantic closed, the Yoldia Sea returned to being a freshwater system, hereafter called Yoldia Sea III, which lasted according to Andrén et al. (2007) approximately 250years. However an open contact with the sea remained through Lake Vänern, which was only closed at the end of the Yoldia Sea stage. This was largely the result of the high isostatic rebound and the associated shallowing of the outlet, leading to a large sea level rise in the Baltic Sea Basin and thus began the third stage of the Baltic Sea development, the Ancylus Lake.

1.3.3 Ancylus Lake

The large water level rise in the Baltic Sea Basin resulted in a similar situation as described in the later phases of the Baltic Ice Lake. In the southern parts of the Baltic Sea, the water level thus rose along with the isostatic uplift of the sills and straits west of Lake Vänern, resulting in large scale transgressions as depicted in Fig, 2D. In the northern parts, approximately north of Stockholm, however, the development was characterized by a regression. The large scale transgression in the southern parts of the Baltic Basin, have been analyzed on submerged and drowned pine forest in the southeastern parts of Sweden as well as through raised beaches found throughout southern Sweden and the Baltic states. (Björck 2008) and drowned soils (Berglund et al. 2005). This first phase of the Ancylus Lake, which lasted about 500 years, can be characterized by fresh water conditions and a low amount of organic matter. It ended when a forced regression set in, lowering the Baltic Sea water level, which was a probably the result of a new outlet forming. This outlet, the Dana River, possibly located in the Great Belt of Denmark, has been widely discussed and several contradicting scenarios have been proposed.

The following complex history of the transitional phase from the Ancylus Lake to Littorina Sea shall not be discussed in this thesis.

2 Material and methods

2.1 Core collection and sample preparation

For this thesis, three sediment cores were analyzed, which were originally retrieved along with several others as part of different BONUS+ projects from the Eastern and Western Gotland Basin as well as the Bornholm Basin (South Baltic Proper) as shown in Fig. 1.

All cores were retrieved by gravity corer with plastic liner and after recovery, cut into 1m long sections which were furthermore cut longitudinally into halves. The relevant data and characteristics are described in Table 1. Subsequently, these cores were stored in a cold room.

After selection, the three cores were described in their entirety based on lithology, texture and color. Varves were counted, but were not included in this thesis, except to serve as a means for the description of the cores. Subsequently the sedimentary descriptions were compared to magnetic susceptibility data provided by Reinholdsson (2014) in order to identify boundaries from Baltic Ice Lake to Yoldia Sea and Yoldia Sea to Ancylus Lake. Since this study focuses on the Yoldia Sea stage, sampling was done at the depths of the cores, which were believed to represent the Yoldia Sea stage and include the proposed boundaries from Baltic Ice Lake to Yoldia Sea and Yoldia Sea to Ancylus Lake. Samples of about 10g were taken every 5cm and every 2-3cm in boundary areas.

Table 1: characteristics of cores used in this study

Core name	**Cruise, year**	**Latitude N**	**Longitude E**	**Core length (m)**	**Water depth (m)**	**Location**
BPL2B	R/V Pelagia, May 2011	57°55’15.60”	17°4’7.68”	5.61	200	W. Gotland Basin
MSM-16/1-045-11	R/V Maria S. Merian, August 2010	57°15’0.18”	19°50’0.72”	11.78	210	E. Gotland Basin
MSM-16/1-040-05	R/V Maria S. Merian, August 2010	55°27’10.56”	15°27’17.40”	14.27	93.6	S. Baltic Proper

Thereafter all samples freeze dried for 48h to 72h. The subsequent analyses were done on the freeze dried sediments.

2.2 X-ray fluorescence analysis

X-ray fluorescence (XRF) is a well-established analytical method which provides chemical data in a fast and undestructive way. It relies on the principal of excitation of electrons when subjected to X-ray radiation, in which electrons from the inner atomic shell are ejected, leaving vacancies. These vacancies are thus filled with electrons from the outer atomic shell, which is accompanied by a surplus of energy emitted as secondary radiation. Since these energy and wavelength spectra are specific and characteristic for each element, an estimation of relative abundances can be carried out (Weltje and Tjallingii, 2008).

In preparation for XRF, all samples were homogenized with a mortar and pestle and transferred to analysis containers. They were analyzed using the Thermo Scientific Niton XL3t GOLDD+ XRF Analyzer at the Department of Geology at Lund University, which is equipped with a 50kV X-ray tube. The Cu/Zn procedure in Mining mode was used to run the samples, with each run lasting 300s and one run per sample. Furthermore for every 15 samples, the Standard Reference material 2709a was run.

For further analysis, the retrieved chemical data was used to calculate chemical ratios, which were subsequently plotted against the corresponding depth for each core.

2.3 Biogenic Silica

The analysis of biogenic silica provides a proxy for aquatic productivity and thus information about hydrologic and climatologic changes in a regional context in both lacustrine and marine environments. Silica, being the second most abundant element on Earth, is taken up as dissolved silicate (DSi) by aquatic organisms such as diatoms, sponges, chrysophytes and radiolarians, and is thereafter precipitated into shells, sponges and cysts as biogenic silica (BSi). Along with the non-biogenic silica, originating from crystalline phases such as quartz and mineral silicates or for example weathering and volcanic glasses, it makes up the silica content of sediments. The chemically derived proxy of Biogenic Silica thus provides information on the biogenic productivity of a system and diatom abundance (Conley & Schelske 2001).

To analyze the BSi content of the samples, the wet chemical digestion technique is more commonly used, as described by Conley and Schelske (2001), in which a weak base is added to a sample as an extraction solution for a period of 5hours. After 3, 4 and 5 hours, aliquots of this solution are sub-sampled and an acid is added to stop the digestion process. Subsequently the amount of Si, extracted from each subsample, is measured.

To analyze the biogenic silica content of the cores, twelve samples were taken from each core in regular intervals. Samples were homogenized with a mortar and pestle. 30mg of a sample were put in propylene bottles, to which 40ml of Na2CO3 were added. Bottles were loosely closed, to allow venting of gases and subsequently placed into a shaking bath for 5hours at a temperature of 85°C and 100rpm. After 3h, the samples were taken out of the shaker and placed into room temperature warm water baths for a short period of time while sub-sampling to place. 1ml of each sample was then added to 9ml of 0.021 N HCl in smaller plastic bottles. After sub-sampling, the samples were placed back into the shaker and the whole process was repeated after 4 hours and 5 hours, respectively.

