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RAPID SEA LEVEL CHANGES IN THE SOUTHERN BALTIC DURING LATE GLACIAL AND EARLY HOLOCENE

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Abstract. In the area of the southern Baltic Sea, the largest and most violent changes in water level took place in Late Glacial and Early Holocene, during the period between 13.0–8.5 ka BP. These changes depended on the varied glacio-isostatic movements between the northern and southern parts of the Baltic Sea, the glacio-eustatic increase in the ocean level and the closing or opening of the connection between the Baltic Sea basin with the ocean.

During the Late Glacial and Early Holocene, the sea level changed within an amplitude as wide as 25–27 m. In some extreme cases, the sea level could have fallen at a rate of about 100–300 mm/a, the sea level rise rate reaching up to about 40–45 mm/a. In Late Glacial and Early Holocene, there were three transgressions: during 12.0–11.2, 11.0–10.3 (the Baltic Ice Lake) and 10.2–9.2 ka BP (the Yoldia Sea and the Ancylus Lake). There were also three regressions, setting on 11.2, 10.3 and 9.2 ka BP. During regressions, depending on the real drainage rate and the local gradient of the bottom inclination, the land possibly grew at a rate of 0.3 to 4 km per year. During transgressions, rate of shoreline migration could reach in some cases up to 150–200 m per year. These processes took place on the surface of the sea bottom currently located at the depth of *c*. 55 to 25 m below sea level and from 30 to 60 km away from the present-day southern coast of the Baltic Sea. Rapid changes of shoreline position are recorded in progradational barrier structures and in the erosion surfaces of the glacial till and glacio-marine clays.

Key words: sea level changes, shoreline migrations, seismostratigraphy, erosional surfaces, progradational structures, Late Glacial, Early Holocene, Southern Baltic Sea.

INTRODUCTION

The early stages of the Baltic Sea related to Late Glacial and Early Holocene are the least known part of the Baltic Sea history. It is true for information about water level changes as well as for the history of environment changes. The water level changes and shoreline migrations in the southern Baltic Sea were controlled by an interplay of deglaciation dynamics, glacio-isostatic movements, and caused by those processes opening or closing the connections with the ocean as well as by the eustatic ocean level rise. The ^{14}C dates and sediment sequences indicate the range of transgressions and regressions during the Late Glacial and Early Holocene in the Southern Baltic Sea area (Fig. 1). Time of this events is determined on the base of data from southern Sweden only (e.g. Svensson, 1991; Björck, 1995).

Fig. 1. Location of the discussed area

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EARLY STAGES OF THE BALTIC SEA HISTORY AS OBSEREVED FROM SCANDINAVIA

The Danish Straits became ice-free about 14.0 ka BP (Lagerlund, Houmark-Nielsen, 1993). As inferred from data collected in southern Sweden and in the Danish Straits (e.g. Berglund, Björck, 1994; Björk, Svensson, 1994; Björck, 1995), the outflow at the initial Baltic Sea stage proceeded through Öresund. This is evidenced also by the contemporaneous sedimentary sequences, identified in the Kattegat (Bergsten, Nordberg, 1992). Large amounts of outflowing meltwater, coupled with a simultaneous glacioisostatic uplift, resulted in rapid erosion of Öresund, so that the outflowing water could remain at a more or less stable level. The situation changed about 12.0 ka BP when the Öresund erosion, having reached the pre-Quaternary bedrock, slowed down and when the outflow from the Baltic Ice Lake stopped due to continuing uplifting caused by the crustal compensation movements of the area (Berglund, Björck, 1994; Björck, Svensson, 1994; Björck, 1995).

As deglaciation progressed, a strait located north of Mt. Billingen in central Sweden was opened for the first time; this happened *c.* 11.2 ka BP and made it possible for the Baltic Ice Lake to reconnect with the ocean. Ice sheet readvance in Younger Dryas (*c.* 10.9 ka BP) resulted in renewed isolation of the Baltic Ice Lake (Svensson, 1989, 1991; Berglund, Björck, 1994; Björck, Svensson, 1994; Björck, 1995). Climate warming at the end of the Younger Dryas and ice sheet melting led, again, to opening of a connection between the Baltic Ice Lake with the ocean, via lowlands of central Sweden. The most recent data (e.g. Björck, Digerfeldt, 1989; Wohlfarth *et al.*, 1993) indicate this to have happened *c.* 10.3 ka BP. The drainage was very rapid, almost — as argued by some workers — catastrophic. According to Strömberg (1992), the water level fell by about 25 m during about 90 years, while Svensson (1989, 1991), Berglund and Björck (1994) and Björck (1995) contended that the drainage took as little as a few years.

