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The Littorina transgression in southeastern Sweden and its relation to mid-Holocene climate variability

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Quaternary Sciences
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Lund University
Lund 2003

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LUNDQUA Thesis 51

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Shi-Yong Yu

Avhandling

att med tillstånd från Naturvetenskapliga Fakulteten vid Lunds Universitet för avläggandet av filosofie doktorexamen, offentlig försvaras i Geologiska institutionens föreläsningssal Pangea, Sölvegatan 12, Lund, fredagen den 14 november kl. 13.15.

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Coring the shallow sea bed of the Smygen Bay, SE Sweden. Photo courtesy of B. E. Berglund (2001).

The Littorina transgression in southeastern Sweden and its relation to mid-Holocene climate variability

By

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This thesis is based on the work carried out while I was a Ph. D. student at the Department of Geology, GeoBiosphere Science Centre, Lund University, between September 1999 and November 2003. The results of this work have been presented in six separate papers listed below as appendices (I–VI) and are hereafter referred to by their Roman numerals. The papers have been submitted to peer-reviewed international journals. Three of them will appear soon and the other three are still under consideration.

Appendix I: Yu, S.-Y., Andrén, E., Barnekow, L., Berglund, B.E., and Sandgren, P. 2003: Holocene palaeoecology and shoreline displacement on the Biskopsmåla Peninsula, southeastern Sweden. *Boreas* **32** (in press).

Appendix II: Yu, S.-Y., Berglund, B.E., Sandgren, P., and Fritz, S.C. 2004: Holocene palaeoecology and shoreline displacement along the Blekinge coast, SE Sweden and implications for climate and sea-level changes. *The Holocene* **14** (in press).

Appendix III: Yu, S.-Y., Berglund, B.E., Andrén, E., and Sandgren, P.: Mid-Holocene Baltic Sea transgression along the coast of Blekinge, SE Sweden — ancient lagoons correlated with beach ridges. Manuscript submitted to *GFF*.

Appendix IV: Yu, S.-Y. 2003: Centennial-scale cycles in middle Holocene sea level along the southeastern Swedish Baltic coast. *Geological Society of America Bulletin* **115** (in press).

Appendix V: Yu, S.-Y., and Sandgren, P.: Mid-Holocene changes in North Atlantic Oscillation patterns and Baltic nearshore hydrography at centennial time scales. Manuscript submitted to *Journal of Quaternary Science*.

Appendix VI: Yu, S.-Y., Berglund, B.E., and Sandgren, P.: Acceleration of Baltic sea-level rise suggests a global meltwater pulse 8000 years ago. Manuscript submitted to *Science*.

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Preface

So God said to Noah, "I have decided to destroy all living creatures, for the earth is filled with violence because of them. Yes, I will wipe them all from the face of the earth... Look! I am about to cover the earth with a flood that will destroy every living thing. Everything on earth will die..."

When Noah was 600 years old, on the seventeenth day of the second month, the underground waters burst forth on the earth, and the rain fell in mighty torrents from the sky...for forty days and forty nights... Finally, the water covered even the highest mountains on the earth, standing more than twenty-two feet above the highest peaks...for 150 days.

GENESIS 6: 13, 17; 7: 11, 12, 19, 20, 24

I believe that it is appropriate to start my thesis with this Biblical story, the Noah's Flood, since it seems to be the closest description of the rapid flooding that occurred 7500 years ago in southeast Sweden, known as the "Littorina transgression". The myth is a myth – accumulating evidence reveals that this transgression may have resulted from a rapid rise of global sea level in response to a sudden collapse of the Antarctic Ice Sheet. As this event occurred under similar climate boundary conditions as to the present, determining the rate and pattern of sea-level adaptations to the changing ice volume and greenhouse gas level during this time may provide valuable insights into potential sea-level response to future global warming. Moreover, when registered in palaeo-records, sea-level changes may not only provide a global perspective on past ice volume, but also a view over regional changes in the physical system of the Earth, such as the isostatic movement and atmospheric activities. For the reasons above, I chose this theme as my Ph. D. thesis work.

This work is principally a continuation of Professor Björn E. Berglund's pioneer studies using state-of-the-art palaeoecological techniques, and with emphasis on shoreline displacement and coastal

vegetation history during the Littorina Sea stage. This thesis is a synthesis of six separate papers and includes inter-site correlations and further discussion, which for practical reasons could not be included in the papers. These papers (Appendices I–III) are the documentation of the Littorina transgression as revealed by multiple stratigraphic sequences from four sites along the Blekinge coast. Appendices IV–VI elucidate the mechanism(s) behind this palaeoceanographic change.

I am the first author of all papers, and thus responsible for the laboratory work, data interpretation, illustrations and text, with the following exceptions: (1) Elinor Andrén (Uppsala University) analyzed the diatoms in the Ryssjön and Färksjön cores. (2) Sherilyn C. Fritz (University of Nebraska) made a diatom census for the Smygen and Hunnemara sites during a sabbatical at the department. (3) Björn E. Berglund and Per Sandgren provided their earlier published results from Siretorp, Kalvöviken, Sörevik, Olsäng, Inlängan and Aspö, as well as the age of isolations of Öppenskär and Utlängan, which enable a wider regional correlation of shorelines along the Blekinge coast.

Introduction

Sea-level changes are the result of the complex interactions among the atmosphere, oceans, ice sheets and solid Earth at different response time scales (Mörner, 1976; Sabadini, 2002). Oscillations of global sea level throughout past glacial-interglacial cycles were primarily governed by periodical mass exchange between the oceans and the ice sheets (Lambeck *et al.*, 2002), ultimately driven by variations in the Earth's orbital parameters (Hays *et al.*, 1976). Superimposed on this general transgression/regression pattern there can be more regional fluctuations, caused by local changes in isostatic conditions (Peltier, 1996; Lambeck and Chappell, 2001) or other factors (van de Plassche *et al.*, 1998). Decadal and annual-scale changes are driven by large-scale atmospheric activities (e.g. NAO, ENSO), tidal action, and polar wander (Sabadini *et al.*, 1990).

Satellite observations and tide gauges generally reveal a steady rise of global sea level over the last 100 years (Cabanes *et al.*, 2001; Douglas *et al.*, 2001). The current accelerated rise is mainly caused by increased meltwater input (Arendt *et al.*, 2002) and steric expansion of the surface ocean (Levitus *et al.*, 2000; Barnett *et al.*, 2001), probably as a consequence of the observed global warming (Levitus *et al.*, 2001). However, other components involved in this complex change remain enigmatic (Munk, 2002, 2003). As yet, the pattern of future sea-level rise cannot be confidently predicted. It is possible that the observed trends represent a "natural" emergence from the Little Ice Age, on a long-term trajectory of cyclic fluctuations. Moreover, we do not know whether there are any physical links between the 20th century sea-level rise and industrial carbon dioxide emissions. Thus, any extrapolation of the current trend (i.e. IPCC, 2001) which is based on these short sea-level records is unwarranted. Sea-level rise may inevitably lead to catastrophic inundation and destructive erosion in coastal lowlands, as well as deterioration of the coastal environments, which may affect human livelihood in serious ways. Investigations of past sea-level variations may not only supplement the recent geologic history of sea-level changes, but also provide a credible scenario for future sea-level changes, which is of particular importance to the long-term probabilistic forecasts for planning purposes (Kallio and Virkki, 2003).