Fig. 3: Stage boundaries, A: core BPL2b, B: core MSM45, C: core MSM40. 1 indicating the boundary of Baltic Ice Lake to Yoldia Sea I, 2 indicating the boundary of Yoldia Sea III to Ancylus Lake

Measuring the extracted silica of the subsamples, taken at 3, 4 and 5 hours, was made by adding ammonium molybdate, ascorbic acid and oxalic acid to the samples, which leads to a color change of the solution. This color change, which is caused by the reaction of the ammonium molybdate with the dissolved silica, could then be measured by a photospectrometer, in this case the Smart Chem 200 AMS Systea. Since the reaction of biogenic silica and crystalline silica phases is taking place at different reaction rates, a linear regression can be calculated, which leads to the determination of the amount of BSi.

2.4 Principal Component Analysis

When analyzing a large chemical data set, obtained by performing X-ray fluorescence analysis, a statistical supplementary approach can be useful. For this thesis, Principal Component Analysis was performed.

Principal Component Analysis (PCA) is a multivariate statistical procedure, with which, by orthogonal linear transformation of a dataset matrix to a new data coordinate system, coordinates with the highest variability or variances of a data set can be identified (Wold 1987). A calculation of factors is thus possible, which represent a combination of the most dominant data points and their importance, "loading", on which the dataset is subsequently plotted. It can be therefore used for the identification of outliers, clusters within a dataset and for analyzing the correlation between data points.

In this thesis, the Excel macro XLStat2014 was used to perform PCA.

3 Results

3.1 Core description and description of boundaries

All three cores were described in their entirety. However, only the descriptions pertaining to the aim of this thesis, are included here and are therefore limited to core depths which supposedly represent the late Baltic Ice Lake, Yoldia Sea and Ancylus Lake.

3.1.1 BPL2b – Western Gotland Basin

For core BPL2b, core depths from 561cm to 165cm were taken into consideration.

In this section of the core, the prevailing grain size was clay and no coarser grain sizes could be identified. From 561 to approximately 205cm, the predominant color was brownish grey with a reddish hue, which changed from 205cm upwards to dark grey. Irregular, hard to distinguish varves could be identified from about 561 to about 520cm depth. Thereafter visible banding was identifiable, but hard to discern.

The Baltic Ice Lake Yoldia Sea boundary was discerned mainly using the identified varves, all illustrated in Fig. 3A1. Being spaced evenly 1 to 2 cm apart for most of the core up to 530cm depth, they disappeared for about 10cm in the relevant boundary section and then reappeared. The Baltic Ice Lake Yoldia Sea boundary was therefore placed at ca. 530cm depth

The boundary of the Yoldia Sea to the Ancylus Lake stage was identified using the described sharp color change from brownish grey to dark grey at approximately 205cm (Fig.3A2).

The Yoldia Sea Ancylus Lake boundary was as a result placed at ca. 205cm depth.

3.1.2 MSM-16/1-045-11 – Easter Gotland Basin

For core MSM45, core depths from 793 to 325cm were taken into consideration.

In this section of the core, the prevailing grain size was clay without coarser grain sizes. From 793 to about 390cm depth the sediment color was brownish grey and changed from 390cm and upwards to darker grey in a sharp transition with a pronounced darker banding. The core sections were predominately characterized by well-preserved varves, which continually decreased in their width, until slowly disappearing into uniform clay between 500 and 400cm.

The boundary of the Baltic Ice Lake to the Yoldia Sea stage was mainly identified using the highly developed varve character of the core. Gradually thinning until approximately 730cm depth, the varves disappeared seemingly completely for about 10 cm before reappearing (Fig. 3B1). The Baltic Ice Lake Yoldia Sea boundary was therefore placed at ca. 730cm depth.

The boundary of the Yoldia Sea to the Ancylus Lake stage was established using a very pronounced described color change and therefore was placed at 390cm depth (Fig. 3B2).

3.1.3 MSM-16/1-040-05 – Bornholm Basin

For core MSM40, core depths from 1220cm to 854cm depth were taken into consideration.

In this section of the core, the prevailing grain size was once again that of clay, although coarser grained layers of silt, mainly around 1080cm could be distinguished and continued upwards in irregular intervals and layer widths. The prevailing color of the sediment was brownish reddish grey which abruptly changed into a light grey at about 950cm depth. In contrast to cores BPL2b and MSM45 no distinct varves could be discerned in this core. The largely prevailing banded character of the core could not be associated with varves.

The boundary of the Baltic Ice Lake to Yoldia Sea stage was mainly established using the very pronounced silt layers around 1080cm, which represented about 15cm of seemingly very chaotic sediment deposition. As a result, the Baltic Ice Lake Yoldia Sea boundary was placed at 1080cm depth (Fig. 3C1).

The boundary of the Yoldia Sea stage to Ancylus stage was established using the very pronounced color change at about 390cm depth, in which the color of the sediment changes from a dominant reddish grey to a light grey without reddish hue (Fig. 3C2).

Table 2: Ratios used in this thesis and indication of reasons behind selection

ratios	proxy for	reference
Si/Ti	biogenic silica	Cunningham et al. 2013
Ca/Ti	sedimentary variability in sediments	Hennekan &De Lange 2012
S/Ti	marine input into the basin	
Ti/Zr	grain size development	personal communication S. Björck
Fe/Ti	indication of oxic conditions	Tjallinghii et al. 2006
Sr/Ca	depth of water sources and shallowing	Tjallinghii et al. 2006
Rb/Sr	weathering intensity of the bedrock	Wenrich et al. 2013

3.2 X-ray fluorescence

Element ratios, which were calculated from the chemical data retrieved by X-ray fluorescence, were plotted against the corresponding depths from each of the cores. After a literature research, seven element ratios were selected for further analysis. These were Si/Ti, Ca/Ti, S/Ti, Ti/Zr, Fe/Ti, Rb/Sr and Sr/Ca, as shown in Table 2. Furthermore, for comparison, magnetic susceptibility was plotted.

Since all three cores displayed different characteristics, they will be described separately.

3.2.1 BPL2b – Western Gotland Basin

The element ratios for core BPL2b were plotted from 561 to 165cm and contained 78 data points (Fig. 4A).