The drainage of the Baltic Ice Lake resulted in the water level fall to the ocean level, a consequence of which was a connection between the Yoldia Sea with the ocean, persisting for about 700–800 years, within 10.3–9.6 (9.5) ka BP (Svensson, 1989, 1991; Björck, 1995) and facilitating water exchange. The fast glacio-isostatic uplift of Scandinavia, faster than the eustatic ocean level rise, brought about — *c.* ok. 9.6–9.5 ka BP — the final closure of the central Sweden straits, whereby the Yoldia Sea was transformed into the Ancylus Lake (Eronen, 1983, 1988; Svensson, 1989, 1991; Björck, 1995). Once the connection with the ocean was closed, the shoreline displacement relied on vertical crustal movements. According to data from southern Sweden (e.g. Svensson, 1989, 1991; Berglund, Björck, 1994; Björck, 1995) and from western Baltic Sea (e.g. Bennike, Jensen, 1998), the transgression peaked *c.* 9.2 ka BP. Until then, the Ancylus Lake drainage had been effected through narrow, and shallowing due to uplift, straits in central Sweden. The progressing transgression in the southern part led to the formation of a new drainage channel (the so-called Dana River) in the area of the present Belt Sea. This resulted in a regression, the duration of which is estimated for the period of 9.2–9.0 ka BP (Svensson, 1989, 1991; Berglund, Björck, 1994; Björck, 1995) or 9.2–8.5 ka BP (Bennike, Jensen, 1998). Incidentally, the more recent data from southwestern Baltic Sea (e.g. Bennike, Jensen, 1998; Lemke, 1998; Jensen *et al.*, 1999) show the extent of the regression to be smaller than assumed earlier (e.g. Kolp, 1979, 1990; Svensson, 1991; Björck, 1995) and not to exceed 5 m. The regression terminated in a renewed equilibration of the water levels in the Baltic Sea and the ocean. Connection with the ocean started new stage of the Baltic Sea history when sea level changes were controlled mainly by eustatic ocean rise.

EARLY STAGES OF THE BALTIC SEA HISTORY AS OBSEREVED FROM THE SOUTHERN BALTIC AREA

The southern Baltic area was the first to be freed from the Scandinavian ice sheet and it was here that the history of the entire Baltic Sea began. At the same time, the southern Baltic was an area in which, as a result of the domination of transgression processes, numerous formations and sediments that could have provided potential evidence of the southern Baltic Sea shoreline location in different periods, had perished. Those forms and sediments that remained are at present located on the seafloor, frequently masked by a younger sedimentary cover.

MATERIALS AND METHODS

Changes in the sea level during the Late Glacial, Preboreal and Boreal (i.e. during the Baltic Ice Lake, Yoldia Sea, Ancylus Lake and at the beginning of the Mastogloia Sea) are, in the southern Baltic Sea area, rather poorly documented by few radiocarbon datings of formations and sediments. The set of peat samples from Pomerania Bay, Słupsk Bank, Vistula Lagoon and Vistula Spit dated by radiocarbon method shows that sea level up to the beginning of Atlantic Period was lower then

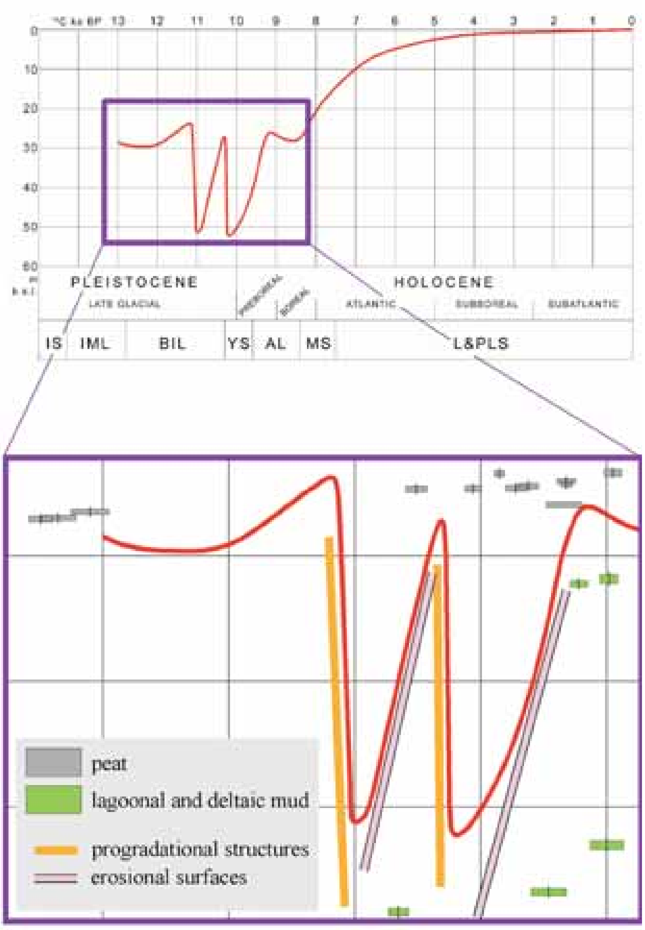

Fig. 2. The relative sea level changes of the Southern Baltic Sea (after Uścinowicz, 2003)

IS — ice sheet, IML — ice marginal lakes, BIL — Baltic Ice Lake, YS — Yoldia Sea, AL — Ancylus Lake, MS — Mastogloia Sea, L&PLS — Littorina and Post-Littorina seas

20 m below the present level. Also a few samples of silts of the similar age indicate that the water level was not lower then *c.* 55 m below present (Fig. 2).

In view of a small amount of datings for discussed period, the relative sea level curve development was assisted by evidence provided by seismoacoustic and echo-sounding profiles. Based on location of various formations on the seafloor, associated with the shoreline development and on the extents of erosional surfaces, progradational structures were analysed. The relative age of those formations was determined from sequentional seismostratigraphic analyses of seismoacoustic profiles. Age of the identified sequences was determined at certain sites by radiocarbon and pollen dating.