Although postglacial development of the Baltic Sea has been one of the classical topics of Quaternary studies in Nordic countries, beginning in the early 18th century (Gudelis and Königsson, 1979), a

number of questions concerning the Littorina transgression remain unsolved. The Littorina transgression is a manifestation of Baltic Sea-level rise, caused by changing global ice volume and continued land uplift in Scandinavia during the middle Holocene. It was concurrent with the mid-Holocene thermal maximum, and seems to have been a return of the extremely rapid sea-level rise during the Bølling-Allerød interstadial, when abrupt warming occurred in the Northern Hemisphere (Kienast *et al.*, 2003). It is unlikely that the transgression was uniform. It consisted of several transgression waves, as documented along the western Baltic coast by Swedish and Danish geologists (Berglund, 1964, 1971; Mörner, 1969; Digerfeldt, 1975; Liljegren, 1982; Christensen, 1995). However, this pattern has been debated by Finnish geologists with experience from the eastern Baltic coast, where a uniform transgression is reflected in the palaeo-data (Eronen, 1974; Hyvärinen, 1991; Miettinen, 2002). As yet, no definitive conclusion has been reached, which could be due to different research strategies (Digerfeldt, 1975) and/or different rates of isostasy versus eustasy between these two regions.

Evidence from Greenland ice cores and deep-sea sediments reveal that the North Atlantic area has experienced millennial-scale changes in climate during the Holocene (Stuiver *et al.*, 1995; Bond *et al.*, 1997). As climate changed, so did the Baltic Sea level (Berglund, 1971; Åse, 1994; Svensson, 1989; Christensen, 1995; Björck, 1995 and others; Schumacher and Bayerl, 1999). Owing to the continued land uplift since the last deglaciation, evidence for sea-level changes along the northern Baltic coast occurs in the form of raised shorelines, specifically as beach ridges, boulder fields and isolated lakes. In eastern Blekinge, southeastern Sweden, detailed history pertaining to the lateglacial and postglacial landscape development and shoreline displacement was revealed by Berglund's pioneer palaeoecological investigation thirty years ago (Berglund, 1971). As the land uplift appears to be uniform along the whole Blekinge coast, the results can be accepted as a regional protocol. Nonetheless, the precision could be improved on the basis of more extensive regional data.

The objectives of this study were focused on the timing, pattern and rate of the Littorina transgression along the southeastern Swedish coast, through studies of isolation basins and lagoons with protecting thresholds located at different elevations. Recent progress in AMS radiocarbon dating techniques and palaeoecology enable a precise constraint on small-scale sea-level changes by dating sea-level-sensitive aquatic floras. Small-scale fluctua-

tions throughout different time intervals are identified from the sediment sequences of these basins using multiple proxies, such as dinoflagellates, diatoms, seagrasses and stoneworts. Mineral magnetic and organic carbon measurements may also provide complementary information for the recognition of minor transgressions. A regional relative sea-level curve is reconstructed and discussed by correlating the minor transgressions and using the isolation/contact of these basins as “index points”. The results provide a long-term perspective on global ice volume and regional climate changes at millennial and centennial time scales. Specifically, the aims of this thesis were to:

1. Document Baltic Sea-level changes during the mid-Holocene (the Littorina Sea stage) from ancient lagoons located at different elevations along the Blekinge coast.
2. Obtain high-precision information of Holocene environmental changes by correlating biostratigraphic and lithostratigraphic sequences from coastal basins.
3. Correlate possible sea-level changes recorded in these basins with Littorina beach ridges.
4. Compare the shoreline history in Blekinge with earlier studies along a transect from the Öresund region to the Gulf of Finland to evaluate the transgression pattern and its causes.

Late Quaternary history of the Baltic Sea

Continued crustal rebound and ice-volume-equivalent sea-level rise have governed the lateglacial and Holocene development of the Baltic Sea (Lambeck, 1999). Following the decay of the Fennoscandian Ice Sheet, temporal variations of these two components led to a periodical alternation of limnic/marine conditions within the Baltic basin (cf. Björck, 1995). Four major stages of Baltic development have generally been identified from litho- and bio-stratigraphic records (Munthe, 1940; Eronen, 1974; Gudelis and Königsson, 1979).

Stage 1 – Baltic Ice Lake

The first limnic stage in the Baltic Sea history, emerging and gradually expanding as a result of the receding Weichselian ice sheet, is the Baltic Ice Lake (BIL) (e.g. Björck, 1995; Jensen *et al.*, 1997). The lake may have reached its maximum size during the Younger Dryas stadial (Olausson, 1982), and varved glacio-lacustrine clay was deposited along the

margin of the receding ice sheet (Andrén *et al.*, 1999). When the ice sheet retreated to the northern tip of Mt. Billingen (Svensson, 1991; Strömberg, 1992), the lake was substantially drained westward through a passage across the central Swedish lowland (Bodén *et al.*, 1997; Jiang *et al.*, 1998). The final drainage of the BIL was dated to 11 560 cal. BP (Wohlfarth *et al.*, 1993), corresponding to *c.* 10 800 varve years BP in the Swedish Time Scale (Wohlfarth *et al.*, 1995; Andrén *et al.*, 2002).

Stage 2 – Yoldia Sea

Approximately 250 years after the final drainage of the BIL, seawater transgressed into the Baltic basin through the Närke/Billingen strait (Björck, 1995), possibly as a result of rapid sea-level rise in response to meltwater pulse 1B (Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996). Thus, weak brackish conditions occurred locally between 11 300 and 11 100 cal. BP (Schoning, 2001; Andrén *et al.*, 2002). Increased freshwater influx to the ocean may have slowed down the formation of North Atlantic deep water (NADW), thereby leading to an episodic cooling referred to as the Preboreal Oscillation (Björck *et al.*, 1996, 1997). This stage is characterized by a regression in the southern Baltic Sea (see below).

Stage 3 – Ancylus Lake

The warmer conditions during the early Holocene led to a more rapid ice-recession and resulted in a pronounced isostatic uplift in the threshold areas in central Sweden (the Göta älv River and Otteid Strait) of the Yoldia Sea. Consequently, the Baltic basin was isolated from the ocean again and became a large freshwater lake. Elevated beach ridges (Svensson, 1989) and well-preserved submerged pine stumps in the southern Baltic Sea (Persson, 1978) suggest a transgression of this lake with its culmination at ~10 700 cal. BP (Svensson, 1991). An approximately 10-m lake-level lowering occurred around 10 300 cal. BP (Björck, 1995). It seems unlikely that such a rapid regression was caused by the early Holocene cold event (Björck *et al.*, 2001). Instead, it may have resulted from a sudden drainage of the lake, although the location of the outlet of this possible drainage is still unknown. Until 10 000 cal. BP, sea level reached the Darss Sill area (Björck, 1995). Gradual erosion led to the formation of an incised Dana River, finally draining the Ancylus Lake (Björck, 1995). However, according to recent investigations, the Darss Sill as a potential pathway for the drainage of the Ancylus Lake can be ruled out (Jensen *et al.*, 1999; Lemke *et al.*, 2001).