The element ratio plots pertaining to this core show generally a stable and constant trend. However fluctuations are common and therefore make it harder to identify big changes in trends. The plots representing element ratios Si/Ti, Ti/Zr, Fe/Ti and Rb/Sr do not display any big increases or decreases for most of the length of the core, although Rb/Sr and Si/Ti depict a slight decrease from 325cm upwards and the Si/Ti ratio shows a slight increase from 325cm upwards. The Ca/Ti ratio records distinct changes. The plot is slightly decreasing, from 520cm upwards, after dropping distinctly at 520cm. However between 420 and 335cm, the ratio first increases and then declines to the initial ratio value. The S/Ti displays distinct changes from 420cm to 335cm as well, where the ratio rises considerably, whereas the rest of the plot seems to be at a constant ratio value. However, due to big fluctuations, it is generally hard to discern trends.

The magnetic susceptibility plot contains some distinct peaks and changes; however the most significant change is from a generally highly fluctuating curve between 561 and 515cm to a generally more constant graph with only minor fluctuations from 515cm and upwards. This is mirrored in most plots of the chemical ratios. The magnetic susceptibility shows a more distinct broad peak at 200cm, which seems to be mirrored in the ratio plots of Si/Ti and Rb/Sr.

3.2.2 MSM-16/1-045-11 – Eastern Gotland Basin

The element ratios for core MSM45 were plotted from 793 to 325cm and contained 86 data points (Fig. 4B).

The element ratio plots of this core fluctuate less and show more articulated trends than BPL2b. Ti/Zr, Fe/Ti and Rb/Sr display a slight increase over the length of core from 793 to 325cm. Lower ratios can be discerned between 680 and 530cm and a more distinct change is evident at around 390cm. The Si/Ti ratio depicts distinct changes, although the element ratio plot is relatively constant between 781 and 390cm. Lower ratios are evident between 735 and 675cm, as well as between 575 and 465cm. The ratio plot drops sharply at around 390cm and thereafter is lower than in the lower parts of the depth section. The Ca/Ti ratio plot shows distinct changes as well, fluctuating greatly from 781 to about 715cm depth, subsequently increasing sharply at 660cm and thereafter decreasing gradually until about 550cm. The element ratio plot remains stable upwards to about 325cm. The S/Ti ratio plots at an approximately constant ratio between 793 and 585cm, with a slight decrease at around 700cm. Upwards of these depths the graph firstly decreases constantly until about 485cm and then increases up to 325cm. A distinct small drop is visible at 390cm. The Sr/Ca ratio depicts small constant ratio values in the lower parts of the depth section from about 793 to 575cm and higher constant values from 530cm to 325cm with a sharp increase in the ratio in between. A moderate increase can be discerned between 725 and 700cm depth, followed by a moderate decline to the initial ratio. A small distinct drop can be discerned at about 390cm.

The magnetic susceptibility displays constant values throughout the length of the core depth with several distinctive peaks.

3.2.3 MSM-16/1-040-05 – Bornholm Basin

The element ratios for core MSM40 were plotted from 1220cm to 854cm and contained 61 data points (Fig. 4C).

The element ratio plots of core MSM-16/1-040-05 show three distinct trends throughout the length of the core. In the lower depth of the core section, from 1220 to about 1080cm, the ratio values either remain approximately stable (Ti/Zr and Sr/Ca), slightly increase (Si/Ti, Fe/Ti and Rb/Sr) or slightly decrease (Ca/Ti and S/Ti). From about 1080 to 950cm depth, the element ratios firstly increase moderately to a maximum at about 1030-1020cm and then moderately decrease to the initial ratio values for ratios Si/Ti, Ca/Ti, S/Ti and Sr/Ca. Ratios Ti/Zr, Fe/Ti and Rb/Sr displays contrary trends with decreases and subsequent increases in the ratio. From 950 to 854cm, in the upper parts of the core the ratio values either remain constant (Ca/Ti, Fe/Ti and Rb/Sr) or increase (Si/Ti, S/Ti and Ti/Zr). Sr/Ca shows a similar trend, in comparison, however the increase in the second trend is of a sharp nature and the ratio values reaches a plateau from 1005 to 909cm. It is followed by a sharp drop to the initial value. This drop is visible in the other ratios as well, but not as distinct.

This above described three phased trend is distinctly visible also in the magnetic susceptibility, remaining stable in the lower parts of the core, moderately increasing and decreasing in the middle parts and remaining approximately constant throughout the upper parts of the core section. In comparison to the magnetic susceptibility plots of cores BPL2b and MSM45, the magnetic susceptibility plot of core MSM40 depicts greater variability and fluctuations from approximately 1050cm depth and upwards.

3.2.4 Correlation of cores

In a subsequent step, the plotted element ratios, the corresponding magnetic susceptibility plots as well as the core descriptions and boundary establishments