RESULTS

Late Glacial, from the Gardno Phase ice sheet retreat from northern Poland and southwestern Baltic (*c.* 14.0 ka BP) until the Southern Middle Bank Phase (*c.* 13.0 ka BP) (Uścinowicz, 1999), is the least known part of the history of the Baltic Sea level changes. As the ice sheet retreated from the southern Baltic Sea and a northwards-inclined surface uncovered, more and more numerous and increasingly larger ice-dam lakes were remaining. Their extent and level changed rapidly as new pathways of meltwater drainage emerged and progressed northwards. Emergence of the Late Glacial Baltic at the first stage of the Baltic Sea history, i.e. the Baltic Ice Lake, is related to the connection opening between ice-dammed lakes of Gdańsk and Bornholm basins via the Słupsk Furrow. This happened *c.* 13.5–13.0 ka BP when the ice sheet margin was retreating from the Słupsk Bank moraines (Uścinowicz, 1996, 1999).

The water level of the early stage of the Baltic Ice Lake (*c.*13–12.5 ka BP) could be, with some approximation, determined on the location of peat in the Pomeranian Bay on the location of sediment top of the then Vistula delta front, and on the glaciofluvial deltas of the Southern Middle Bank (Fig. 2). According to data from those sites, presented and discussed by author (Uścinowicz, 2003), the water level was initially (i.e. 13–12.5 ka BP) lower than the present one by about 30 m. The extent of transgression that began in the southern part of the Baltic Ice Lake about 12.1–12.0 ka BP is difficult to reconstruct, but the most probably, the Baltic Ice Lake level within period 12.0–11.2 ka BP did not reach the present depth of 18–20 m (Fig. 2).

Opening a strait located north of Mt. Billingen in central Sweden caused the first drainage of the Baltic Ice Lake within *c.* 11.2–11.0 ka BP, to become lower by about 50 m than at present (Fig. 2). The magnitude of *c.* 25 m of the first regression of the Baltic Ice Lake can be estimated from the extent of progradational deltaic structures found in the southeastern part of the Gulf of Gdańsk and from barrier structures on the western slopes of the Gdańsk Basin. The sea level of the first Baltic Ice Lake regression is also approximated by the lower range of erosional cut-off of the till top in the southern part of the Bornholm Basin and Słupsk Furrow, visible on seismoacoustic and geological profiles (Przezdziecki, Uścinowicz, 1989; Kramarska *et al.*, 1995; Uścinowicz, 2003). The till top in the southern part of the Bornholm Basin and the Słupsk Furrow, and the top of deltaic sediments in the southeastern part of the Gulf of Gdańsk were eroded during the subsequent sea level rise caused by renewed isolation of the Baltic Ice Lake during ice sheet readvance in Younger Dryas.

Because of isolation from the ocean, melt water discharge and glacio-isostatic uplift much slower then in Scandinavia, the southern coast of the Baltic Ice Lake experienced a rapid water level rise at that time, its maximum occurring *c.* 10.3 ka BP. The highest sea level stand did not, to be sure, exceed 25–26 m below the present sea level, as evidenced by the position and radiocarbon dating of peat in the Słupsk Bank and in the Southern Middle Bank (Fig. 2) (Uścinowicz, 2003).

The magnitude of the Baltic Ice Lake final regression within the southern Baltic area can be inferred from extend of progradational barrier structures (Fig. 3), position of the layers of the Late Glacial and Preboreal sediments of the Baltic Sea, deposited in the vicinity of the Vistula mouth, dated to 10.65 ±0.16 ka BP (Gd-4632) and 9.0 ±0.26 ka BP (Gd-4833) (Fig. 2). The late-glacial deltaic Vistula sediments in the Gulf

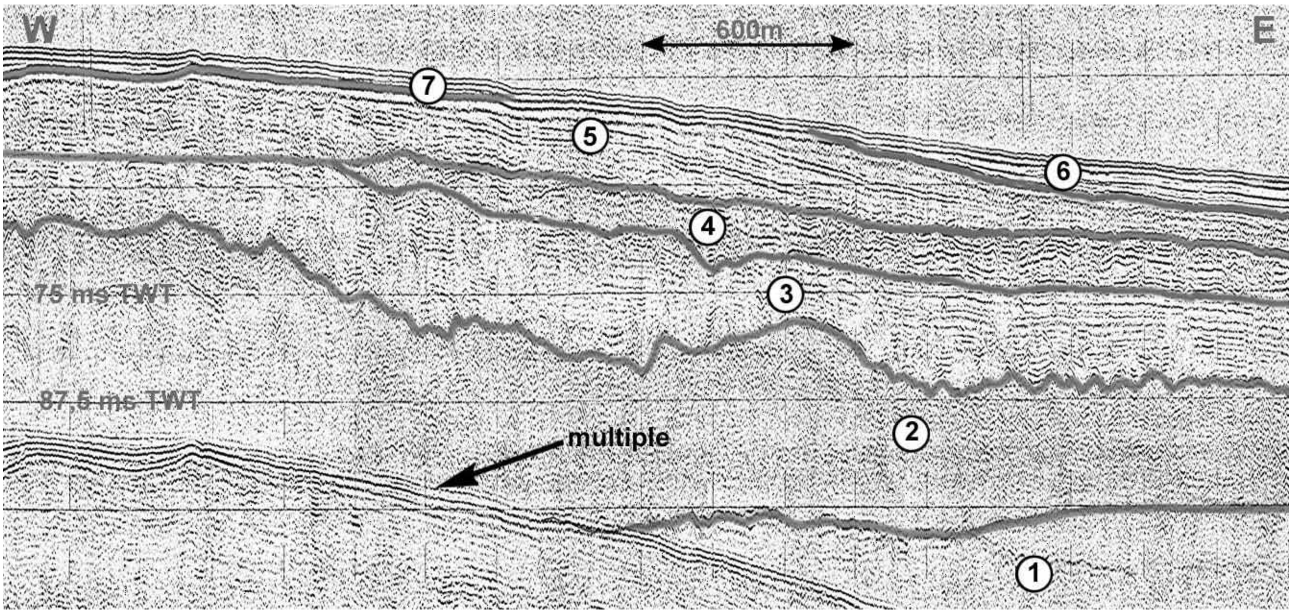

Fig. 3. Late Glacial progradational barrier structures in the Puck Bay (western part of the Gulf of Gdańsk); seismoacoustic (boomer) record

