Holocene evolution of the Pomeranian Bay environment, southern Baltic Sea*

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Abstract

This article focuses on the diatom assemblages and geochemical composition of sediment cores retrieved from the Pomeranian Bay. We also discuss similarities and differences in the diatom assemblages and the palaeogeographic development of nearby regions. Our main objective was to determine the characteristics and rate of the Littorina transgression in the Pomeranian Bay area. Sediments were divided into units based on differences in the distribution of diatom ecological groups and in geochemical ratios, such as Mg/Ca, Na/K and Fe/Mn. This study identified lacustrine sediments deposited during the time of the Ancylus Lake. This lacustrine-period sedimentation took place in a shallow lake under aerobic conditions. The record of the onset of marine environment dates to 8900–8300 cal BP and corresponds to the Littorina transgression. After about 8300 cal BP, sedimentation took place in a deeper marine environment with higher biogenic production and anaerobic conditions. The abrupt appearance of marine diatom

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species and increased geochemical salinity indicators reflect the large impact of the Littorina transgression on the Pomeranian Bay environment.

1. Introduction

The evolution of the Pomeranian Bay environment during the last 10 000 years is not well known. Previous studies have suggested that the basin was formed as a result of marine transgression into the hinterlands around 7200 cal BP (Kramarska 1998, Krzymińska & Przeździecki 2001, Broszinski et al. 2005). The study area of the Pomeranian Bay was land covered by numerous lakes in the Early Holocene. At 20 m below sea level (b.s.l.) the maximum water level of the Ancylus Lake did not flood the terrestrial areas (Lemke et al. 1998). Kramarska (1998) reported the existence of a lagoon separated from the marine Littorina Sea Basin by the barrier of the Odra Bank until ca 5500 cal BP (5100 ± 200 BP, calibrated by the authors). The global eustatic sea-level rise in the Atlantic period caused the inflow of marine water (Rosa 1963, Borówka et al. 2005, Lampe 2005) that led to the Littorina transgression.

The glacio-isostatic factor could have an important influence on the formation of the southern Baltic coast (Mörner 1976, Rotnicki 2009). Rotnicki (2009) suggested that a hypothetical northward shift of the foreland bulge could have been partially responsible for the transgression and regression periods.

The transgression produced an open marine bay that extended southwards into the lower Odra River Valley. Some researchers (Rosa 1963, Borówka et al. 2005) have suggested that this event may have been dramatic. The rapid transgression may have been caused by the disruption and destruction of the sand bar between the Odra Bank and the east coast of the Pomeranian Bay during extremely severe storms (Borówka et al. 2005). However, marine conditions could have affected this area at ca 7000 BP (Kramarska 1998). Uścinowicz (2006) also described a rapid sea level rise in north-western Europe at ca 8500 to 6500 cal BP.

Earlier geological studies of Pomeranian Bay were based on diatomological (Broszinski et al. 2005) and malacological (Krzymińska & Przeździecki 2001, Borówka et al. 2005) analyses of a few cores taken from the eastern part of the bay. Research to date has not determined the intensity of flooding of the former terrestrial environment caused by the Littorina transgression, or the nature of the early Holocene terrestrial depositional environments. The main objectives of this study were to determine the characteristics and rate of the Littorina transgression, and to ascertain the importance of coastal pre-Littorina lagoons and lake basins in the development of the Baltic Sea transgression. The study was based on geochemical and diatomological studies and AMS ^{14}C dating.

2. Material and methods

2.1. Site description

The Pomeranian Bay is a large, shallow basin in the south-western Baltic Sea, off the Polish and German coasts. The basin is delimited to the south by the Świna Gate, to the west by the German island of Rügen, and to the north by the Danish island of Bornholm. The bay is located in the vicinity of the Arkona Basin, Eagle Bank and Bornholm Basin. It is no more than 30 m deep. The main form of bottom relief is the Odra Bank, which rises to 7 m b.s.l. in the central part of the basin, and the old Odra Valley, which descends to a depth of 20 m b.s.l. in the western part of the basin. Tromper Wiek is the shallow bay adjacent to Pomeranian Bay and north-east of Rügen. It is separated from Prorer Wiek by the Jasmund peninsula.

2.2. Sample collection and analysis

Six sediment cores were taken with a gravity corer from the Pomeranian Bay by the Institute for Baltic Sea Research (Warnemünde, Germany) aboard the research vessel FS *Alexander von Humboldt*. The cores were obtained from Prorer Wiek and Tromper Wiek, in the western part of the Pomeranian Bay (Figure 1).