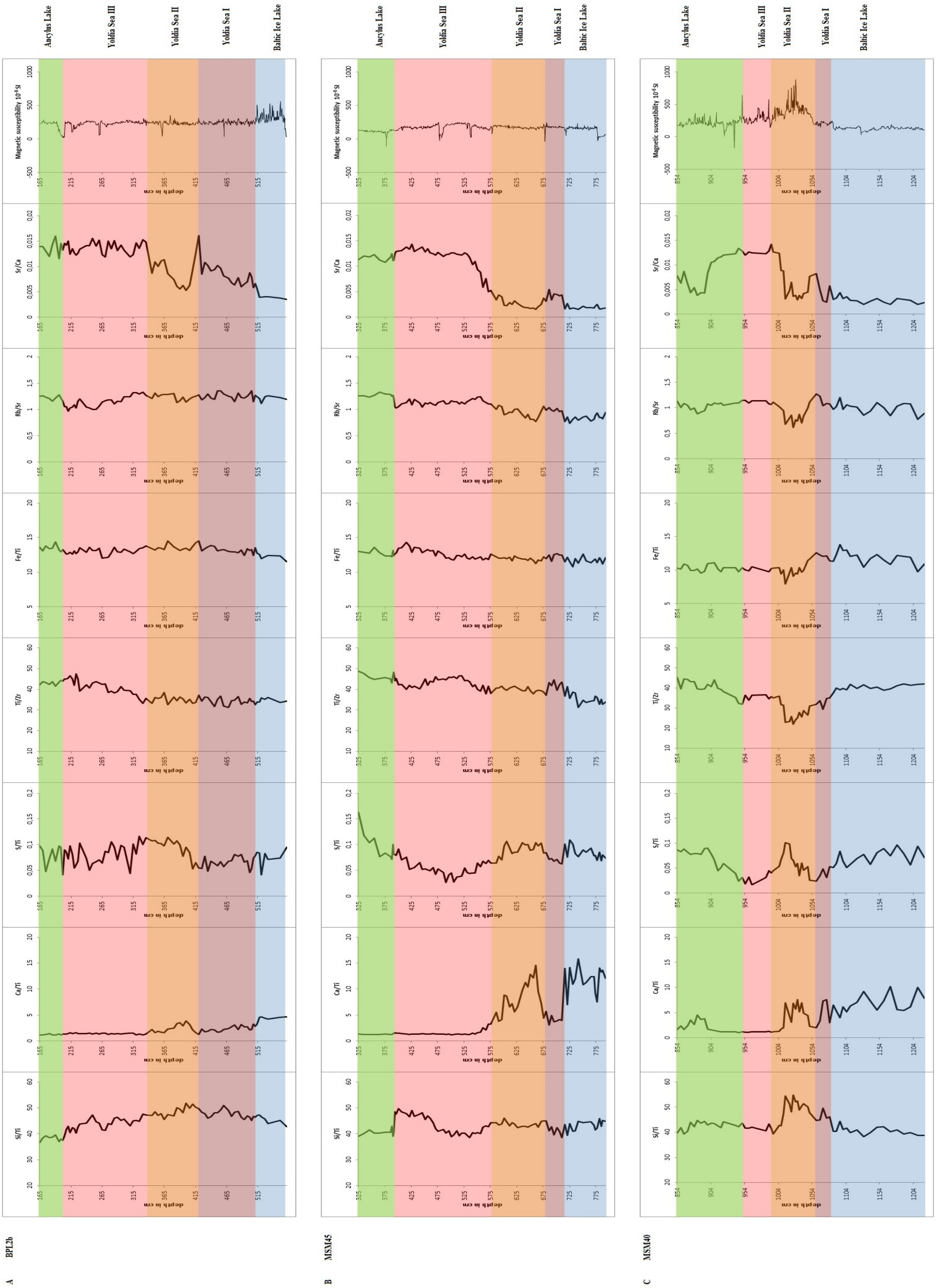

Fig. 4: Correlation of element ratios; A: BPL2b—Western Gotland Basin, B: MSM45—Eastern Gotland Basin, C: MSM40: Bornholm Basin

were taken for all three cores and used to identify the different stages of the Baltic Sea development in the

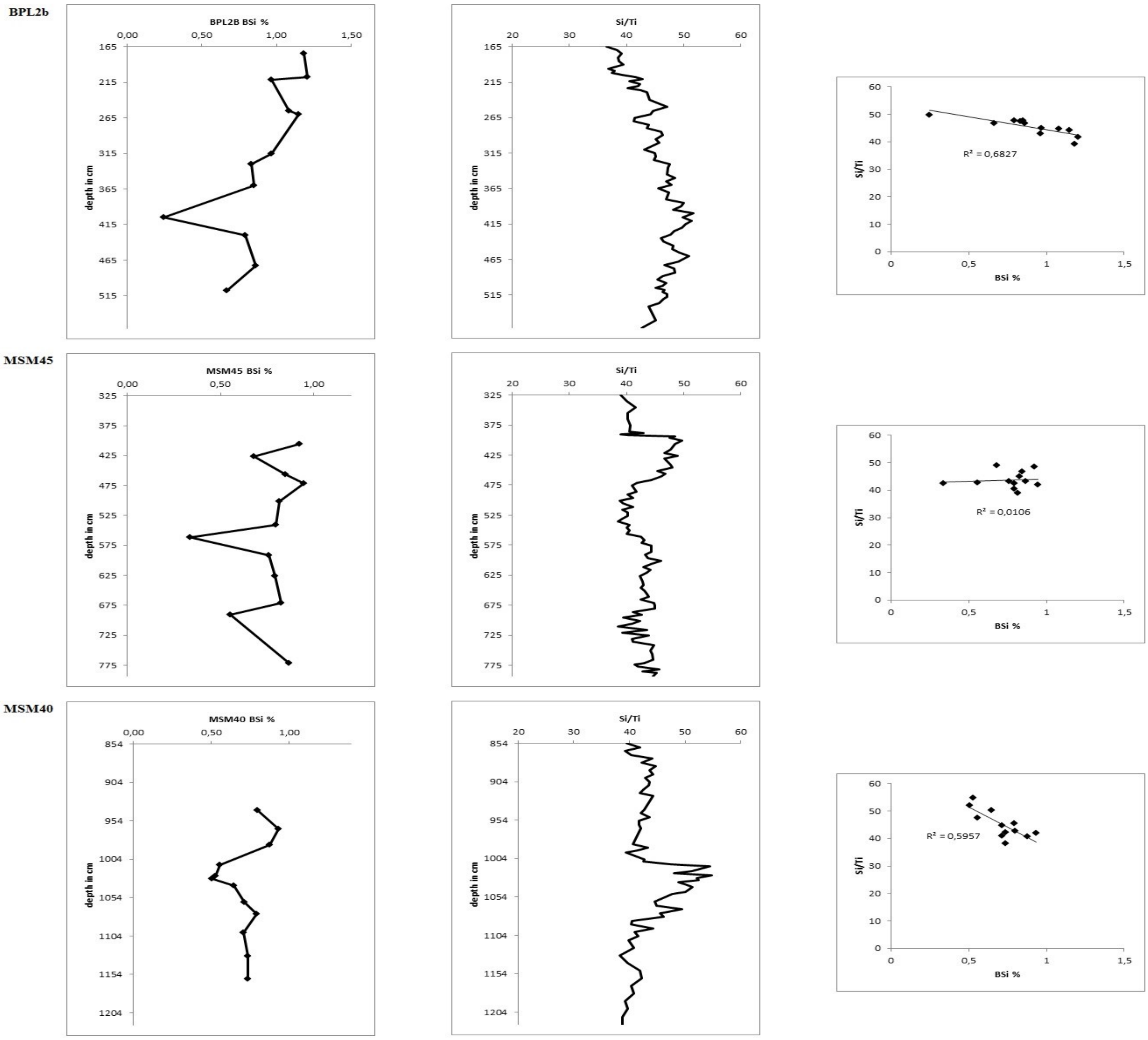

Fig. 5: plots of Biogenic Silica amounts in comparison to Si/Ti ratio; A: BPL2b Western Gotland Basin, B: MSM45 Eastern Gotland Basin, C: MSM40 Bornholm Basin

