Quaternary International xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Environmental evolution of western Baltic Sea in the Holocene in the light of multidisciplinary investigations of sediments cores from Arkona Basin

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ARTICLE INFO

Keywords:
Diatoms
Grain size
Geochemistry
Acoustic profiling
Littorina transgression
South-western Baltic Sea
Arkona Basin

ABSTRACT

A multidisciplinary investigation performed on gravity cores, supplemented by a new radiocarbon dating of macrofossils, outlined the environmental evolution of Arkona Basin in the Holocene. Studies comprising the analysis of diatoms, geochemistry, grain size, and radiocarbon dating clarified the knowledge about the age and environmental changes during freshwater and marine transgressions and regressions. The acoustic profiling method allowed proper interpretation of the analysis results from sediment cores and created a proper lithostratigraphic model of the investigated basin. Baltic Ice Lake and Yoldia Sea sediment layers were identified acoustically and cores penetrated the final regression surface of the Baltic Ice Lake. The analyses of cores concentrated on Ancylus Lake and Littorina Sea sediments. Two phases of the Ancylus Lake stage were identified. The peaks of loss on ignition in the cores, observed as a strong acoustic reflector, were identified as a marker of Ancylus Lake regression between the first, high-water level phase and the second, shallow-water phase. The age of onset of Littorina transgression was estimated at around 7000–7200 cal BP and was younger than some previous estimations. The retrieved age confirmed the suggestion that the marine environment appeared first in Mecklenburg Bay and then after a few hundred years in Arkona Basin as an intensive transgression. The appearance of Littorina Sea revealed a fast shift of the environment from lacustrine to marine. The first phase of the Littorina stage was recognised as a rapidly increasing water level and high-energy environment; the second showed rapidly increasing salinity in the calmer conditions of sedimentation.

1. Introduction

The specific location of the Arkona Basin at the mouth connecting it to the Baltic Sea through the Danish straits with the North Sea and water depth below −40 m make this basin interesting for investigation of the sea-level fluctuation of the Baltic Sea during the Holocene. High stands of the water level, interrupted by dramatic drops, were recorded in the Arkona Basin sediments. After the last deglaciation, the first high stand of the water level of −20 m (Jensen et al., 1997) appeared as the Baltic Ice Lake and was interrupted by regressions to a depth of around −40 m: the first at around 12,800 cal BP (Bennike and Jensen, 2013) and the second as final drainage at 11,600 cal BP (Kortekaas et al., 2007). The period of the Baltic Ice Lake (BIL) recorded in the Arkona Basin as grey and reddish-brown clay sediments with sandy layers corresponded to the abovementioned drainage events (Moros et al., 2002). The Yoldia stage and Ancylus Lake appeared in the studied area as dark grey silty clay sediments with organic detritus deposited in the freshwater reservoir (Jensen et al., 1999). The Ancylus Lake transgression reached its maximum at −19 m at around 10,500 cal BP (Lemke, 1998; Jensen et al., 1999). The stepwise increase of the water level was interrupted by slight regression to −32 m at 10,200 cal BP (Moros et al., 2002). The first weak saline inflows into the Baltic basin dated at 10,100 cal BP (Andrén et al., 2000; Berglund et al., 2005) led to the formation of the initial Littorina Sea. The early marine inflows were reported in the south-western Kattegat and Great Belt at about 9500 cal BP (Jensen et al., 2005; Bendixen et al., 2015), suggesting the pathway of the first transgression via the Danish straits and Mecklenburg Bay. Previous studies confirmed the existence of a slight marine environment in Mecklenburg Bay during 8800–7700 cal BP (Witkowski et al., 2005; Kostecki et al., 2015), called the Mastogloia stage, due to the typical diatom flora composition. Arkona Basin was isolated from direct marine inflows at this time. The evidences found in Arkona Basin undoubtedly confirmed the occurrence of marine transgression a few hundred years later than in Mecklenburg Bay and dated at around 7200–6500 cal BP at the bottom part of Littorina mud (Kortekaas, 2007; Rößler et al., 2011). This age is younger than previously reported dates

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https://doi.org/10.1016/j.quaint.2018.07.007
Received 10 April 2018; Received in revised form 4 July 2018; Accepted 27 July 2018
1040-6182/

of onset of Littorina transgression in the south-western Baltic Basin (Andrén et al., 2000; Berglund et al., 2005). The inconsistency in the age of the beginning of the proper Littorina Sea stage remains a matter of debate. Some discrepancies are due to a lack of macrofossils in the studied sediments, which restricted proper dating, and dates based on bulk samples that could contain old reworked carbon (Rößler et al., 2011). The salinity during the Littorina Sea stage was characterised by large variations, which have also been discussed (Gustafsson and Westman, 2002; Ning et al., 2017). Ning et al. (2017) identified the period of 7300–6400 cal BP as the Littorina transgression maximum with a relatively high sea level and the period of 6400–3900 cal BP as the phase characterised by high salinity. The youngest period, called the Post-Littorina Sea (3900–3000 cal BP to present), was characterised by decreased salinity (Andrén et al., 2000; Ning et al., 2017). Another interesting unresolved problem that could affect environmental reconstruction is the differential thickness of the Littorina mud sediments in the deepest part of the Arkona Basin (water depth below 45 m). The thickness of the Littorina sediments was estimated as 4–3 m in the central and southern parts of the basin (Moros et al., 2002), 2 m in the northern part (Trimonis et al., 2008), and 3 m in the eastern part (Kortekaas et al., 2007). These differences could be explained by the depth position of the uppermost till surface (Lemke, 1998; Rößler et al., 2011) and also by the proximity to sediment sources resulting from currents of water exchanged between the Baltic Sea and the North Sea. Thus, there is a need to refine our knowledge about the evolution of the depositional environment of the Arkona Basin. The main aim of the presented study based on multidisciplinary investigation of sediments cores is to ascertain the proper chronology of transgression and regression events in the studied area and also salinity and water level changes. The reconstruction of salinity and water depth changes is based on new results of analysis of diatom assemblages and radiocarbon dating, mainly of calcareous fossils. Furthermore, the results are compared to the grain size and geochemical analyses and the results of acoustic profiling.