Cores 246040 and 246050 were collected from Prorer Wiek at 16 m b.s.l. and were 540 and 485 cm in length, respectively. Core 246060 was taken

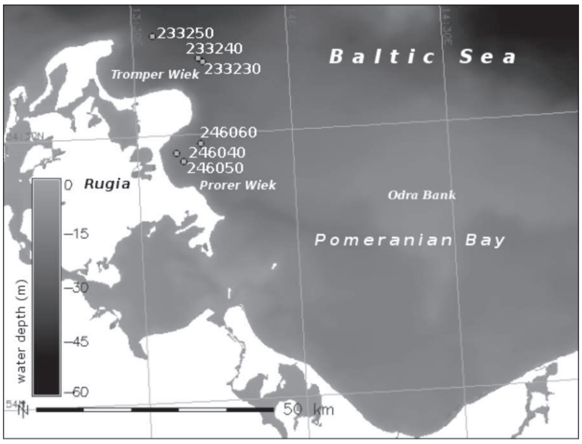

Figure 1. Location of the sampling sites from which sediment cores were taken

below 20 m b.s.l. and was 610 cm in length. Cores 233230, 233240, and 233250 were collected from Tromper Wiek at 28.7, 29.5, and 30.7 m b.s.l. and were 423, 328, and 431 cm in length, respectively.

Sub-samples of 5- to 10-cm-thickness were collected from the cores, depending on the lithology.

Geochemical analyses were conducted to determine loss on ignition, terrigenous silica and biogenic silica, as well as sodium (Na), potassium (K), magnesium (Mg), calcium (Ca), iron (Fe) and manganese (Mn) contents. Dried samples were combusted at 550°C to determine loss on ignition. The terrigenous silica content was obtained by digestion in aqua regia, and the biogenic silica content was determined by digestion in sodium hydroxide (NaOH). The main elements were measured in digested liquid samples using flame atomic absorption spectrometry (FAAS; Boyle 2001).

Samples were prepared for diatom analysis according to the standard method described by Battarbee (1986). Analyses were conducted using an illuminating microscope (Nikon Eclipse E200) with 100× lenses. Approximately 300 valves per sample were counted. Diatom taxonomy and their ecological grouping were determined according to the classifications of Krammer & Lange-Bertalot (1991a, 1991b) and Witkowski et al. (2000).

Bulk sediment samples and shells of *Cerastoderma* sp. were dated at the Poznań Radiocarbon Laboratory by ^{14}C accelerator mass spectrometry (AMS; Table 1). Radiocarbon dates were calibrated with OxCal software (Bronk Ramsey 1995) using the Marine09 data set (Reimer et al. 2009), with the Baltic Sea regional ΔR value of -100 ± 100.

Table 1. Radiocarbon and calendar ages of the sediments analysed in this study

Sample code	Type of material	Depth below bed surface [m]	Radiocarbon age ^{14}C [BP]	Calibrated age [cal year BP]	Laboratory code
246060/180	shell	1.8	5560 ± 50	5885–6000 (68.2%) 5840–6115 (95.4%)	Poz-33882
246060/250	organic mud	2.5	7720 ± 50	8139–8275 (68.2%) 8046–8315 (95.4%)	Poz-33884
246060/280	gyttja	2.8	8300 ± 50	8785–8961 (68.2%) 8660–8999 (95.4%)	Poz-33885
246060/370	silty clay	3.7	9700 ± 60	10499–10609 (68.2%) 10424–10704 (95.4%)	Poz-33886

3. Results

3.1. Cores from Prorer Wiek

3.1.1. Core 246040

Three sediment cores were taken and examined from Prorer Wiek (Figures 1, 2). The shallowest of these cores (core 246040, 15.7 m b.s.l.) consisted of three parts (Figure 3). The lowest part (E1) contained olive-grey clay silt with few plant remains. The sediments of this zone exhibited the highest contents in a core of biogenic silica (6%) and loss on ignition (6%), and the lowest content of terrigenous silica (69%). This zone was also characterized by lower ratios of Mg/Ca, Fe/Mn and Na/K than in other zones. The Na/K ratio was highest in this zone only at the base of zone E1.