chemical data as depicted in Fig. 4. These stages were: Baltic Ice Lake, Yoldia Sea I, Yoldia Sea II, Yoldia Sea III and Ancylus Lake with Yoldia Sea II representing the marine phase of the Yoldia Sea. The boundary of Baltic Ice Lake to Yoldia Sea I and the boundary of Yoldia Sea III to Ancylus Lake were determined using the sediment descriptions and applying those to ratio plots and magnetic susceptibility plots. The boundaries of the marine phase of the Yoldia Sea stage, namely Yoldia Sea II, were determined using the ratio plots and correlating those with each other.

In general, all three cores show distinct phase divisions. Yoldia Sea II can possibly be distinguished in all three cores.

3.3 Biogenic Silica

After performing the analytical methods to obtain BSi, the results were plotted against the depth, for each respective core. Furthermore, since a correlation between biogenic silica and Si/Ti has been proposed, the Si/Ti is plotted for comparison (see Fig. 5).

In general, the chemical analyses yielded very low amounts ranging from 0.24% to 1.2% weight percent SiO2 for all three cores. Furthermore all three plots showed similar trends of being approximately constant with one pronounced minima in the middle part of the plotted depths.

When compared to the Si/Ti ratio, no clear correlations between BSi and Si/Ti could be found, although it can be proposed that minima in the BSi occurs when maxima in the Si/Ti ratio are being displayed, at least for cores BPL2b and MSM45. To further analyze the correlation between both, the biogenic silica percentage was plotted against the Si/Ti ratio and the correlation coefficient was calculated. This is illustrated in Fig. 6. BPL2b and MSM40 displayed good correlation coefficients, of 0.68 for BPL2b and 0.59 for MSM40. For MSM45, a non-significant correlation was calculated (0.01). It has to be furthermore noted that all three cores showed inverse trend lines.

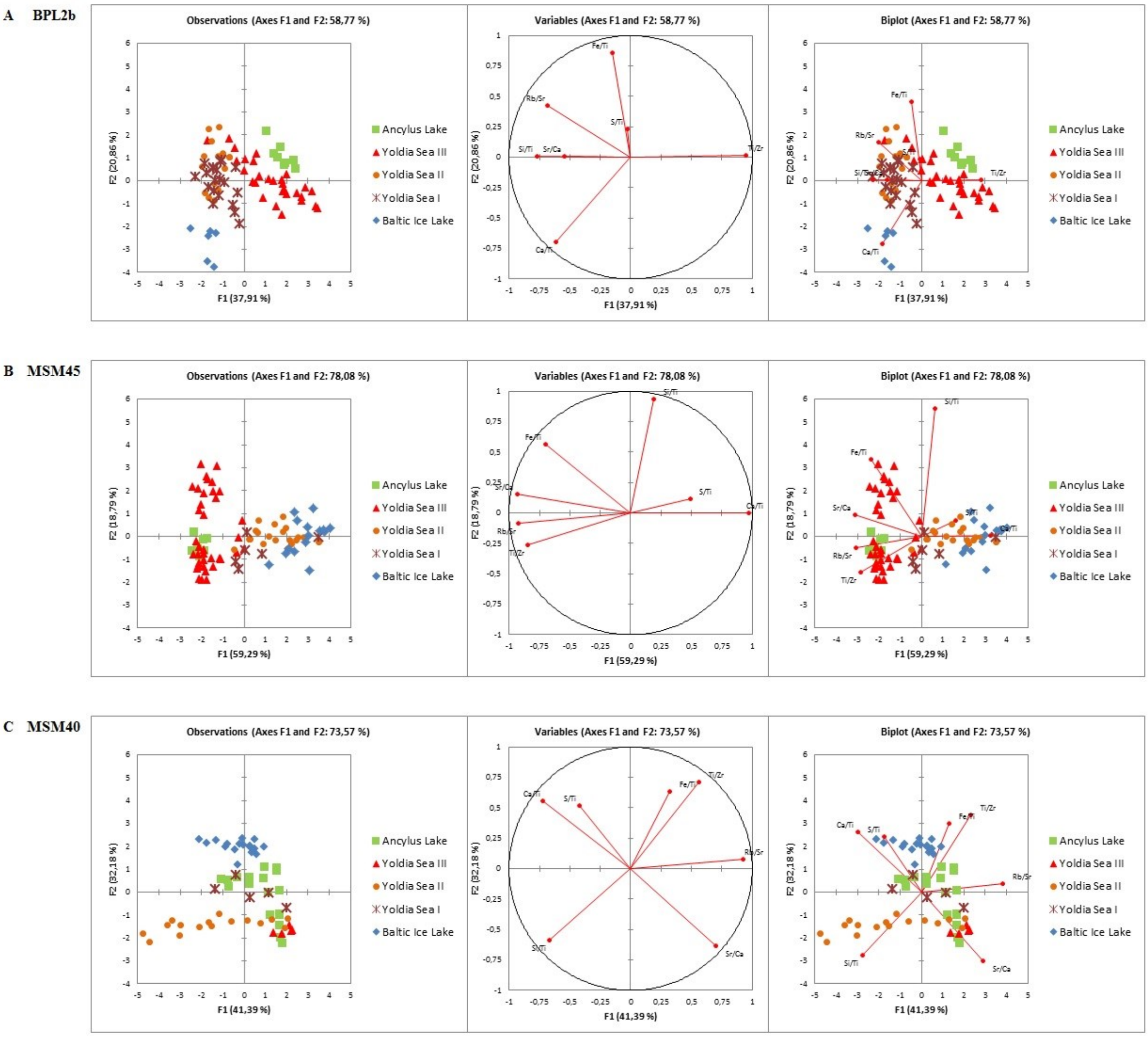

Fig. 6: Principal Component Analysis for each of the cores, including plot of observations, variables and biplot; A: BPL2b Western Gotland Basin, B: MSM45 Eastern Gotland Basin, C: MSM40 Bornholm Basin

3.4 Principal component analysis

To further analyze the chemical data, PCA was performed. For each core the seven element ratios, derived by calculating the chemical data were used in the analysis. Subsequently, the observations were clustered according to the Baltic Sea development stages which were established in 3.2.4. Observations, variables and biplots, containing both observations and variables, were plotted for each core as depicted in Fig. 7.