1 — Tertiary; **Pleistocene**: *2* — till; **Late Glacial**: *3* — marginal ice lake silt and clay, *4* — clay (Baltic Ice Lake), *5* — barrier sand; **Early Holocene**: *6* — sandy silt (Ancylus Lake); **Middle and Late Holocene**: *7* — marine mud and sandy mud (Littorina and Post-Littorina seas)

of Gdańsk contain, too, erosional incisions reaching down to about 40–45 m b.s.l. (Fig. 4) (Uścinowicz, Zachowicz, 1992). Similarly, erosional surfaces cutting off the capping of the Baltic Ice Lake clayey sediment, formed during a later transgression, do not extend deeper than about 60 m below the present sea level (Fig. 5).

The evidences discussed above indicate that the water level during the final drainage of the Baltic Ice Lake did not fall, in the southern Baltic Sea area, more than 50–52 m below the present sea level (Fig. 2). The evidence shows also that the magnitude of the terminal regression of the Baltic Ice Lake, as inferred for the southern Baltic area, did not exceed 25–26 m and is in good agreement with the southern Sweden data, referred to above.

The sea level rise subsequent to the Baltic Ice Lake regression at the end of the Younger Dryas (the onset of the Yoldia Sea transgression) began, as already mentioned, from the depth of about 50–52 m below present sea level and terminated towards the end of the Proboreal (the maximum Ancylus Lake water stand) at a level not higher than about 25–26 m below present sea level. The maximum water level at the turn of the Preboreal and Boreal (the maximum Anclus Lake level) is indicated again by the Słupsk Bank peat. The peat capping in core 14 097, occurring 23.38 m below the present sea level, was dated to 8.95 ±0.07 ka BP (Gd-3229). The peat capping in core 14097B is found at the ordinate of 24.05 m below present sea level, the peat age

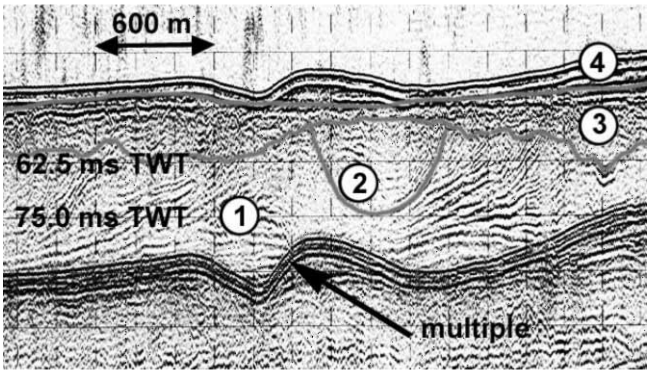

Fig. 4. Erosional channel incised into Late Glacial sediments of the Vistula delta front — southwestern part of the Gulf of Gdańsk; seismoacoustic (sparker) record

Late Glacial: *1* – delta front sandy sediments; **Late Glacial or Early Holocene**: *2* — fluvial sands; **Middle and Late Holocene**: *3* — deltaic sandy sediments, locally mud and peat, *4* — marine sand (Littorina and Post-Littorina seas)

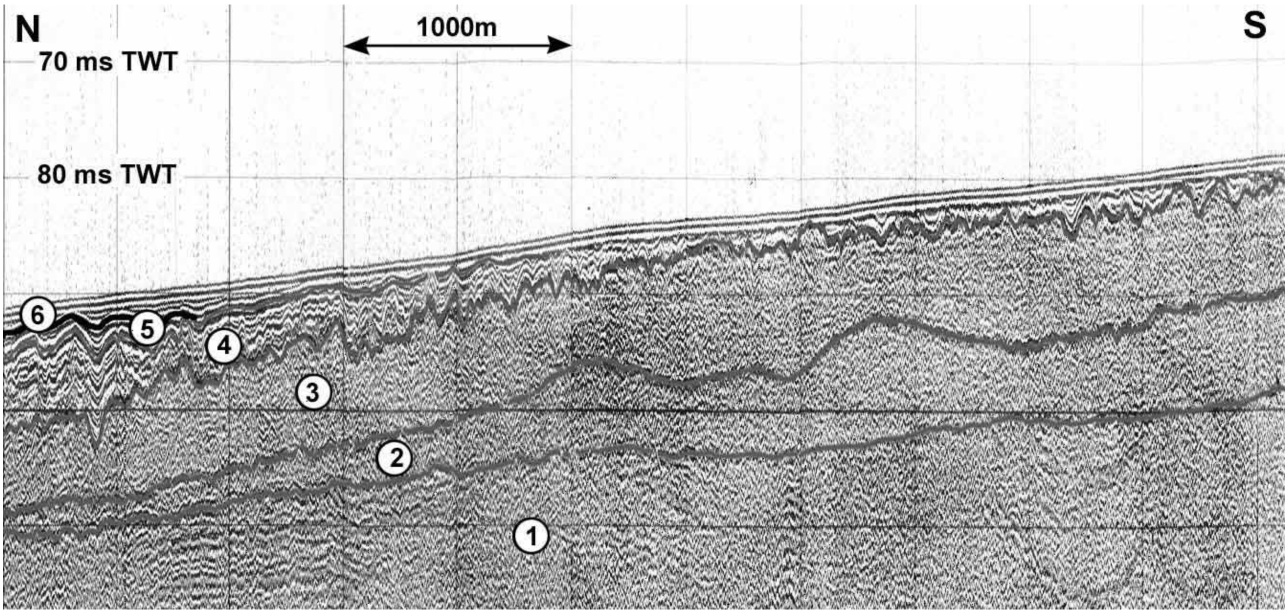

Fig. 5. The erosional surface of the Baltic Ice Lake clay on the southeastern slope of the Bornholm Basin (northwestern slope of the Słupsk Bank)