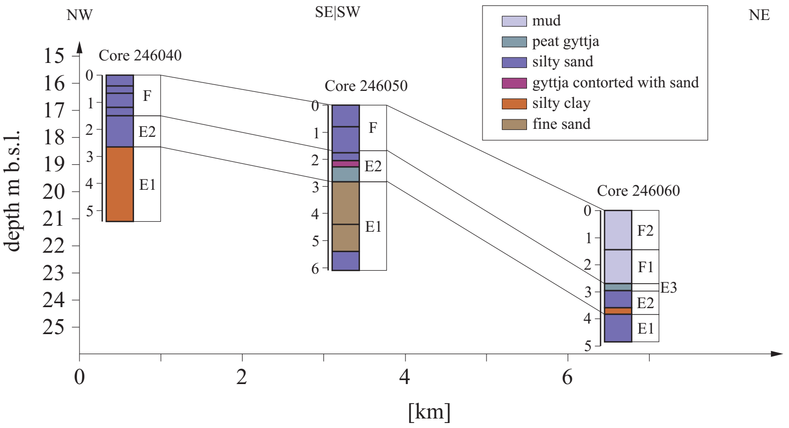

Figure 2. Sedimentological logs and correlations of the cores from Prorer Wiek

The second zone (E2) began at a depth of 265 cm and contained fine, olive-grey, silty sand with fine shell debris of the *Ancylus*, *Pisidium* and *Spherium* genera. The geochemical composition of this zone yielded a slightly higher contribution than in zone E1 of terrigenous silica and higher ratio of Fe/Mn and Na/K, whereas the contribution of biogenic silica and loss of ignition decreased.

The uppermost zone (F) of core 246040 began at a depth of 176 cm and consisted of fine, olive-grey sand with shells of the *Macoma*, *Cerastoderma*, *Mytilus*, and *Hydrobia* genera. The ratio of Mg/Ca, Fe/Mn and Na/K and the content of terrigenous silica (95%) were the highest observed in this core, while the content of biogenic silica and loss on ignition were the lowest.