Stage 4 – Littorina Sea

The transition from the Ancylus Lake to the Littorina Sea *sensu lato* in the Baltic basin is marked by evidences of a weak brackish phase between 9800–8500 cal. BP, called the Early Littorina Sea in nearshore areas (Berglund *et al.*, in press) or the Initial Littorina Sea in the Baltic proper (Andrén *et al.*, 2000a, b). The later part of this phase is also named the Mastogloia Sea. Anoxic conditions occurred in some deep basins (Sohlenius *et al.*, 1996, 2001), probably caused by a low saltwater influx when the connection of the Baltic basin with the North Sea was weak and intermittent. The following brackish-marine stage is defined by evidences of significantly increased seawater influx (Hyvärinen, 1988) and an opening of the Öresund Strait, which has been dated to around 8500 cal. BP (Björck, 1995). The Littorina Sea was characterized by an oscillatory pattern of its water table, along with synchronous changes in salinity (Westman and Sohlenius, 1999). The rapid flooding of the Littorina Sea with its culmination around 7500 cal. BP, which is known as the “Littorina transgression”, may have been a response of Baltic Sea level to the increased meltwater discharge from Antarctica (Blanchon and Shaw, 1995). Spatial variations in the riverine discharge caused a distinct salinity gradient between the Kattegat Sea and the Gulf of Bothnia. The substantial regression after *c.* 3000 cal. BP not only reduced the water exchange between the Baltic and the North Sea (Hyvärinen, 1988), but also shaped the geometry of the basin and finally led to the formation of a predominantly landlocked brackish water body.

Postglacial shoreline displacement in southeastern Sweden

Melting of the continental ice sheets after the Last Glacial Maximum resulted in a *c.* 120-m rise of global sea level at variable rates (Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996). Superimposed upon this global signal are the local variations in the rate of land uplift in the glaciated areas in southern Scandinavia, which resulted in a complex temporal and spatial pattern of postglacial shoreline displacement along the Baltic coast (cf. Hyvärinen, 1991). The highest shoreline in Blekinge, developed during the BIL stage, has been determined to *c.* 65 m a.s.l. (Berglund, 1966; Ringberg, 1971). A first drainage of the BIL occurred around 12 700 cal. BP, and led to a substantial lowering of the water level by *c.* 25 m (Björck, 1995). This event was succeeded by at least two minor transgressions

until the final drainage (Björck, 1981) took place at around 11 560 cal. BP (Wohlfarth *et al.*, 1993). The following Yoldia Sea stage was characterized by a short period of regression in Blekinge. The lowest shoreline may have been located at approximately 20 m below present sea level off the Blekinge coast (Berglund *et al.*, 1986; Hansen, 1987; Björck and Denegård, 1988; Svensson, 1991; Björck, 1995), which led to a widespread isolation of the coastal lakes from the Baltic basin and forest expansion in nearshore areas, prior to subsequent flooding (Gaillard and Lemdahl, 1994). The Ancylus Lake stage began as a synchronous transgression in southern Sweden (Björck, 1987), and the highest shoreline in Blekinge during this stage was around 5 m a.s.l. (Berglund, 1964, 1971).

Following the final drainage of the Ancylus Lake, seawater intruded through the Danish straits at 9800 cal. BP, marking the onset of the early Littorina Sea (Andrén *et al.*, 2000a, b; Berglund *et al.*, in press). Several transgressions were identified during the Littorina Sea stage in southern Sweden and eastern Denmark (Berglund, 1964, 1971; Mörner, 1969; Digerfeldt, 1975; Liljegren, 1982; Christensen, 1995). In Blekinge, the maximum transgression occurred between 7700 and 5600 cal. BP (Berglund, 1971; Liljegren, 1982). A beach ridge complex on Inlängan suggests that the maximum transgression was not uniform (Berglund, 1964, 1971). It might have been comprised of two minor transgressions (Liljegren, 1982), corresponding to the still-stands of shoreline in South-Central Sweden and southern Finland (Eronen *et al.*, 2001; Hedenström, 2001). From 6500 cal. BP, global sea-level rise slowed down (Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996) to a rate lower than the isostatic uplift in Scandinavia, thereby causing a gradual isolation of elevated basins.

Study area

The Baltic basin is located within the depression between the Fennoscandian Shield in the west and the mountains of eastern and central Europe, which developed along an early Paleozoic geosyncline with its axis trending N–S. The Blekinge coast (Fig. 1) lies in the southeastern part of the Fennoscandian Shield, which is built up by Precambrian gneiss and granite. It is a low-lying peneplain, which has been tectonically deformed by Pleistocene glacial activities. The till is generally sandy, rich in boulders, and often occurs in the form of drumlins. Glaciofluvial deposits like eskers and deltas are common in the N–S trending tectonic valleys below the highest

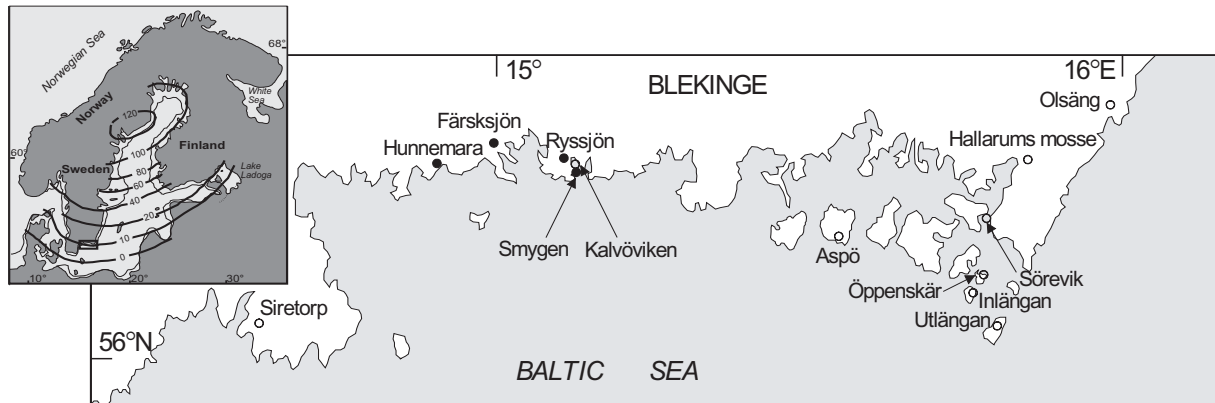


Fig. 1. Maps of Fennoscandia with *Littorina* isobases (inset) and the Blekinge coast. Filled circles indicate sites investigated in this study. Other locations of sites discussed in text are indicated with open circles.

shoreline, while fine-grained sediments like silt and clay are found in the low-lying coastal areas. There is a gradual slope from south to north. Only a few upland areas in the north reach over 100 m a.s.l., and most of them in the south are lower than 20 m a.s.l. Such a landscape is prone to the transgression of seawater into the lake basins that took place during the mid-Holocene sea level high, as evidenced by the continuous accumulation of gyttja in the present day lakes, which contains evidence of brackish water conditions.

The spatial distribution of both temperature and precipitation in Blekinge follows a gradient from the upland to the shore (Sveriges Nationalatlas, 1995). At the coast, mean January temperature is around 0°C, and mean July temperature is 16.5°C. Mean annual precipitation is ~600 mm. Westerly to south-westerly winds prevail. Blekinge is also a transition area of forest zones: broad-leaved forests occur to the south and mixed forests with broad-leaved and coniferous trees occur to the north. The modern vegetation is, for the most part, a result of human activity.

Site descriptions

Smygen Bay

Smygen Bay (15°07'E, 56°09'N) is a modern lagoon lying in central Blekinge. It is well protected from the Baltic Sea with only a narrow (25 m) connection to the open sea and with a bedrock sill *c.* 1 m below present sea level (Fig. 2a). The shallow seabed was cored in the winter of 2000, and an 11.5 m long sediment sequence was recovered. To obtain a sufficient quantity of macrofossils, three

juxtaposed cores were taken from the same coring location in summer 2001 from a raft. Water depth at the coring site was 1.4 m. Analytical results from this site are presented and discussed in Appendices II and V.