3.4.1 BPL2b

Factor 1 explained 37.91% and Factor 2 explained 20.86% of the variance of the data set. When clustering the observations, clear distinct groups were displayed for each of the five phases classified in the correlations in section 3.2.4. The cluster moved in a distinct way along the factor axes, moving from quadrant III diagonally along the x-axis to quadrant I from supposedly older data points representing the Baltic Ice Lake to younger data points, representing the Ancylus Lake.

When analyzing the biplot, the Ca/Ti ratio plotted in direction of the Baltic Ice Lake cluster, while Ti/Zr plotted in direction of the Yoldia Sea III and Ancylus Lake cluster, both with high loadings. Fe/Ti, which has a higher loading as well, did not show a clear indication of being correlated to a certain observation cluster. Rb/Sr, Si/Ti, Sr/Ca and S/Ti, all with smaller loadings, plotted in direction of the Yoldia Sea cluster.

3.4.2 MSM45

Factor 1 explained 59.29% and Factor 2 explained 18.79% of the variance of the data set. Thus factor 1 had a much larger influence on the variability. When clustering the observations, distinct groups were formed for each of the classifications in point 3.2.4. The cluster did not move in a distinct way, as seen in 3.4.1, but nevertheless had a direction along the x-axis. Contrary to core BPL2b, the movement of the cluster pertaining to the Baltic Ice Lake to Ancylus Lake occurred from quadrant I to quadrant III.

When analyzing the biplot, the ratio with the highest loading, Si/Ti, did not correlate with any of the proposed clusters. Ca/Ti plotted into the direction of the cluster of Baltic Ice Lake, while the other ratios with an equally high loading plotted into the direction of the Yoldia Sea III and Ancylus cluster. The S/Ti ratio, containing the smallest loading, plotted into the direction of Yoldia Sea II.

3.4.3 MSM40

Factor 1 explained 41.39% and Factor 2 explained 32.18% of the variance of the data set. When clustering the observations, clear distinct groups can be discerned, using the stages which were established in 3.2.4. However when comparing the movement of the cluster along the axes to the movement of the clusters pertaining to cores MSM45 and BPL2b, no clear directional movement can be discerned for core MSM40, due to the horizontal groupings of the clusters.

When analyzing the biplot, a very diverse picture can be observed. Ca/Ti, Ti/Zr, Si/Ti and Sr/Ca having the highest loadings, are directed in contrary directions. Si/Ti shows a correlation with the cluster of Yoldia Sea II, while the Sr/Ca ratio correlates with the clusters pertaining to Yoldia Sea III and Ancylus Lake. Ca/Ti and Ti/Zr do not show clear correlation to any group, which is similar to the ratios with lower loadings, namely S/Ti and Fe/Ti.

4 Discussion

The aim of this thesis was to identify and establish the boundaries of the Yoldia Sea and furthermore, if possible, to analyze the marine ingression phase, which gave the Yoldia Sea its name. The whole premise therefore was to juxtapose the macroscopic sediment description of the core with the chemical data retrieved from the XRF analysis.

4.1 Macroscopic sedimentary considerations

When solely analyzing the sedimentary description of the cores, it is evident, that the boundaries of Baltic Ice Lake to Yoldia Sea and Yoldia Sea to Ancylus Lake can be identified. However this identification tends to be rather imprecise and is solely based on color changes or differences in the frequency or width of occurring varves since major grain size differences do usually not occur or are not visible to the naked eye. Furthermore it is also clearly evident, that the location of the core influences the characteristics of the sediment deposition. While both core MSM45 and BPL2b originate from the Gotland Basin, it is clear, that a Western or Eastern Gotland Basin provenance can have different characteristics due to apparently different prevailing conditions during the time span analyzed in this thesis. Both cores were similar in color and only clay sized grain sizes could be observed. The color of both cores and also the color changes throughout the development from Baltic Ice Lake to Ancylus Lake have previously been described by Andrén et al. (2000) and mirror the authors results. However, when comparing varve characteristics, it is already evident, that different conditions must have influenced the core locations. Although both are varved, the varves of core MSM45, originating from the eastern part of the basin, are more distinctively developed and can be more easily discerned. However in both cores the boundary from Baltic Ice Lake to Yoldia Sea is distinguishable by analyzing the varves, because they clearly disappear or are too thin to be visible by the naked eye. This is obviously the result of the drainage of the Baltic Ice Lake, which is described as a very abrupt and fast event (Björck, 1995), clearly able to disrupt the general development of varves. In both cores, varves reappear after the proposed drainage of the Baltic Ice Lake and subsequently continue well into the next stage, the Yoldia Sea. This is due to the continued glacial character with the ice margin being located at that time south of Stockholm according to Fig. 2B.

When analyzing core MSM40, with its provenance of the Bornholm basin, varves cannot be discerned. This is the result of the location of the basin in comparison to the location of the ice margin during the Late Baltic Ice Lake stage and thus the diminished glacial influence. In comparison to the cores of the Gotland Basin, silt layers however can be identified. The latter point towards an environment with a higher degree of energy, as would have prevailed during the drainage of the Baltic Ice Lake.

In all three cores no macroscopic indications have been found, that conditions changed from a freshwater environment to a brackish environment during Yoldia Sea II. However in all three cores, clear and sharp color changes seem to indicate the transition from Yoldia Sea III to Ancylus Lake. Additionally magnetic susceptibility data was compared to the macroscopic observations. Magnetic susceptibility, a method in which sediments are analyzed by magnetizing the sediment and thus quantifying the minerogenic content of the sediment, is mostly interpreted as a means to analyze the input of minerogenic particles from the surrounding environment. The magnetic susceptibility data did contribute to the establishment of the boundaries of the Baltic Ice Lake and Yoldia Sea I transition and the Yoldia Sea III transition to Ancylus Lake, since most observations seem to be mirrored by peaks in the magnetic susceptibility. However when comparing the cores, the magnetic susceptibility plot of core MSM40 has more fluctuations and indicates a larger minerogenic input into the location then in the magnetic susceptibility plots of MSM45 and BPL2b, due to a higher input of terrestrial material.