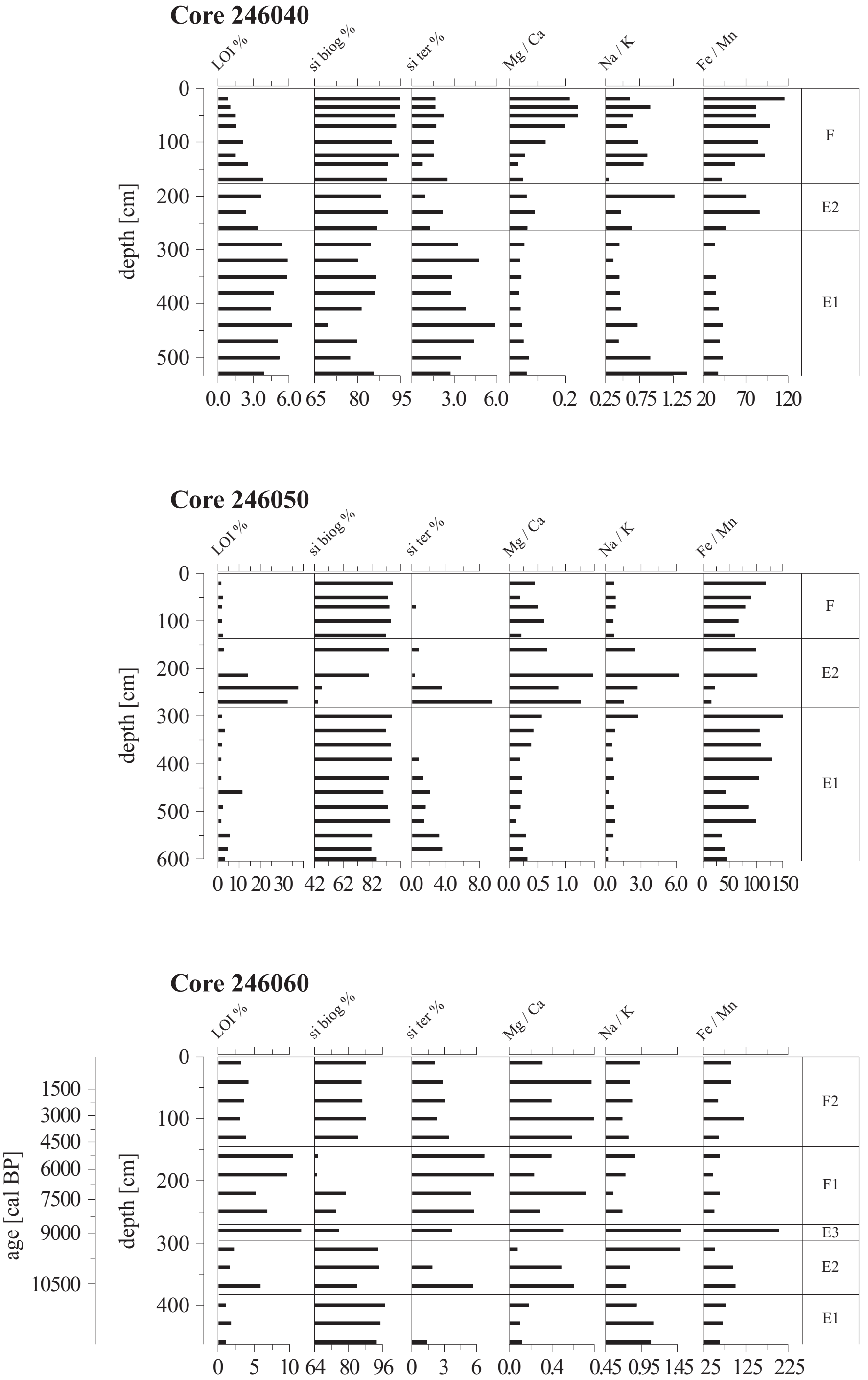

Figure 3. Geochemical composition of the sediment in the cores from Prorer Wiek

3.1.2. Core 246050

Core 246050 was taken at a depth of 16.8 m b.s.l., to the south-east of core 246040 (Figures 1, 2). This core also consisted of three distinct zones (Figure 3). The lowest zone (E1; 283–610 cm) contained fine, olive-grey sand with humus particles and abundant plant remains. The geochemical composition of this zone exhibited a high content of terrigenous silica (95%) and Fe/Mn ratio, and a low content of biogenic silica (0–3%), loss of ignition (1.5–11%), and ratio of Mg/Ca and Na/K. This zone did not contain diatom flora.

The central zone (E2; 136–283 cm) contained brownish-black peat gyttja and detritus gyttja (205–283 cm) with wood and reed remains, and fine, olive-grey sand (136–205 cm) with plant remains. The sediment in the gyttja portion of this zone was characterized by higher contents in the core of biogenic silica (9%) and loss on ignition (37%), a low content of terrigenous silica (44%) and low Mg/Ca, Na/K and Fe/Mn ratios. However, the sand portion of E2 contained the highest amount of terrigenous silica, and all the elemental ratios were the highest. Zone E2 contained benthic freshwater diatom species, such as *Fragilaria martyi*, *F. brevistriata*, *F. pinnata* and *Amphora pediculus*, and brackish-water species, such as *F. guenter-grassi* and *F. geocollegarum*.

The uppermost zone (F; 0–136 cm) contained fine, olive-grey sand with shells of the *Macoma*, *Mytilus*, *Cerastoderma*, and *Hydrobia* genera. Terrigenous silica (95%) was the dominant contributor in this zone. The ratios of Mg/Ca, Na/K and Fe/Mn were low at the base of this zone, but increased gradually in the upper levels of the core. Diatoms were too few to count.

3.1.3. Core 246060

The deepest core from Prorer Wiek (core 246060) was taken at a depth of 20.7 m b.s.l., 5 km north-east of core 246040 (Figures 1, 2). Its geochemical composition suggested a division into five parts (Figure 3). The lowest zone (E1; 383–485 cm) contained fine, olive-grey sand with humus particles. The sediment of this zone had the highest content in this core of terrigenous silica (97%) and a low content of biogenic silica (0.5%), loss on ignition (1%) and ratio of Mg/Ca (0.2) and Fe/Mn (70). This zone did contain diatom flora.

The next zone (E2; 296–383 cm) consisted of olive-black silty clay and olive-grey sandy silt. The contents of biogenic silica (6%), loss on ignition (6%) and the ratios of Mg/Ca (3.5) and Fe/Mn (100) were higher than in zone E1. In zone E2, we found abundant diatom flora dominated by freshwater benthos species, including *F. lapponica*, *F. martyi*, and *A. pediculus* (Figure 4). The dominant brackish-water forms included