Hunnemara ancient lake

The basin is situated in western Blekinge (14°53'E, 56°10'N). It is developed in a nearly NE–SW trending valley, with an outflow threshold around 3.0 m a.s.l. (Fig. 2b). The lake was drained and converted to agriculture land and a meadow by local farmers in the 19th century, and is now partly used as a garbage dump. An 8.5 m long core was taken near the center of the ancient lake in summer 2001. Four additional cores for stratigraphic analysis and correlation were also collected along a NW–SE transect from the shore to the center of the lake. Analytical results from this site are presented and discussed in Appendix II.

Lake Ryssjön

Situated on the Biskopsmåla Peninsula, Lake Ryssjön (15°05'E, 56°10'N) is a shallow lake, which developed in a nearly N–S trending tectonic valley (Fig. 2c). The lake has an outflow creek that discharges into the Baltic Sea. The outflow threshold was leveled to *c.* 4.5 m a.s.l. (Liljegren, 1982). The average water depth of the lake is 1.5 m. In winter 1999, corings were performed along a N–S transect from the shore to the center of the lake to find a site with the best stratigraphic resolution. A 5 m long overlapping sediment sequence was taken from the best site and these sediments were used for the analyses. The results from this site are presented and discussed in Appendices I and IV.

Lake Färsksjön

The basin of Lake Färsksjön (14°59'E, 56°10'N) developed in a nearly N–S trending tectonic valley with a bedrock outflow threshold leveled to 7.2 m a.s.l. (Fig. 2d). The lake was drained once by the local farmers in the 19th century through blasting of the outflow bedrock threshold. This anthropogenic drainage led to a significant drop in lake level (today at *c.* 4.5 m a.s.l.) and several peat islands were formed. In the summer of 2001, the central lakebed was cored from a raft, and a 4 m long overlapping sediment sequence was obtained. Water depth at the coring site was 1.4 m. A complementary stratigraphic investigation was conducted in the autumn of 2002, by coring along a W–E transect from the shore onto the largest peat island. Analytical results from this site are presented and discussed in Appendix III.

Other sites discussed

Inlångans Mosse (fen)

This site was investigated by Berglund (1964). It is a fen on an island in the exposed outer sea off eastern Blekinge (Fig. 1). The threshold has been leveled to *c.* 5 m a.s.l. Radiocarbon dates reveal a depositional hiatus during the lacustrine/brackish-marine transition, probably caused by erosion during a sea-level rise. Continuous brackish gyttja was deposited after the basin became sheltered at 4170 ± 75 ¹⁴C yr BP (Berglund, 1964). The transition from brackish to limnic conditions in the basin was dated to 3145 ± 65 ¹⁴C yr BP by Berglund (1964), which indicates the finally isolation of the basin from the Baltic Sea.

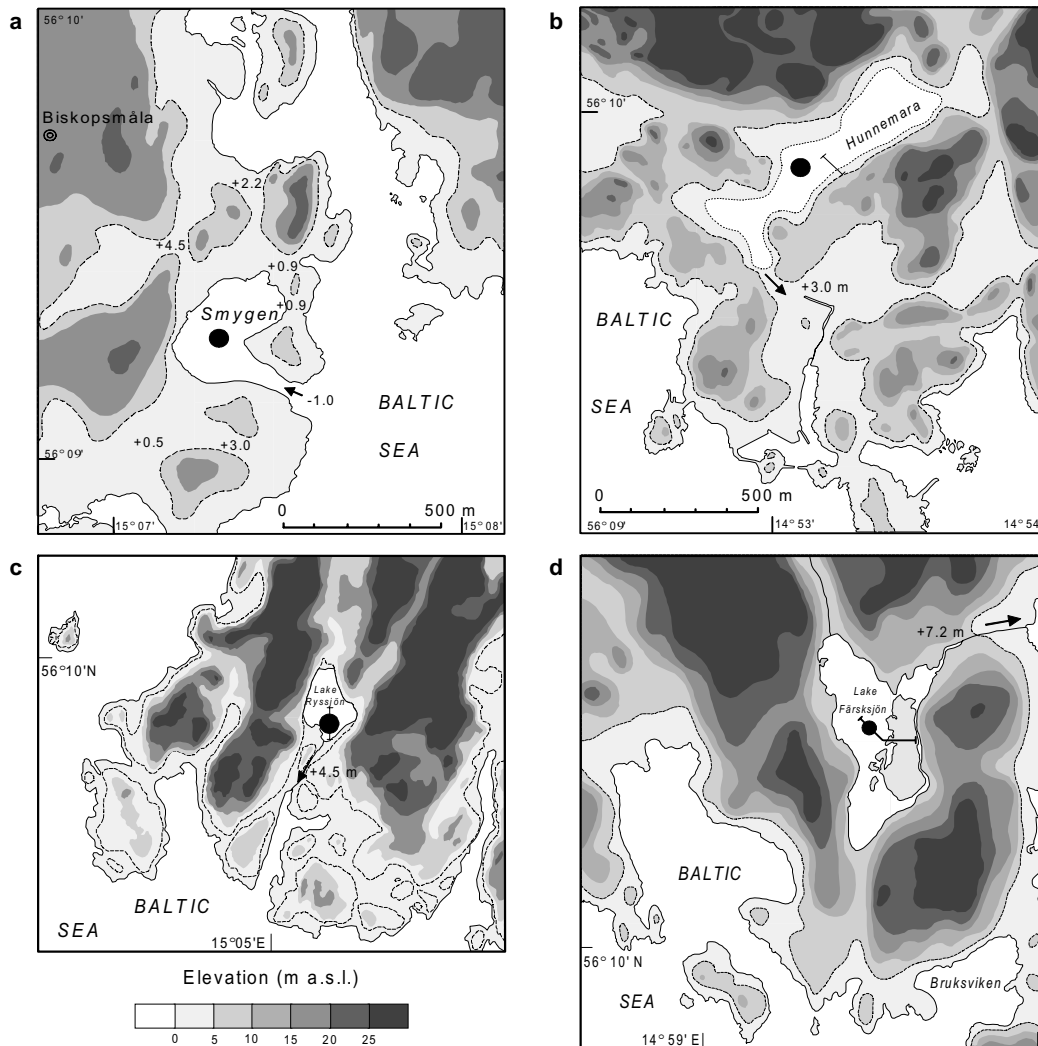


Fig. 2. Topographical maps showing the terrain of studied basins. (a) Smygen Bay; (b) Hunnemara ancient lake; (c) Lake Ryssjön; (d) Lake Färsksjön. Arrows indicate the outflow/inlet thresholds of the basins. The figures show the altitude of leveled thresholds. Coring position and stratigraphic transects are indicated.

Siretorp ancient lake

This small basin is situated on the coastal plain on the Lister Peninsula (14°36'E, 56°01'N), SW Blekinge (Fig. 1). It has been a lagoon, which developed within a valley depression with a sandy till threshold *c.* 5 m a.s.l. Beach ridges on the peninsula were formed between drumlins during the Littorina Sea stage. In most cases, the beach ridges have a W–E direction and are exposed towards the sea to the south. Extensive archaeological excavations were performed in the 1930's, together with reconnaissance mapping of Neolithic settlements. Detailed studies of sediments in the basin, including pollen, diatoms, $\delta^{13}\text{C}$ and organic content analyses, were made in 1968 to reveal the transgression history (Berglund, 1971). A correlation of this site with Färsksjön is presented and discussed in Appendix III.

Hallarums Mosse (peat bog)

This peat bog, located in a basin with rather deep slopes, is situated in eastern Blekinge (Fig. 1). The outflow threshold lies at *c.* 4.7 m a.s.l. The site was drained and partly reclaimed by the local farmers, but the easternmost part is still almost intact. Detailed stratigraphic investigations and palaeoecological analyses were made by Berglund (1964). Radiocarbon dates of bulk sediments reveal that the basin was connected to the Baltic Sea from 6950 ± 90 ^{14}C yr BP, and isolated at 4585 ± 70 ^{14}C yr BP (Berglund, 1964).