Thus the conclusion drawn from the macroscopic sedimentary description of all three cores seems to be that the boundaries from Baltic Ice Lake to Yoldia Sea I and Yoldia Sea III to Ancylus Lake are distinguishable and that Yoldia Sea II cannot be identified. Furthermore in all three cores, different regional developments of the sedimentary sequences can be observed.

4.2 Considerations of chemical data and Principal Component Analysis

The chemical data retrieved by X-ray fluorescence analysis was analyzed and correlated with the macroscopic observations and the magnetic susceptibility data. Element ratios were calculated and chosen after a literature search had taken place (Table 2). All these ratios were taken into consideration to assess if the established boundaries of the visual sediment descriptions could be replicated and to identify the Yoldia Sea II phase. The Fe/Ti and Sr/Ca ratio do not completely fit the context of this thesis when considering the depositional environment, Fe/Ti being mainly used in the context of identifying periods with different redox conditions and Sr/Ca being mainly analyzed when comparing data retrieved from the analyses of for example foraminifera. However, both ratio plots seemed promising and distinct enough to be considered. Furthermore it has been indicated by Dypvik & Harris (2001), that Sr may not only be associated with carbonate minerals, more commonly used, but is also associated with feldspars as well as biotite at lower concentrations. This might apply to the present chemical data set. To calculate ratios is generally considered a better approach in the analysis of chemical data by normalizing the element to a reference element, which is considered to remain conservative throughout its deposition. These stable lithogenic reference elements most commonly are Ti, Zr, Al or Rb (Boe et al. 2011) and are used in this thesis as well.

It was furthermore considered, to log transform the element ratios, used in this thesis, as argued for by Weltje and Tjallinghii (2008) to achieve a better description of recorded changes in the plots. However since the recorded increases and decreases in the presented plot, did not surpass a certain magnitude, a log transformation was not performed.

When comparing the correlation of cores, it is evident that not all cores have the same influences, since the element ratios develop in a different manner along the core sections and are specific to each core.

4.2.1 Core BPL2b – Western Gotland Basin

Core BPL2b with a provenance of the Western Gotland Basin, does not show many conclusive features to warrant the correlation achieved. The Baltic Ice Lake Yoldia Sea I boundary is not completely evident when analyzing solely the chemical data, which is mirrored by the boundary of Yoldia Sea III to Ancylus Lake. The Yoldia Sea II can be discerned by increases in the Si/Ti ratio, the Ca/Ti ratio and in the S/Ti ratio. The Ca/Ti ratio increases before decreasing. Therefore an apparently higher input of silica, calcium and sulfur points to a higher degree of variability in the sediment and an influx of marine water. However if the Zr/Ti ratio is interpreted as a mean to assess grain size changes, no apparent grain size changes are distinctive throughout the development from the Baltic Ice Lake to the Ancylus Lake. It is notable as well, that the magnetic susceptibility only fits these descriptions when analyzing the boundaries from Baltic Ice Lake to Yoldia Sea I and Yoldia Sea III to Ancylus Lake. It does not seem to indicate an influence of input of minerogenic particles, thus terrestrial influences, during the development of the Yoldia Sea including the marine Yoldia Sea II. Thus the peaks for core BPL2b seem to be rather small and constant. When comparing these results to the results of PCA, it is evident that this statistical method results in the movement of cluster of observations diagonally along the x-axis, thus validating not only the phase establishment of point 3.2.4 and the boundaries of each phase to another but also the successional temporal aspect of the development from older to younger phase. The biplot of both observations and loadings, seems to indicate a high degree of sediment variability during the older Baltic Ice Lake phases by showing a correlation of Ca/Ti to the cluster of Baltic Ice Lake, fitting with the deposition of a glacially influenced environment with deglaciations as well as with the drainage of the Baltic Ice Lake into the Baltic Sea Basin. The younger phases are correlated with Ti/Zr, originally plotted as a mean for assessing grain size changes. This correlation was not apparent by solely analyzing the results of the chemical data. However it might be explained when considering the apparent nature and reasoning of plotting Ti, indicating a terrigenic influence and input into a system to Zr, an element which remains largely constant and conservative over long geological periods. In relation to the knowledge of the beginning of the Ancylus Lake, this seems to point to an increase in terrestrial input during transgressions. The S/Ti ratio correlates with a smaller loading to the Yoldia Sea II phase, which supports a marine influence.

4.2.2 Core MSM45 – Eastern Gotland Basin

When analyzing core MSM45 from the Eastern Gotland Basin, it is immediately evident that different conditions must have prevailed during the deposition of sediments in the eastern part of the basin, compared to the results of core BPL2b. The element plots are more varied and boundaries between phases are more evident, yet still the boundaries of the Yoldia Sea II phase are clearly more distinguishable than the boundaries of Baltic Ice Lake to Yoldia Sea I and Yoldia Sea III to Ancylus Lake. Once again the Si/Ti ratio, the Ca/Ti ratio, the S/Ti ratio and the Sr/Ca ratio influence the establishment of boundaries, indicating a higher degree of variability of the sediment and a higher degree of marine input during Yoldia Sea II. Additionally it is important to note that although the plots of Si/Ti and Ca/Ti seem to mirror the same plots of core BPL2b, fluctuations are higher in MSM45 located in the Eastern Gotland Basin. A higher degree of energy throughout the Eastern Gotland Basin can be proposed due to the location of the outlet at the time of Yoldia Sea II, through the Närke Strait and Göta Älv. The saltwater inputs by the marine ingression were of a higher salinity and therefore resulted in deep water bottom currents. When comparing the chemical data to the PCA results it is immediately evident that results do not compare well to the results of core BPL2b. While the variability of the data set was quite evenly contributed to by Factor 1 and Factor 2, the variability of core MSM45 is mostly contributed to by Factor 1. Although clustering of the different developmental phases was successful for core MSM45 too, the movement along the x-axis is directly opposite to the direction of core BPL2b and that the trend of movement is not as clearly developed. Furthermore although the Si/Ti ratio has the highest loading, it is not correlated with any cluster. Additionally, S/Ti seems to be correlated to the Yoldia Sea II phase, indicating a marine influence, while the correlations of Ca/Ti to the Baltic Ice Lake cluster and Ti/Zr to the Ancylus Lake are mirrored in this core as well.