1 — **Tertiary**: silty sands; **Pleistocene**: *2* — till; **Late Glacial**: *3* — subaqueous till (Southern Baltic diamicton), *4* — clay (Baltic Ice Lake); **Early Holocene**: clay (Ancylus Lake); **Middle and Late Holocene**: marine mud (Littorina and Post-Littorina seas)

being determined at 9.32 ±0.15 ka BP (Gd-4190) (Fig. 2) (Uścinowicz, Zachowicz, 1991). A similar radiocarbon age, 9.33 ±0.14 ka BP (Gd-15304), was ascribed to the peat sampled from the Vistula Spit, from the Dziady 3 borehole, 26.0–26.1 m b.s.l. (Uścinowicz, 2003).

THE RATE OF WATER LEVEL CHANGES AND SHORELINE MIGRATIONS

Transgression is understood as submergence of the land by the sea, i.e., retreating of the shoreline caused by relative sea level rise. Regression means retreat of the sea because of the sea level fall. In such a case, rate of the transgression or regression means the rate of the shoreline displacement and depends on the rate of sea level changes and inclination of the terrain (onshore or offshore) influenced by the sea.

During the first (11.2–11.0 ka BP) drainage of the Baltic Ice Lake, the water level could have fallen *c.* 25 m, at a rate of 100–150 mm/year, and happened on real time of drainage. Such an extensive and fast drop of water level must have caused big changes in the shoreline location. The shoreline could have retreated by about 5 km in the Gulf of Gdańsk to *c.* 90–95 km in the south-east part of Bornholm Basin. Depending on the real drainage rate and on the local inclination of the sea-bed, the land possibly grew at a rate of 25–50 m to 300–500 m per year (Fig. 6).

During the transgression in period 11.0 (10.9)–10.3 ka BP, water level rise rate was approaching about 35–45 mm/year, and shoreline migrated back to position similar to 11.2 ka BP. The rate of shoreline migration could reach *c.* 15 to 150 m/year. It was lower then during regression, but rather catastrophic according to present point of view (Fig. 7).

Final drainage of the Baltic Ice Lake occurred *c.* 10.3 ka BP and during a very short time, say — a few to dozens years, the water level lowered at the rate of *c.* 0.3 to 3 m per year, and the coastline migrated back, similarly as during the first regression; from 5–10 to 50–95 km during that time. Depending on the real drainage rate and the local gradient of the water region's bottom, the land possibly grew at a rate of 50–100 m per year to 600–1000 m per year. If drainage really occurred, during a few years shore could migrate up to 5–10 km per year, in some extreme cases (Fig. 8).

The total water level rise in the southern Baltic Sea area, subsequent to the Baltic Ice Lake regression, within about 1000 years of the end of the Younger Dryas and Preboreal (Yoldia Sea and Ancylus Lake transgressions), spanned about 25–27 m, the mean rate of the water level rise amount to about 25–27 mm/year. Most probably, the Yoldia Sea (10.2–9.6 ka BP) water level rose from about 50–52 to about 40 m below present sea level at a rate of about 15–20 mm/year. It was slightly less than or close to the rate of the eustatic ocean level rise at that time (Fairbanks, 1989; Bard *et al.*, 1996). Major uplift on the southern coast of the Baltic Sea had ceased by that time, and only the residual uplift remained at most (Uścinowicz, 2003). Within 9.6–9.2 ka BP (the Ancylus Lake trans-