Öppenskär and Utlängan (fens)

These two fens are located on islands off eastern Blekinge (Fig. 1). Previous investigations revealed a fen history similar to that of Inlängans Mosse (Berglund, 1964). A rather thin layer of clayey fine-detritus brackish gyttja overlies the coarse-detritus lacustrine gyttja, although erosion of the gyttja may have occurred before the overlying layer accumulated. The outflow threshold was leveled to *c.* 2 m on Öppenskär, and to *c.* 0.4 m a.s.l. on Utlängan. The isolation was dated to 385 ± 70 ^{14}C yr BP on Utlängan, whereas pollen zone correlation suggests that the isolation on Öppenskär occurred at approximately 2000 cal. BP (Berglund, 1964).

Kalvöviken Bay

This site is located on the Biskopsmåla Peninsula (15°07'E, 56°10'N) between Karlshamn and Ronneby and faces northeast (Fig. 1). Water depth is less than 2 m, but this depth increases eastwards to 15 m in the Väby fjord. The basin is situated in a N–S trending bedrock depression, which was a sheltered cove during the mid-Holocene sea level high

(Berglund *et al.*, in press). Detailed pollen, diatom, macrofossil and mineral magnetic analyses revealed a transgression during the time span 9800–5000 cal. BP (Berglund *et al.*, in press). It comprises a slight brackish phase between 9800 and 8500 cal. BP and a full brackish phase that lasted from 8500 to 5000 cal. BP (Berglund *et al.*, in press).

Sörevik Bay

The bay is situated on the Senoren Island (15°46'E, 56°07'N), southeast of Karlskrona (Fig. 1), and is exposed southwards. Water depth is less than 2 m, with a gradual increase to 6 m in the fjord southeast of the bay. Previous investigations have not found any submarine threshold (Berglund, 1964). Multiple stratigraphic sequences of pollen, diatom, macrofossil and mineral magnetic parameters reveal a transgression history similar to the Kalvöviken Bay site (Berglund *et al.*, in press).

Olsäng beach ridges

Olsäng beach ridges (15°59'E, 56°12'N) are situated on the coastal plain in eastern Blekinge (Fig. 1). These ridges are a large complex of Ancyclus and Littorina beach ridges, exposed ESE towards the Baltic Sea. Three parallel ridges from the Ancyclus time have been dated to 10 600–10 200 cal. BP (Mikaelsson, 1978). The easternmost part is covered by sand and gravel, which has been dated to 6570–6400 cal. BP (Mikaelsson, 1978), corresponding to the Littorina transgression.

Inlängan and Aspö beach fields

On the Inlängan Island (15°46'E, 56°31'N) a boulder field overlies the south-facing slope of a bedrock hill (8–9 m a.s.l.) of this island (Fig. 1). Although slightly discontinuous, it is still possible to distinguish three distinct boulder ridges, where the highest parts have been leveled to 9.5, 8.2 and 6.8 m a.s.l., respectively (Berglund, 1964). Absolute ages of the ridges are unknown. However, a Neolithic grave field situated on the sand terrace provides an estimate of the uppermost age of *c.* 4000 cal. BP (Berglund, 1964). A triplet of sand ridges can be found on the gentle south-exposed slope of the larger island Aspö (15°32'E, 56°06'N). The three sand ridges have been leveled to 9.4, 8.1 and 6.3 m a.s.l. (Berglund, 1964), implying a sea-level history similar to Inlängan.

Methods

Fieldwork

All the cores in this study were taken using a Russian peat sampler (1 m long and 5 or 7 cm in

diameter). It is a chamber corer widely used in Fennoscandia for retrieving lake or peat sediment sequences (Jowsey, 1966). Most of the lakes and the lagoon were cored during winter, when the surface was iced. Coring in summer was performed from a raft, which had been anchored in the coring location with steel rods. Preliminary stratigraphic descriptions were made in the field. The core segments were subsequently wrapped with plastic film, transferred to D-shaped plastic liners and sealed for transport to Lund, where they were stored at 4°C in a core repository.

The thresholds of most of the basins have been well preserved due to slow weathering of the bedrock, but some (e.g. Färsksjön and Hunnemara) may have been blasted by the local farmers for agricultural purposes. In these cases, the lowest undisturbed ground surface was leveled and used as an approximation of the original threshold. Leveling of the thresholds of the isolation basins was implemented using a Wild Kern Level. The elevation of the submarine sill of the Smygen Bay was determined with a hand-held echo sounder (Echotest II).

Core logging and magnetic-susceptibility scanning

In the laboratory, the stratigraphy of the cores was described in detail following the system proposed by Troels-Smith (1955). Then the core segments were scanned for initial magnetic susceptibility along a flat surface covered with a thin plastic film. The scanning was performed at 4 mm intervals, using a Bartington Instruments Ltd. MS2E1 surface scanning sensor and MS2 meter coupled to a TAMISCAN-TS1 automatic stage.

Core splicing and subsampling

The overlapping core segments were spliced mainly on the basis of visual stratigraphic boundaries, with confirmation from the long-core magnetic-susceptibility scanning. Subsamples for loss-on-ignition (LOI) and mineral magnetic measurements were contiguously taken along the core by pushing the 7 cm³ polystyrene pots into the cleaned sediment surface, representing *c.* 2 cm stratigraphic intervals. Subsamples of 1 cm³ bulk sediments were taken at every 6–8 cm intervals for absolute pollen and dinoflagellate analyses. The cores were sliced contiguously at 2–4 cm intervals for macrofossil analysis.

Organic content, organic carbon and mineral magnetism

Magnetic susceptibility (χ) was determined using a

Geofyzika Brno KLY-2 KAPPA bridge. Anhyseretic remanent magnetisation (ARM) was imposed along a single axis using a Molspin AF demagnetizer in a direct bias field of 0.1 milliTesla (mT) imposed upon a peak alternating field of 100 mT. After ARM measurements, each sample was placed in a 1 Tesla (T) magnetic field induced by a Redcliff BSM-700 pulse magnetizer. This field was assumed to magnetically saturate the samples. The induced saturation isothermal remanent magnetisation (SIRM) was measured using a Molspin Minispin magnetometer. Coercivity of remanence ($(B_o)_{CR}$) was measured by placing the samples in a series of reversed magnetic fields induced at 10 mT steps until the magnetization reversed. $IRM_{-100\text{ mT}}$ was finally measured by exposing the samples to a reversed field of 100 mT to allow calculation of the S-ratio ($IRM_{-100\text{ mT}}/SIRM$). All magnetic analyses were performed at room temperature in the Mineral Magnetic Laboratory of Lund University. After the magnetic measurements, the samples were dried at 50°C in an oven to calculate mass specific SI magnetic parameters. Subsamples were desiccated at 105°C and then combusted at 550°C to allow the calculation of organic content as LOI. Organic carbon was measured on dried subsamples of ~0.2 g from the Smygen site using a Leco RC-412 multiphase carbon analyser.