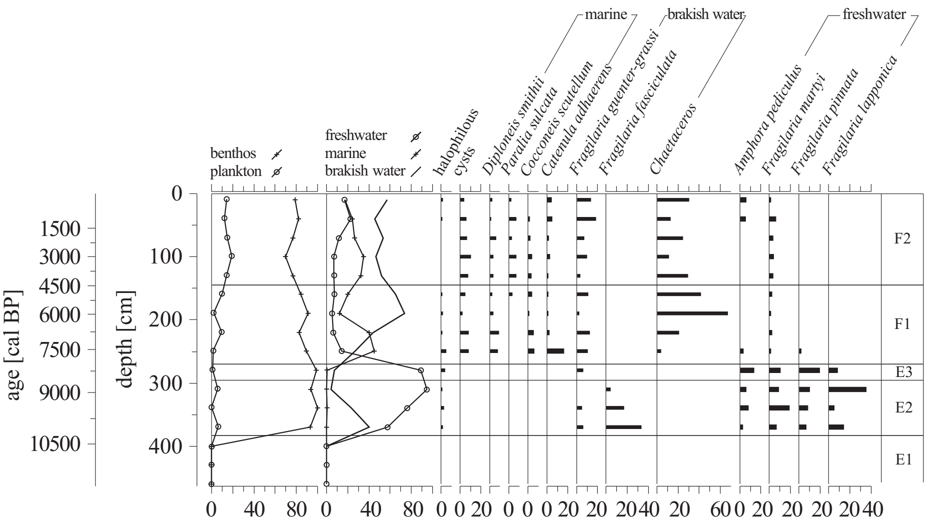

Figure 4. Distribution of diatom ecological groups and diatom species in core 246060

F. guenter-grassi and *F. fasciculata.* The silty clay sediments at 370 cm depth were dated to 10 704–10 424 cal BP (9700 ± 60 ^{14}C years BP; Table 1).

Zone E3 (270–296 cm) consisted of olive-black peat gyttja. The sediments of this zone exhibited a 12% loss on ignition, 3.6% biogenic silica content and high ratios of Na/K (1.5) and Fe/Mn (200). Like zone E2, the diatom assemblage of zone E3 was dominated by freshwater benthos taxa. A sediment sample from 280 cm depth was dated to 8999–8660 cal BP (Table 1; 8300 ± 50 ^{14}C years BP). Radiocarbon dating yielded ages that corresponded to the Ancylus Lake.

Zone F1 of core 246060 (145–270 cm) contained mainly olive-grey mud with *Mytilus* and *Cerastoderma* shells. The biogenic silica content (3–7%), loss on ignition (6–10%) and ratios of Mg/Ca (0.5–3), Na/K (0.5–0.8) and Fe/Mn (50–60) increased gradually towards the top of the zone, whereas the contribution of terrigenous silica (78–65%) decreased. The diatom assemblage changed abruptly from freshwater to marine/brackish water-species at the base of zone F1 (Figure 4). Marine species such as *Diploneis smithii*, *Cocconeis scutellum*, *Pseudosolenia calcar-avis* and *Paralia sulcata*, and brackish taxa such as *F. guenter-grassi*, *F. geocollegarum*, and *Chaetoceros* sp. spores were predominant throughout this zone. The sample taken from the bottom portion of the zone (250 cm) was dated to 8315–8046 cal BP (7720 ± 50 ^{14}C years BP; Table 1), and a *Cerastoderma* shell from 180 cm depth was dated to 6115–5840 cal BP (5560 ± 50 ^{14}C years BP). These dates place the deposition of these sediments in the period after the Littorina transgression. The diatom assemblages and geochemical composition confirm the development of a marine environment.

The uppermost zone F2 (0–145 cm) contained olive-grey mud with *Scrobicularia* shell debris. The main geochemical features of this zone were the high content of terrigenous silica (88%) and large Mg/Ca, Na/K and Fe/Mn ratios.

3.2. Cores from Tromper Wiek

3.2.1. Core 233230

We examined three sediment cores taken from Tromper Wiek (Figure 1). All were characterized by a similar lithology and geochemical composition. The shallowest (core 233230) was taken at a depth of 28.7 m b.s.l. (Figure 5). The sediments could be divided into two zones (Figure 6). The lower zone (E; 132–423 cm) contained olive-grey silt with fine humus particles in the lower portion, and fine sand with plant remains in the upper portion. The sediment of zone E had the highest content of terrigenous silica (97%) and a low content of biogenic silica (2%), loss on ignition (2%) and ratios of Mg/Ca (0.2), and Fe/Mn (40). The Na/K ratio was less than 1.