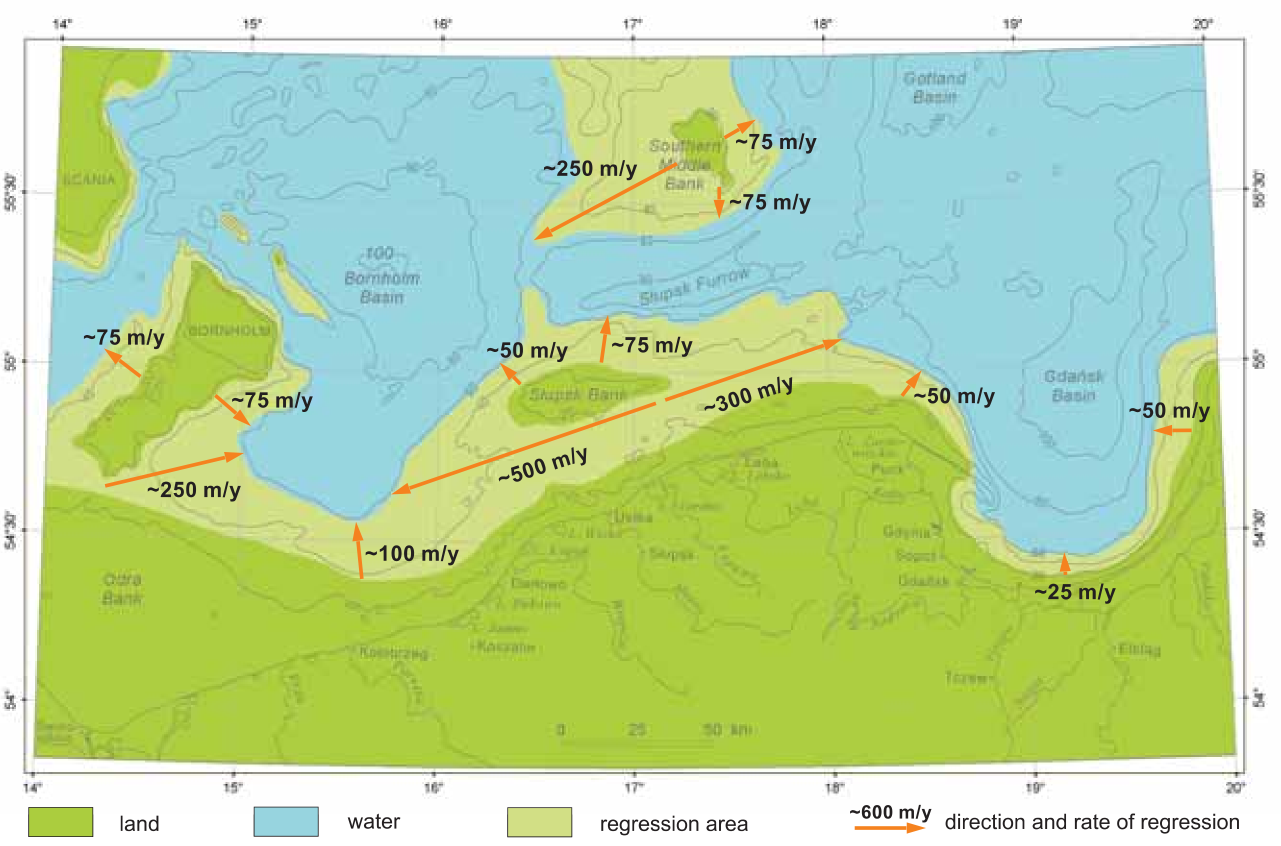

Fig. 6. Shore line displacement during the first regression of the Baltic Ice Lake *c.* 11.2–11.0 ka BP

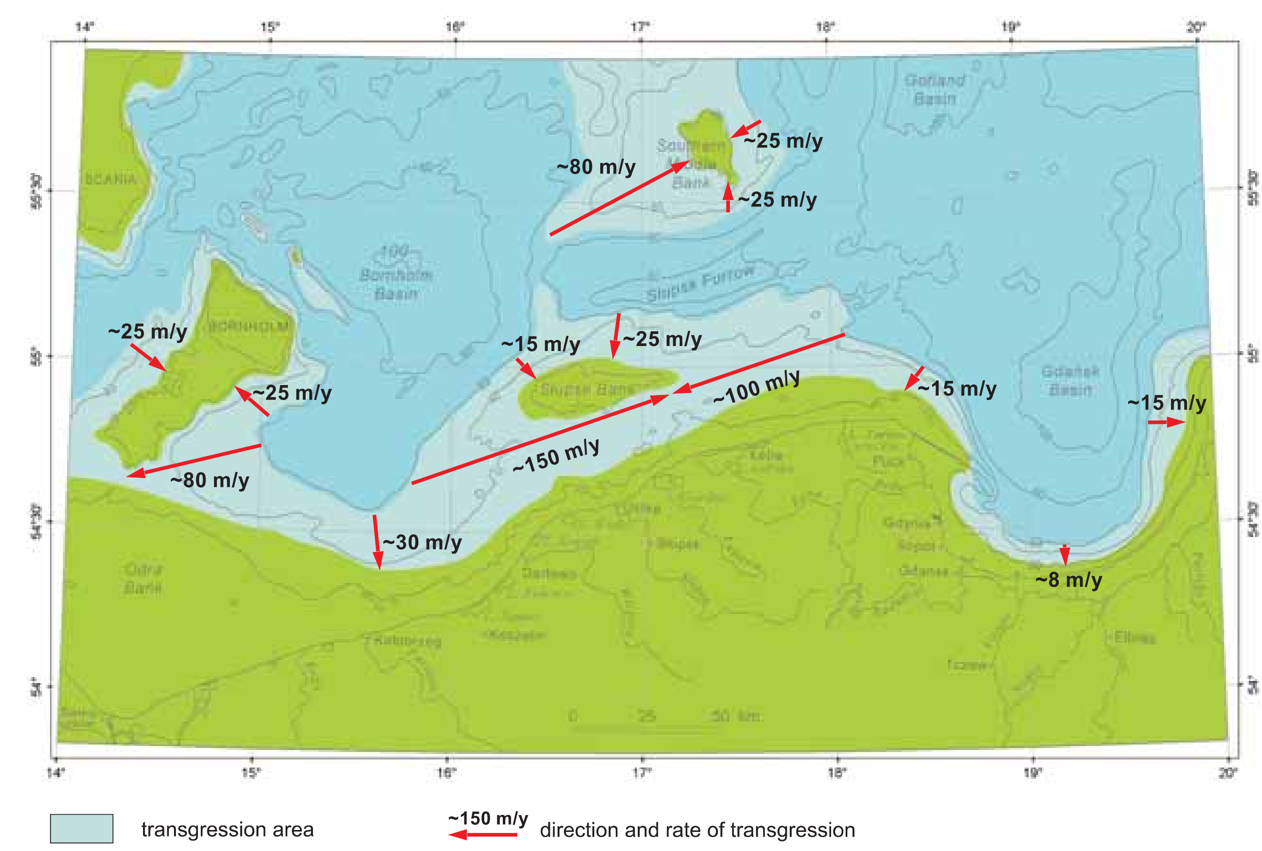

Fig. 7. Shore line displacement during the transgression of the Baltic Ice Lake *c.* 11.0–10.3 ka BP