Pollen and dinoflagellates

Samples for pollen and dinoflagellate analyses were processed following the guidelines proposed by Berglund and Jasiewiczowa (1986). Pollen and spores were identified using the standard morphology depicted by Fægri and Iversen (1989). More than 500 pollen grains and spores were counted for each level. All pollen percentages were calculated on the basis of a sum including tree, shrub and upland herb pollen, but excluding aquatic and wetland pollen. Division of pollen zones is based on terrestrial taxa by using CONISS in the TILIA computer program (Grimm, 1988). All of the pollen zone boundaries are statistically significant. Subsamples for dinoflagellate analyses were processed following the guidelines of Rochon *et al.* (1999). Five tablets of exotic marker grains of *Lycopodium* spores were added as spikes to allow calculation of the dinoflagellate cyst abundance, expressed as concentration by volume. Dinoflagellate nomenclature and morphology follow Rochon *et al.* (1999).

Diatoms

Small amounts of bulk sediments were prepared for diatom analysis according to the method described

by Battarbee (1986). The enriched diatom samples were dried onto coverslips and mounted in Naphrax™. Quantitative analyses were carried out with a light microscope at a magnification of $\times 1000$. The counting convention of Schrader and Gersonde (1978) was used, and 300 to 400 diatom valves, excluding *Fragilaria* spp. sensu Hustedt, were counted at each level. The genus *Fragilaria* sensu Hustedt has been divided into several different genera (Williams and Round, 1987). Diatom abundance is expressed relative to the sum of all valves, excepting *Fragilaria*. *Fragilaria* abundance is expressed as a percentage of all counted valves.

Macrofossils

Subsamples of 50–100 mL bulk sediments were disaggregated using a jet of water and sieved at 200 μm . The $>200 \mu\text{m}$ residue was examined under a dissecting microscope at $50\times$ magnification, and all identifiable remains were picked out and stored in plastic vials. Macrofossils were identified to the lowest possible taxonomic level with the aid of published keys (Martin and Barkley, 1961; Tomlinson, 1985) and modern reference collections at the Department of Geology, Lund University. All macrofossils were counted, and their frequencies are presented as concentrations per unit volume. After identification and if a sufficient amount was available, terrestrial plant macrofossils from certain levels were submitted for radiocarbon dating.

Radiocarbon dating

Accelerator mass spectrometry (AMS) radiocarbon dating was performed at the Department of Geology, Lund University. Bulk sediments and seagrass fruits were also used for dating if terrestrial plant macrofossils were absent. A local reservoir age of $108 \pm 24 \text{ }^{14}\text{C yr}$ was subtracted to correct the radiocarbon dates of marine sediments in this area (Berglund, 1971). The reported standard error of the radiocarbon dates is 1σ . All of the radiocarbon dates were calibrated and converted to calendar ages using the radiocarbon calibration program CALIB 4.2 (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). The range of the calibrated ages is 2σ , and the ages were rounded to the nearest 10 years.

Results — summaries of papers

Paper I

Yu, S.-Y., Andrén, E., Barnekow, L., Berglund, B.E., and Sandgren, P. 2003: Holocene palaeoecology and shoreline displacement on the

Biskopsmåla Peninsula, southeastern Sweden. *Boreas* **32** (in press).

The aim of this study was to revise the chronology of the Littorina transgression in Lake Ryssjön, a lagoon with a threshold at 4.5 m a.s.l., previously investigated by Liljegren (1982), and to analyse and explain the closer details of the mid-Holocene sea-level changes. The timing of the Littorina transgression in this basin was established by AMS ^{14}C -dated biostratigraphy, specifically diatoms, seagrasses and dinoflagellates. The diatom flora is sensitive to salinity changes, and thus has been widely used for the identification of transgressions along the Baltic coast. Replacement of freshwater diatoms by those with brackish-water affinity indicates that the basin was initially connected to the Baltic at 8100 cal. BP, but probably only during storm events. The continuous presence of brackish-marine diatoms, seagrasses and dinoflagellates indicates that full brackish conditions prevailed in the basin between 7500 and 3600 cal. BP. By 3000 cal. BP a freshwater diatom assemblage indicates that the basin was finally isolated from the Baltic, marking the end of the regression.

Temporal variations in the biostratigraphies demonstrate an oscillatory pattern of the mid-Holocene Baltic Sea level superimposed on the main transgression wave. Four minor transgressions are dated to 7500–7000, 5900–5300, 5000–4700 and 4400–4000 cal. BP. Peaks of brackish-marine diatoms and dinoflagellates suggest that the earliest minor transgression was caused by increased saltwater influx to the Baltic Sea, which can be correlated to global meltwater pulse 3. In contrast, the other three minor transgressions may have only regional significance, associated with centennial-scale variations in atmospheric pressure.

The palaeoecology of this peninsula during the majority of the Holocene was revealed by detailed pollen and plant macrofossil analyses. The vegetation was quite mosaic during the Preboreal/Boreal transition, where lateglacial dwarf shrub/steppe communities were dispersed within heaths and *Pinus*-dominated mixed woodland. During this period the lake productivity was low and the basin was still isolated from the Yoldia Sea. The amelioration of the regional climate started around 10 700 cal. BP, as indicated by substantial reduction in the lateglacial shrub/steppe communities. *Pinus*-dominated mixed forests with *Betula*, *Ulmus* and *Corylus* were initially established on the peninsula, along with improved soil conditions. The lake was still oligotrophic and may have been connected to the Ancylus Lake

until 10 100 cal. BP. The lake became isolated again from the Baltic basin between 10 100–8100 cal. BP, corresponding to the early Littorina Sea stage. Expansion of broad-leaved trees began around 8700 cal. BP, indicating the onset of the mid-Holocene thermal maximum in Scandinavia (Seppä and Birks, 2002). The landscape of the peninsula was significantly affected by the Littorina Sea stage between 8100 and 3000 cal. BP. The flooding affected large areas of the coastal lowland, which therefore was divided into several small peninsulas and islands. The lake became a lagoon with a narrow sound southward to the Baltic Sea. The isolation occurred at *c.* 3000 cal. BP, and thereafter the landscape was gradually more influenced by human activities.

Paper II

Yu, S.-Y., Berglund, B.E., Sandgren, P., and Fritz, S.C. 2004: Holocene palaeoecology and shoreline displacement along the Blekinge coast, SE Sweden and implications for climate and sea-level changes. *The Holocene* **14** (in press).

The aim of this study was to document Holocene shoreline displacement and coastal vegetation history in western Blekinge, related to regional climate and Baltic Sea-level changes. A growing body of evidence supports the hypothesis of a fluctuating mid-Holocene sea level along the Baltic coast, probably caused by localized variations in meteorological conditions. However, mid-Holocene sea-level changes in west Blekinge are poorly constrained. To date the detailed history of the shoreline displacement during the transition from the Ancylus Lake stage to the Littorina Sea stage is not clear. Moreover, sea-level rise was probably rapid around 7500 cal. BP, as indicated by the sudden increases in marine diatoms and warm demanding dinoflagellates in several basins located above 4.5 m a.s.l. To determine the pattern and rate of sea-level rise during this time, more basins located below this level should be studied.

The paper presents a fresh insight into the post-glacial shoreline displacement and coastal landscape development in west Blekinge, southeast Sweden by correlating AMS ¹⁴C-dated pollen, macrofossil and mineral magnetic records from two lagoons – Hunnemara ancient lake (threshold *c.* 3 m a.s.l.) in the west and Smygen Bay (threshold 1 m below sea level) in the east. Pollen assemblages at both sites are similar to those documented in Lake Ryssjön, suggesting the control on the coastal landscape development by both Baltic Sea level and regional climate changes.