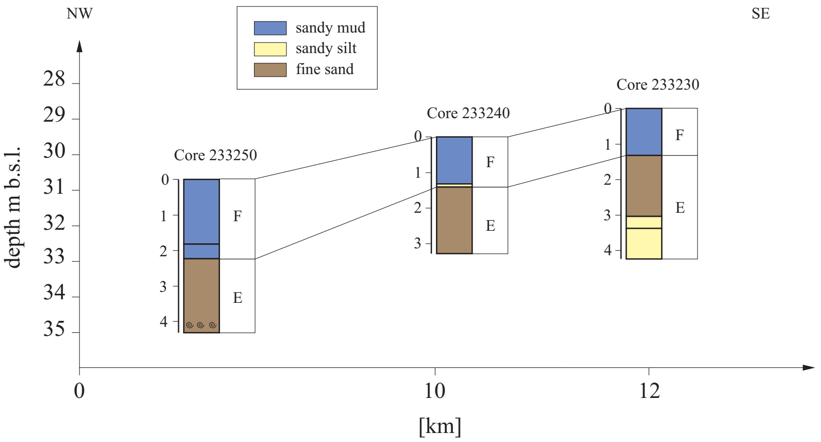

Figure 5. Sedimentological logs and correlations of the cores from Tromper Wiek

The upper zone (F; 0–132 cm) consisted of olive-grey mud with some shell remains. It was indistinctly laminated below 96 cm and slightly darker and sandy below 127 cm. The base of zone F had the lowest content of terrigenous silica (70%), which gradually increased in the upper portion of the core. This zone had a higher content of biogenic silica (7.3%) than zone

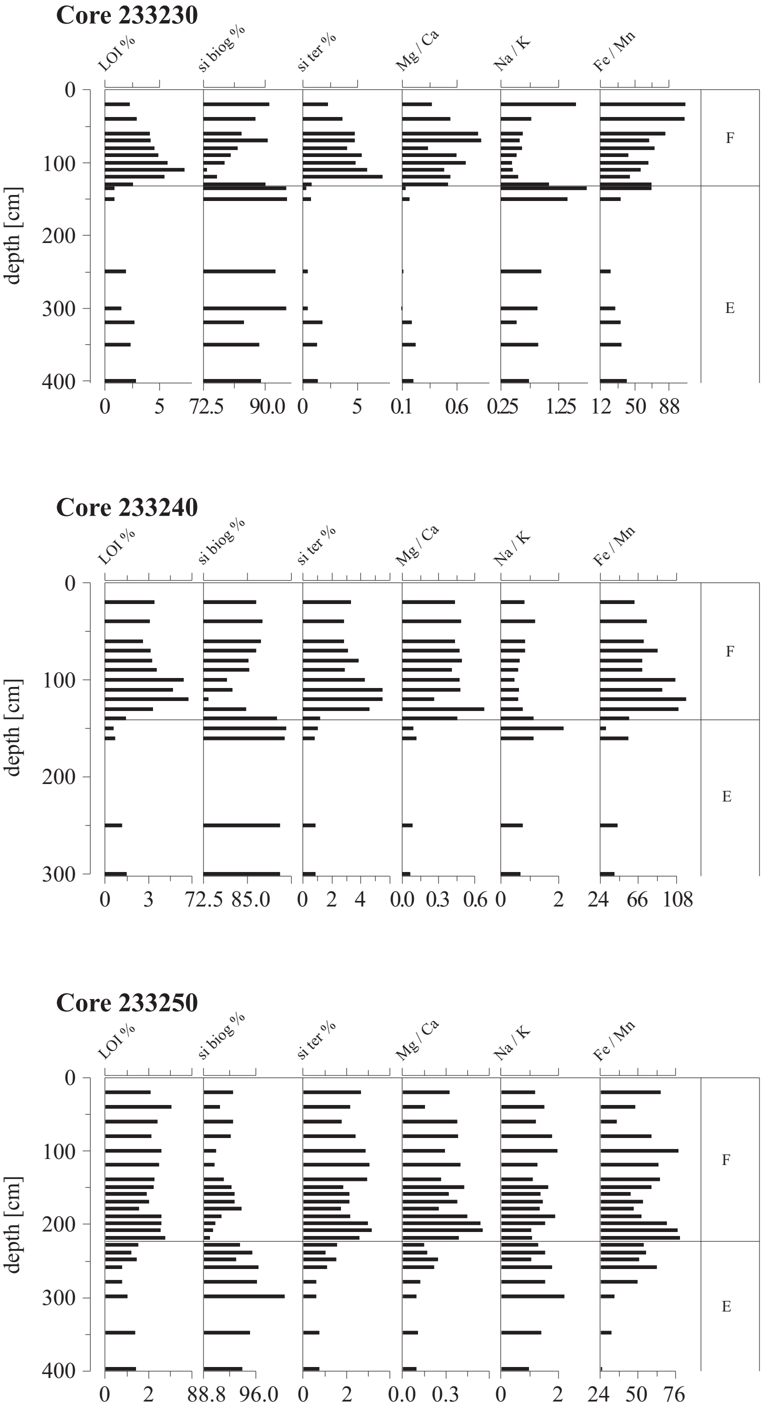

Figure 6. Geochemical composition of the sediment in the cores from Tromper Wiek

E, a higher loss on ignition (7.4%) and greater ratios of Mg/Ca (0.8), Na/K (1.5) and Fe/Mn (100).