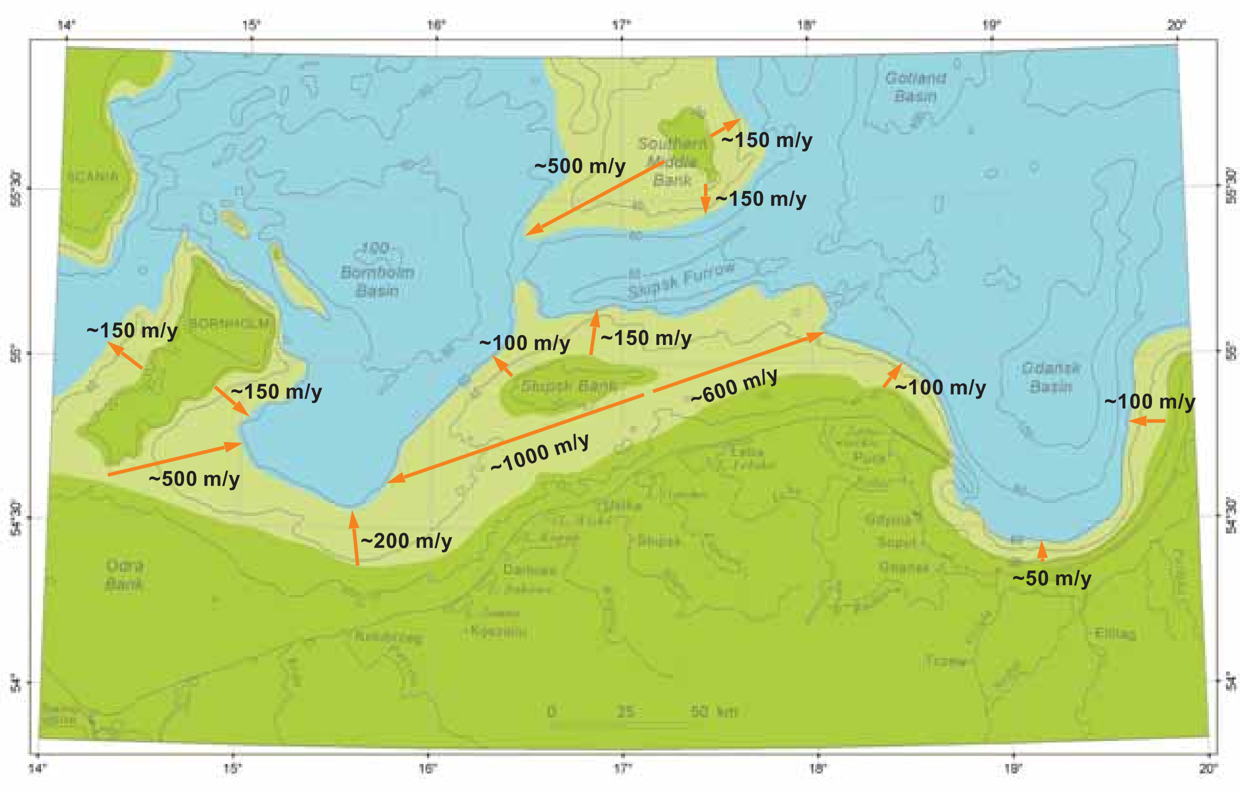

Fig. 8. Shore line displacement during the final regression of the Baltic Ice Lake *c.* 10.3–10.2 ka BP