The two basins were isolated from the Yoldia

Sea between 11 300 and 11 000 cal. BP. Increasing mineral magnetic concentrations from *c.* 11 000 cal. BP imply that the two basins may have been in contact with the Ancylus Lake during the period of 10 700–9800 cal. BP. The extremely low abundance of brackish-water diatoms in Smygen suggests a weak and intermittent connection of the basin to the Baltic between 9800–8600 cal. BP, while Hunnemara was still isolated. Occurrences of brackish-water stoneworts, dinoflagellates, marine diatoms and seagrasses indicate the beginning of the Littorina Sea stage in the two basins, dated to 8600 cal. BP in Smygen Bay and to 8300 cal. BP in the higher located Hunnemara ancient lake. A sedimentary hiatus corresponding to between 8300 and 7500 cal. BP is present at Hunnemara and is assumed to have been caused by erosion associated with the rapid sea-level rise corresponding to meltwater pulse 3. Aquatic macrofossil and mineral magnetic parameters reveal several minor transgressions at both sites. The small-scale fluctuations superimposed upon the ice-volume-equivalent sea-level rise were probably related to variations in regional atmospheric circulation, specifically the prevailing wind direction over the threshold area. Disappearances of dinoflagellates, seagrasses and stoneworts as well as a drop in the χ_{ARM} and an increase in LOI values from 3100 cal. BP mark the final isolation of the Hunnemara basin from the Baltic Sea. Although not isolated, a lowering of the sea level in Smygen at the same time is indicated.

Paper III

Yu, S.-Y., Berglund, B.E., Andrén, E., and Sandgren, P.: Mid-Holocene Baltic Sea transgression along the coast of Blekinge, SE Sweden — ancient lagoons correlated with beach ridges. Manuscript submitted to *GFF*.

As part of a wider study of coastal sediments in Blekinge, which addresses the sedimentary response to oceanographic and climatic changes during the Holocene, this paper is a re-investigation of Lake Färsksjön, a former Littorina lagoon in central Blekinge, SE Sweden. The aim of this study was to provide a powerful constraint on the highest Holocene shoreline of the Baltic Sea in Blekinge, by correlating stratigraphic records from Färsksjön and Siretorp in western Blekinge with a beach ridge system in the eastern part.

Detailed stratigraphic investigation of Färsksjön reveals a homogeneous limnic sedimentation overlying the clayey gyttja, which is assumed to have been deposited during the Yoldia Sea stage, suggesting that the basin remained isolated during the

Ancylus Lake stage. Seagrasses and stoneworts occur immediately after the disappearance of fresh-water taxa, indicating a rapid transgression in the basin around 7700 cal. BP, which led to erosion at the bedrock sill, as revealed by the strong mineral magnetic signals. A significant increase in dinoflagellates and a brackish-water diatom assemblage indicate that full brackish conditions prevailed in the embayment between 7600 and 5600 cal. BP. A short regression occurred in between, evident as an extreme peak of *Fragilaria* and minima of *Achnanthes fagedii* and maxima of *A. submarina* during the time span between 6800 and 6400 cal. BP. The episodic lowering of sea level also can be supported by the occurrence of *Carex*, a wetland herb that grows in very shallow waters near the shore. More frequent twigs and wood pieces, as well as the mineral magnetic stratigraphy, also reflect increased in-washing of terrigenous materials as sea level was lowered. The values of dinoflagellate cysts decrease continuously, along with a gradual expansion of *Nitella*, generally indicating a sustained regression in the lagoon. Peaks in mineral magnetic concentration parameters around 5400 cal. BP indicate erosion at the bedrock sill when sea level was lowered, and the basin was finally isolated from the Baltic basin.

The timing of the mid-Holocene sea-level changes documented in Färsksjön is perfectly correlated with that in Siretorp, a lagoon sheltered by a beach ridge, where transgressions L2–L5 can be correlated to the lithostratigraphy. In addition, the lagoon was isolated from the Baltic Sea during the regression L2/L3, thereby providing favorable conditions for the Neolithic coastal settlers. Beach ridges are deposited by wave wash during sea level high, thus providing strong evidence for sea-level changes. Three *Littorina* beach ridge sites have previously been found and studied in Blekinge. Only the Olsäng beach ridge was dated from the swale peat behind the ridge, which gave an age of 6570–6400 cal. BP, corresponding to the maximum transgression between 6400 and 5600 cal. BP identified both in Färsksjön and in Siretorp.

The sea-level records from the two lagoons also provide a framework within which the rise and fall of Neolithic cultures on the Blekinge coast may be better understood. The Blekinge coast has been colonized from the mid-Holocene onwards. However, there have been periods less favorable for livelihood for the Neolithic people on the wind-exposed beaches. The Early Neolithic funnel-beaker culture is correlated with the regression phase before transgression L4 and the Middle Neolithic pitted-ware culture with the following regression.

Paper IV

Yu, S.-Y. 2003: Centennial-scale cycles in middle Holocene sea level along the southeastern Swedish Baltic coast. *Geological Society of America Bulletin* **115** (in press).

Submerged seagrasses and stoneworts growing in the immediate nearshore of the Baltic Sea are sensitive indicators of sea level. The alternating changes in concentrations of seagrass and stonewort macrofossils are ascribed to mid-Holocene sea-level fluctuations. This paper presents a spectral perspective on centennial-scale fluctuations of mid-Holocene sea level along the southeastern Swedish Baltic coast, based on Fourier and wavelet transforms of stonewort and seagrass records from Lake Ryssjön.

Harmonic spectral analysis based on the Lomb-Scargle Fourier transform reveals a multi-scale oscillatory mode of mid-Holocene Baltic Sea level with periods of 1470, 940, 480, 220, and 180 yr. Furthermore, Morlet-wavelet analysis shows that these periods have changed over time. A weak 1500 yr cycle dominated the time series prior to 6000 cal. BP. By 6000 cal. BP, this cyclicity was suddenly replaced by two consistent and relatively strong 750–1250 (quasi-1000) yr and 450–550 (quasi-480) yr cycles. The most significant 150–450 yr cycle prevailed only between 6000–4500 cal. BP.

These well-defined cycles in the sea-level proxies do not seem to be the manifestation of internal oscillations of the atmosphere-ocean system. Instead, they are most probably the in-phase response of sea level to some external forcing. All of the centennial-scale cycles lie in frequency bands characteristic of the Holocene atmospheric $\Delta^{14}\text{C}$ variation (Stuiver *et al.*, 1995), which implies that the cycles may have been produced by solar activities. It is generally thought that the modest changes in solar output are far too small to trigger large-scale sea-level fluctuations by directly changing the thermal conditions of the upper water column. However, such minor variations in solar irradiance may change the thermal advection of the stratosphere and thus modulate the wind pattern of the troposphere by changing the location and strength of the atmospheric pressure cells, such as the dipole of the North Atlantic Oscillation (NAO). The macrofossil records are closely correlated with the Greenland sea-salt Na^+ and ^{10}Be concentrations between 6000–5000 cal. BP, suggesting that the observed high-frequency fluctuations of Baltic Sea level were forced by wide-ranging storm activities over the North Atlantic, regulated by solar activities within the 210 yr Suess band.

Periodic tidal actions related to lunar cycles exert another important influence on the neritic

environments of the ocean. The recorded cycles may also be the whole-number multiples of the lunar perigee cycle or the lunar full nodal cycles. As the 480, 940, 1470 yr cycles prevailed even during the period when the macrofossil records were out of phase with ^{10}Be concentrations, they are most likely of tidal origin, thus providing a physical link between the North Atlantic climate and Baltic Sea-level changes.

Paper V

Yu, S.-Y., and Sandgren, P.: Mid-Holocene changes in North Atlantic Oscillation patterns and Baltic nearshore hydrography at centennial time scales. Manuscript submitted to *Journal of Quaternary Science*.