3.2.2. Core 233240

Core 233240 was taken at a depth of 29.5 m b.s.l., 2 km north-west of core 233230 (Figures 1, 5). The sediments of this core were divided into the same two zones as in core 233230 (Figure 6). The lower zone (E; 132–328 cm) consisted of fine, pale-olive sand with a thin silty layer at 160 cm and olive-grey silt with a 1 cm layer of peat gyttja at 141 cm. The geochemical composition of zone E had the highest content in the core of terrigenous silica (96%) and low biogenic silica content (1%), loss on ignition (1.5%) and ratios of Mg/Ca (0.1) and Fe/Mn (55). The Na/K ratio increased gradually to a value of 2 in the upper levels of zone E.

The upper zone (F; 0–132 cm) consisted of fine, olive-grey sandy mud with a large broken *Arctica* shell at 119 cm. The geochemical composition of this zone had the lowest content of terrigenous silica (70%) in the core and a higher contribution of biogenic silica (5.5%), loss on ignition (6%) and ratios of Mg/Ca (0.7), Na/K (1.5) and Fe/Mn (120).

3.2.3. Core 233250

The deepest core from Tromper Wiek (core 233250) was taken at a depth of 30.7 m b.s.l., 10 km north-west of core 233240 (Figures 1, 5). This core consisted of two sediment zones (Figure 6). The lower zone (E; 233–431 cm) consisted of fine, dark-grey sand with a downward decreasing number of humus particles. The main features of the geochemical composition were the high content of terrigenous silica (99%), and the low biogenic silica content (1%), low loss on ignition (1.5%) and low ratios of Mg/Ca (0.2) and Fe/Mn (50). The Na/K ratio exhibited poor variability along the core.

The upper zone (F; 0–233 cm) consisted of fine, olive-grey sandy mud with shell debris at 90 cm. The geochemical composition of zone F was similar to that of the upper zones of the previously described cores, with a higher content of biogenic silica (3%), a higher loss on ignition (3%) and also higher ratios of Mg/Ca (0.8) and Fe/Mn (106).

4. Discussion

The aim of this study was to reconstruct the development of the Littorina transgression in the south-western Baltic Sea area.

Our investigation involved the analysis of three sediment cores taken from Prorer Wiek, near the west coast of the island of Rügen, and three cores taken from Tromper Wiek, a few kilometres from the island's north coast.

The sediments from all the cores were divided into two main units. The lower one consisted of sand and silt deposited from 10 700–8300 cal BP, which corresponds to the Ancylus Lake period (Lemke et al. 1998, Jensen et al. 1999). This unit contained zone E (233230, 233240, 233250), zones E1, E2, (cores 246040, 246050), and zones E1, E2, E3 (core 246060). As a result of lithological and geochemical differentiation, the lower unit in cores 246060, 246040, and 246050 was subdivided into sub-zones. The lake environment represented by these sediments originated with the glacio-isostatic land uplift of central and southern Sweden caused by the melting of the land-ice masses (Schmölcke et al. 2006). The existence of a lacustrine environment was confirmed by the predominance of freshwater diatom species, such as *F. martyi*, *F. brevistriata*, *F. pinnata*, *F. lapponica*, *F. martyi* and *A. pediculus*. All of these species are benthic, which is indicative of the development of a shallow-water environment in the coastal zone of the Ancylus Lake and/or other lakes in the area.

The geochemical composition of the lacustrine-period sediments from all the cores was characterized by the predominance of terrigenous silica, low contents of biogenic silica and low loss on ignition. This composition indicates a dynamic environment with mineral input likely from adjacent rivers. The lower ratio of the geochemical indicator Mg/Ca confirms the existence of the lacustrine environment, whereas the low Fe/Mn ratio (< 50) appears to be related to the aerobic conditions of the shallow lake.