4.2.3 Core MSM40 – Bornholm Basin

When analyzing core MSM40 from the Bornholm Basin, a different interpretation emerges than for the cores in the Gotland Basin. The element ratios as a whole clearly indicate the occurrence of the Yoldia Sea II phase, which is mirrored by the magnetic susceptibility data as well. Higher sediment variability is once again indicated by the Ca/Ti ratio, a marine influence by the S/Ti ratio and the Si/Ti ratio indicates a higher input of silica into the Baltic Ice Lake. When compared to the magnetic susceptibility, a larger influence and input of minerogenic particles is evident as well. This is contrary however to the Ti/Zr and Rb/Sr ratio plots describing a decrease in the general grain size and a diminished influence of the weathering of the bedrock. This can be explained when considering that the marine ingression of the Yoldia Sea phase and thus the brackish influences reached the Bornholm Basin much later than the Gotland Basin and had maybe a diminished influence. While it might be argued that along with a marine influence, the Gotland basin experienced a higher energy input and thus a higher degree of sediment variability, the Bornholm Basin might have had only a brackish influence. This proposed temporal succession stands in stark contrast to Andrén et al. (2000), who proposed that the marine influence reached the Bornholm Basin before the Gotland Basin, by describing a circulation similar to the cyclonic circulation of today, driven by salinity differences. No evidence has been found here to substantiate this hypothesis. A larger terrestrial input is additionally very likely when analyzing the low shore levels and large land connections described by Björck (1995) in the south of the Baltic Sea during the Yoldia Sea. Comparing these element ratio results to the results of the PCA however, a clear picture is not evident. While the clusters for each developmental phase are clearly and distinctly formed, no movement along the x-axis, as described in the other two cores, can be discerned. Furthermore no successional temporal trend from older to younger phase is evident. Additionally when comparing the biplot results to the results of the other two cores, it is clearly evident that trends in correlations between elemental ratios and clusters cannot be identified and are not mirrored.

4.2.4 Summary of the cores

When considering the chemical results with the PCA together, conclusions which can be drawn are that each basin has its own developmental trends and that all basins together cannot be analyzed and interpreted together as an entity. Additionally, in contrast to the visual sedimentary descriptions, boundaries of the Baltic Ice Lake to the Yoldia Sea I and Yoldia Sea III to Ancylus Lake are not as clearly distinguishable. Moreover, the the Yoldia Sea II phase, is clearly not visible in the sedimentary sequences, but is the only phase being clearly identifiable in all three cores. Additionally, when assessing the usability of the different element ratios used in this thesis, it is evident, that the Ca/Ti ratio indicated the marine ingression phase best in all three cores.

4.3 Biogenic Silica considerations

BSi analysis was performed to assess the usability of the Si/Ti ratio plot. The very low values of all three plots in terms of BSi were expected as described by Björck (1995) and Andrén et al. (2000) and therefore only 12 data points were chosen along the depth of the core sequences. The results did not show a clear correlation of Si/Ti and BSi, but instead showed inverse negative trends or non-significant correlation coefficients. It is therefore clearly evident, that the BSi fraction of the sediment does not influence the Si/Ti ratio in these sediment cores and therefore that the latter must have other dominating influential sources. When taking into consideration that the sediment is composed of mainly clay, higher terrestrial influences throughout the development of these Baltic Sea phases largely governed the terrigenic fraction and thus the Si/Ti ratio. The plotted BSi in Fig. 5, although clearly following the assumption of having very low amounts of BSi, do not indicate a higher amount during the marine ingression phase Yoldia Sea II. With most authors, for example Brenner (2005) describing an intense diatom bloom due to the influx of warmer waters and higher nutrient contents, during Yoldia Sea II, one would expect a maximum in BSi, whereas the plots all show minima. The determining factors resulting in this observation are unknown and cannot be explained by statistical or analytical errors.

5 Conclusions

The results in this study clearly demonstrate the juxtaposition of knowledge gained by macroscopic analysis in comparison to knowledge gained on a microscopic or atomic scale and the need for a conclusive methodology, encompassing a variety of methods.

All three core locations experienced different influences throughout the development of the Baltic Sea result in largely different data.

Macroscopic analysis of the sediment allowed for the identification of the sediments deposited during the Baltic Ice Lake, the Yoldia Sea and the Ancylus Lake. Furthermore, discerning the boundaries of Baltic Ice Lake to Yoldia Sea I and Yoldia Sea III to Ancylus Lake was possible. However no indication of the Yoldia Sea II phase, indicating a marine ingression into the Baltic Sea Basin, could be distinguished.

When analyzing the sediment using X-ray fluorescence, correlations of element ratio plots yielded a clear identification of the Yoldia Sea II phase, which was present in all three cores. However, identifying the boundaries of the Baltic Ice Lake to Yoldia Sea I and Yoldia Sea III to Ancylus Lake was only possible in combination with the sedimentary description and magnetic susceptibility. The Ca/Ti ratio was the ratio which showed the most promise in depicted a marine ingression into the Baltic Sea during the Yoldia Sea II phase.

BSi was very low in the core throughout the temporal span addressed in this thesis and the Si/Ti was ratio was unable to distinguish changes in BSi concentrations.

To further complement this thesis, different methods could be performed to increase the understanding of changes in sediment deposition during different phases. Grain size analysis could be a good means to assess and complement the chemical results, while micro -palaeontological analysis of diatoms and calcareous microfossils could be improving the knowledge regarding the marine ingression of the Yoldia Sea II phase into the Baltic Sea. Further investigation of the use of the varves pertaining to cores MSM45 and BPL2b could be beneficial in giving dates to the events during this studied time span.

6 Acknowledgements

Firstly, I would like to thank my supervisors Daniel Conley and Svante Björck for giving me the possibility to work on this project and the support and patience throughout. I would furthermore like to thank Åsa Wallin for first introductions to the sedimentary laboratory, Leif Johansson for the introduction to the X-ray fluorescence analysis and Carolina Funkey for her help while performing the biogenic silica analysis. In addition, I owe a big deal of gratitude to my family especially my parents, for supporting me throughout my studies and giving me the possibility to study in Lund. Last but not least, I thank René Heistermann for his help and never ceasing support.

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