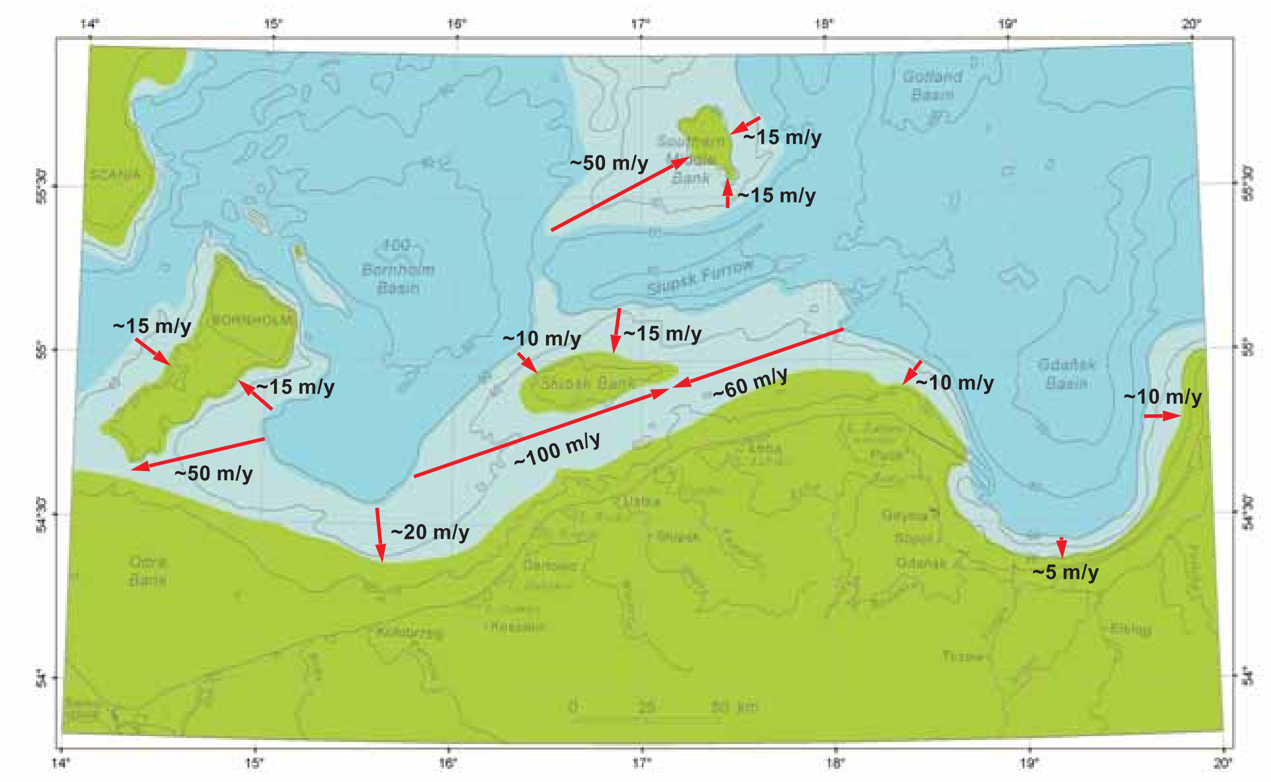

Fig. 9. Shore line displacement during the transgressions of the Yoldia Sea and Ancylus Lake *c.* 10.2–9.2 ka BP

gression), the water level was most probably rising from about 40 to about 25 m below present sea level, at a rate of about 35–45 mm/year. The shoreline migrations of Ancylus Lake within 9.6–9.2 ka BP, in spite of the very fast water level rise, were relatively insignificant. Over 400–300 years, the shore moved south by not more than about 10 km in the southern part of the Bornholm Basin and by about 5 km in the Gdańsk Basin (Fig. 9). That was caused by relatively steep northward tilting of the slopes of those basins. Catastrophic migrations of the shoreline occurred at that time south of the Słupsk Bank. The shores of a gulf formed off the Bornholm Basin side were moving east at a rate of about 150–200 m a year. During 300 years, the shoreline moved by about 50–60 km, cutting the Słupsk Bank off the land. The connection between the land mass and Bornholm and Adlergrund was cut off at a somewhat slower rate. At the terminal stage of the Ancylus Lake transgression, the sea level was close to the maximum level of the Baltic Ice Lake *c.* 10.3 ka BP.

CONCLUSIONS

In the area of the southern Baltic Sea, the largest and most violent changes in water level took place in Late Glacial and Early Holocene, during the period between 13.0–8.5 ka BP. These changes depended on the varied glacio-isostatic movements between the northern and southern parts of the Baltic Sea, the glacio-eustatic increase in the ocean level and the closing of the connection between the Baltic Sea basin with the ocean. These processes took place on the surface of the sea bed currently located at the depth of *c.* 55 to 25 m below sea level and from 30 to 60 km away from the present-day southern coast of the Baltic Sea.

In the Late Glacial, due to the oscillation of the continental glacier's front in central Sweden (e.g. Svensson, 1991; Björck, 1995), *c.* 11.2 ka BP a very quick regression took place, followed by an only slightly slower transgression which reached its maximum *c.* 10.4–10.3 ka BP. The water level fluctuations reached up to 25–30 m. The water level could have lowered at the rate of up to 100–200 mm/year, and the rate of increase reached up to *c.* 40–50 mm/year. Such significant and fast changes in the water level caused catastrophic changes in the location of the coastline. The southern coast of the Baltic Ice Lake first moved, in general, from 10 to 40 km northwards, and then only slightly slower — to the south again.

Second (final) drainage of the Baltic Ice Lake started *c.* 10.3 ka BP, and according to opinions of some authors (e.g. Svensson, 1991; Berglund, Björck, 1994; Björck, 1995), could be more rapid then first drainage, even catastrophic, and took as little as a few years. In such a case, rate of shoreline retreat could reach up to a few kilometres per year.

During the period between 10.3 and 9.6 (9.5) ka BP (the Yoldia Sea), the water level in the Baltic Sea basin increased by *c.* 10–12 m, and the rate of the increase was *c.* 15–20 mm/year. During transgression of the Ancylus Lake (9.5–9.2 ka BP), the water level was most probably rising from about 40 to about 25 m below present sea level, at a rate of about 35–45 mm/year. The total shifts of the coastline during *c.* 1000 years was from *c.* 5 km in the Gulf of Gdańsk, and 20–30 km in the southern parts of the Bornholm Basin. The most extensive and rapid shifts of the coastline ccurred in southeastern part of Bornholm Basin (south-west of the Słupsk Bank).

A very high rate of water level increase on the southern coasts, during the repeated transgressions and regressions in the period between 11.2 and 9.2 ka BP reaching 35–45 mm/year, caused destruction processes to become predominant. Clay sediments of the Baltic Ice Lake in the area shallower than 40 m were almost completely eroded. The roof of glacial till was also destroyed on a large areas. Repeated erosion processes caused the almost complete levelling of the original topographic profile and the formation of vast abrasion surfaces, inclined slightly towards the north (Kramarska *et al.*, 2002).

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