A significant environmental change is visible at depths 130 to 270 cm b.s.l. in cores from Prorer Wiek. and depths 130 to 230 cm in cores from Tromper Wiek. This change took place around 8900–8300 cal BP. The lithology of sediments from all the cores changed to olive-grey mud with marine shells at these depths. Because of lithological and geochemical differentiation, the marine sediment was subdivided into zones F1 and F2 (core 246060). Zone F in cores 246040, 246050, 233230, 233240, and 233250 belongs to the marine unit. The main cause of these lithological changes was the Littorina transgression, which began around 8700 cal BP (Lemke 1998). The abundance of freshwater diatoms suddenly decreased and marine and brackish-water taxa such as *D. smithii*, *C. scutellum*, *P. calcar-avis*, *P. sulcata*, *F. guenter-grassi*, and *F. geocollegarum* emerged. The greater number of plankton forms in the marine unit than in the lacustrine unit indicates the greater depth of the basin. The composition of the marine diatom assemblages in our study was similar to that from Mecklenburg Bay (Witkowski et al. 2005).

Studies conducted in Mecklenburg Bay (Jensen et al. 1999, Witkowski et al. 2005) have reported dates similar to those obtained in this study. Our results and previous studies indicate a drastic rise in water level and fully marine conditions from 8300–7800 cal BP.

The geochemical composition of the marine-period sediments was characterized by a lower content of terrigenous silica and a higher content of biogenic silica and loss on ignition than the sediments from the lacustrine unit. These characteristics suggest the development of an environment with a higher input of nutrients than was the case in the lake period, which caused an increase in biogenic production that led to anaerobic conditions. This development of anaerobic conditions is confirmed by the high Fe/Mn ratio (Boyle 2001). The increasing Mg/Ca ratio confirms the change from the freshwater to the marine environment.

The age, diatom assemblage and geochemical composition of the freshwater unit, deposited during the Ancylus Lake stage, correspond to unit E4 of sediments from Tromper Wiek (Lemke et al. 1998). The sediments of the marine unit were deposited during the Littorina Sea stage and correspond to unit E5 from Tromper Wiek (Lemke et al. 1998).

The diatom flora species and geochemical indicators at the transition between units E and F show the impact of the marine waters from the Littorina transgression. The Littorina transgression in our study area is dated to 8900–8300 cal BP. It should be borne in mind, however, that these dates come from bulk material and may be too old.

Studies from Arkona Basin reported younger dates based on calcareous fossils from the onset of the Littorina transgression (7200 cal BP) (Moros et al. 2002, Rößler et al. 2007, 2010). Older dates for the first marine stage have been reported by Witkowski et al. (2009) for the Rega River Valley (8640 cal BP) and Rotnicki (2008, 2009) for the Gardno-Łeba Plain (8550 cal BP).

Studies in Wismar Bay have placed the beginning of the Littorina transgression at a similar period, around 8650 cal BP (Lübke 2002, Lampe et al. 2005, Schmölcke et al. 2006, Lübke & Lüth 2009). Lübke & Lüth (2009) discovered submerged Mesolithic human settlements at a water depth of 11 m below mean sea level (MSL) dated 8350–7950 cal BP. The rise in sea level forced people to abandon earlier settlements (Schmölcke et al. 2006).

A study of deposits from the Szczecin Lagoon places the transgression at 7200 cal BP (Borówka et al. 2005). The similar age of the pre-Littorina limnic deposits from Pomeranian Bay (7000 cal BP, Kramarska 1998) and Szczecin Lagoon (7200 cal BP, Borówka et al. 2002, 2005) indicate the rapid rate of the marine transgression. The rapid change in diatom species from freshwater to marine taxa in our study confirmed the abruptness of the transgression. The change could have taken place during extremely strong surges that broke through the sand barrier that once existed on the contemporary Odra Bank (Kramarska 1998, Borówka et al. 2005).

5. Conclusions

The diatom and geochemical records of the sediment deposits in the Pomeranian Bay area reflect a substantial change in environmental conditions during the Holocene. The record of cores began in the Ancylus Lake period, around 10 700 cal BP. During this period, sedimentation took place in a shallow lake under aerobic conditions. The record indicates that marine sediments covered lacustrine ones. This onset of marine deposition was dated 8900–8300 cal BP and corresponded to the Littorina transgression. This age estimate is a tentative one because the date comes from one single core of bulk material.

The sediments were deposited in a deeper, anaerobic marine environment with a high nutrient inflow.

The most important finding of this study is the clearly defined transitional layer between the lacustrine and marine units, which indicates the abrupt onset of the Littorina Sea period.

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