1.1. Study area

The Arkona Basin is the deepest basin of the western Baltic Sea, with a maximum depth of −48 m situated between the coast of Germany to the south, the Danish islands to the west, the south coast of Sweden to the north, and Bornholm Island to the east. The central part of the basin is characterised by a flat bottom at a depth below −40 m. The basin is connected with the Great Belt via Mecklenburg Bay and Darss Sill threshold to the west and with Öresund to the north-west. The area of Arkona Basin is limited to the east by the Bornholm Basin.

2. Materials and methods

2.1. Sample collection

The investigated material originated from four sediment cores. The cores were taken by the gravity corers aboard research vessels R/V *Maria S. Merian* in 2006 (318210, 318320) and FS *Elisabeth Mann Borgese* in 2013 (EMB058-15-8, EMB058-17-7). All analysed cores were located in the central and southern parts of the Arkona Basin and were taken at a water depth of 45–47 m (Figs. 1 and 2). The westernmost core EMB058-17-7 was taken at a water depth of 46.3 m at 54° 56.87′ N, 13° 18.20′ E, 30 km to the north of Rügen Island and 49 km to the east of Møn Island. The easternmost core, EMB058-15-8, was taken at a water depth of 46.14 m at 54° 55.288′ N, 13° 44.093′ E, 28 km to the east of core EMB058-17-7. Core 318310 was taken from the southern part of the Arkona Basin at a water depth of 46 m, at 54° 50.335′ N, 13° 32.030′ E, 19 km north-east of Rügen Island. The following core, 318320, was taken at a water depth of 45 m at 54° 49.786′ N, 13° 39.365′ E, 7.8 km to the east of core 318310. The cores were cut into 1-m opaque tubes onboard and stored in cooling conditions. Grain size, geochemical, and diatom analyses were performed on 1-cm samples at 1–5 cm intervals depending on the lithology.

2.2. Acoustic profiling

Acoustic profiles were recorded with an Innomar SES-2000 medium parametric sub-bottom profiler at secondary frequencies set to 5, 10, and 15 kHz. The narrow sound beam (4°) for all frequencies and the absence of sidelobes resulted in high-resolution records. Similarly, an Atlas Parasound system installed on the R/V *Maria S. Merian* operated at a secondary frequency of 4 kHz. The motion reference unit delivered data to compensate for the heave, roll, and pitch of the ship. The recording gain (adjusted for the AD converters) was stored for post-processing to create comparable acoustic images. MATLAB tools were used for post-processing, enabling the coring data to be plotted precisely onto the acoustic profile. The raw data were used for acoustic images using procedures with swell filters and compensations for p-wave attenuation and distortions. The different secondary frequencies were stacked to increase the signal-to-noise ratio and combine the better penetration of 5 kHz with the higher resolution of 15 kHz. However, this also results in softening effects, since different frequencies record different acoustic reflectors, but the image includes information of these three frequencies.

2.3. Diatom analysis

The standard methods (Battarbee, 1986) were used for the preparation of diatom samples. The diatoms between 300 and 500 valves were counted in each sample in order to estimate the percentage abundances of particular taxa (Schrader and Gersonde, 1978). The diatom species were divided into groups according to their biotope requirements; planktonic and benthic groups were distinguished (Round, 1981). Diatoms were grouped with respect to their salinity requirements according to Kolbe's (1927) halobous system: polyhalobous (salinity > 30 PSU), mesohalobous (5–20 PSU), oligohalobous halophilous (< 5 PSU), indifferent (0–2 PSU), and halophobous (0 PSU). The identification and ecological information was based on studies by Bąk et al. (2012), Denys (1991), Krammer and Lange-Bertalot (1988, 1986, 1991a, 1991b), Lange-Bertalot and Genkal (1999), Krammer (2002), Pliński and Witkowski (2009, 2011), Reichardt (1999), Snoeijs (1993), Snoeijs and Vilbaste (1994), Snoeijs and Popova (1995), Snoeijs and Kasperoviciene (1996), Snoeijs and Balashova (1998), Witkowski (1994), and Witkowski et al. (2000). The percentage content of all ecological groups was estimated in each sample. Diatom assemblage zones (LDAZs) were distinguished based on differences in the species compositions, the relative frequencies of diatom taxa, and the prevalent ecological and habitat groups.

2.4. Geochemical and grain size analyses

Geochemical analyses of cores were performed to determine organic matter as loss on ignition (LOI) and contents of terrigenous and biogenic silica and the metals magnesium (Mg), calcium (Ca), iron (Fe), and manganese (Mn). The LOI was a result of the combustion of dried samples at 550 °C. The total silica content was measured as a result of digestion in aqua regia in a water bath, while the terrigenous silica content was measured after dissolution of biogenic silica in a solution of 0.5 N sodium hydroxide. The metal content was determined in digested liquid samples using flame atomic absorption spectrometry (Boyle, 2001). The grain size distribution was measured in the core EMB058-15-8 using the laser diffraction method with a Malvern Mastersizer 2000 in the samples cleaned previously from carbon and organic matter with HCl and by boiling with H_2O_2 and washing with distilled water.