The North Atlantic Oscillation (NAO) is the dominant mode of winter climate variability in the area ranging from central North America to Europe and much into Northern Asia. It is a manifestation of a large-scale seesaw in atmospheric masses between the subtropical high and the polar low, which modulates mid-latitude storminess and the frequency of high-latitude blocking and cold air outbreaks. The nearshore hydrological conditions of the Baltic Sea are sensitive to atmospheric forcing. Statistical analyses of instrumental data reveal a close correlation between Baltic Sea level and the NAO index. However, centennial-scale variability in Baltic Sea level and its phase relationship with the NAO-induced westerly winds are not yet known. Moreover, reconstruction of Holocene nearshore environments in the Nordic seas may also provide a long-term perspective on the dynamic changes of North Atlantic atmospheric system.

This paper reveals centennial-scale changes in the nearshore hydrology of the Baltic Sea during the middle Holocene, using high-resolution dinoflagellate, organic carbon and mineral-magnetic proxies from the Smygen Bay. Superimposed on a general trend of sea-level changes are the small-scale variations in the hydrological conditions, as indicated by a high variability in the dinoflagellate flux. Peaks in the Anhyseretic Remanent Magnetization (ARM) indicate a slight increase in erosion due to the lowering of sea level, which covary with minima in the flux of *Operculodinium centrocarpum*. A close correlation between these proxies and the GIPS2 ice-core Na^+ concentrations implies that these variations may have been modulated by periodical changes in the strength of the prevailing westerly winds, through governing the inflows of saline and warm seawater to the lagoon. The periodical changes

in Baltic hydrological conditions with a characteristic frequency of 200–300 years may reflect the regulation of centennial-scale storminess by solar activities in the Suess band, probably through a thermodynamic mechanism.

Paper VI

Yu, S.-Y., Berglund, B.E., and Sandgren, P.: Acceleration of Baltic sea-level rise suggests a global meltwater pulse 8000 years ago. Manuscript submitted to *Science*.

Coral-reef records from tectonically stable areas, such as Barbados, New Guinea and Tahiti only give a general picture of Holocene sea-level changes. Our knowledge on the pattern, rate and magnitude of mid-Holocene sea-level changes deduced from coral records is quite fragmentary. This time has been poorly covered by other coral records too. Furthermore, the existing coral data sets demonstrate a large divergence during the middle to late Holocene. Thus, detailed changes in Holocene sea level should be recovered using other type of geological materials. This may not only bridge the gap in coral records between the early and late Holocene, but also provide an important crosscheck of coral records during these two time slices. Coastal lakes and lagoons with identifiable bedrock sills in southeastern Sweden provide powerful constraints on Holocene sea-level changes. These basins were flooded during the middle Holocene sea level high, and then isolated gradually from the Baltic as a result of isostatic rebound during the late Holocene. Thus, dating the isolation/contact of these basins may establish a precise timing of Holocene sea-level changes.

This paper provides concrete evidence for a global meltwater pulse 8000 years ago, by dating the isolation/contact of nine coastal basins with the Baltic Sea in southeastern Sweden. Our results show that sea level rose at a modest rate of 3 mm yr^{-1} during the early Holocene and 1 mm yr^{-1} during the late Holocene, matching well with the values inferred from coral records. The rapid rise occurred between 8100 and 7500 cal. BP, which led to a relative sea-level rise of *c.* 8 m in 500 years at an accelerated rate of $\sim 15 \text{ mm yr}^{-1}$. Both the magnitude and rate of sea-level rise during this time are not consistent with coral records.

Concurrent with the mid-Holocene thermal maximum was a widespread flooding of the world's coastal low-lying lands. In the Caribbean-Atlantic region, a break in the shallow-water coral framework suggests a meltwater pulse 7600 calendar

years before the present, corresponding to the beginning of the transgression in the Black Sea, popularly known as the Biblical flood. However, our Baltic dates, along with those from the Chesapeake Bay, North America, strongly suggest that this event started as early as at 8000 cal. BP. The discrepancy may have resulted from the application of an erroneously large reservoir correction to obtain ages of the Caribbean corals and Black Sea marine samples. Similar problems also may apply to other coral records.

Several lines of evidence suggest that this rapid rise event can be ascribed to the partial collapse of the Antarctic Ice Sheet, as the major continental ice sheets in the Northern Hemisphere had already melted. Increased meltwater discharge to the Southern Ocean also had great impacts on the ocean circulation and thus global climate.

Discussion

Timing and pattern of the Littorina transgression

Slightly brackish conditions in low-lying sites of the Blekinge coast prevailed between 9500–8600 cal. BP (Berglund *et al.*, in press; Paper II), suggesting a weak and intermittent connection of the Baltic basin to the North Sea. Nevertheless, the inlet of seawater during this period is still unknown (Jensen *et al.*, 1999; Lemke *et al.*, 2001). The Littorina Sea *sensu stricto* began at around 8600 cal. BP in the Blekinge area (Paper II). It is defined in this study by the occurrence of brackish-marine conditions, when the land uplift in the Danish straits slowed down that enabled seawater to continuously enter the Baltic basin within the context of ice-volume-equivalent sea-level rise (Lambeck, 1999).

Several minor transgressions were identified during the Littorina Sea stage in low-lying basins along the Blekinge coast (Papers I–III; Fig. 3a), suggesting an oscillatory pattern of mid-Holocene Baltic Sea level as proposed by Berglund (1964, 1971) and others (Digerfeldt, 1975; Liljegren, 1982; Christensen, 1995). A minor transgression is defined by the overlapping sea-level highstands lasting about 500–1000 years in the study sites. The somewhat incoherent excursions of sea-level highstands in the different sites may arise from either the uncertainties of radiocarbon dating or the individual basin geometry. A trans-Baltic correlation between Blekinge and Ingermanland, NW Russia has shown that these minor transgressions occurred synchronously at least between 8000 and 5500 cal. BP (Sandgren *et al.*, in prep.).

Baltic Sea level experienced submillennial-scale fluctuations throughout the middle Holocene, and exhibited strong coherence with North Atlantic climate (Fig. 3b). However, the in-phase changes do not necessarily mean that all the transgressions were caused by increased meltwater discharge to the oceans from the Northern Hemisphere. For example, Transgression L2, marked by a sudden flooding in the isolation basins between 8100–7600 cal. BP (Paper VI), is a strong signal of partial collapse of the Antarctica Ice Sheet (Blanchon and Shaw, 1995). Increased meltwater from the Antarctic Ice Sheet not only raised global sea level, but also modified the ocean circulation (Weaver *et al.*, 2003), thereby leading to a Northern Hemisphere warming concurrent with global sea-level rise. Note that superimposed upon a sea-level highstand, submillennial scale storm activities might be a major cause for other minor transgressions.

Baltic Sea level during the late Holocene was characterized by a general regression. However, widespread development of dunes in the northwest European coasts suggests that elevated storminess in the North Atlantic sector may have resulted in episodic sea-level rises, as recorded in the southern Baltic coast (Schumacher and Bayerl, 1999; Schwarzer *et al.*, 2003). Continuous and undisturbed sediments are missing in the shallow bays along the Blekinge coast due to wave erosion and reworking. Thus, the detailed sea-level history during the last 3000 years is unknown. Other proxies such as archaeological excavations and historical documents are required to bridge the gap between geological records and tide gauge data (Miller, 1982).

Irregular isostasy or variable ice volume?

At the central Baltic coast, localized variations in the Littorina transgression limit imply an irregular isostatic rebound during the Littorina Sea phase (Heinsalu *et al.*, 2000; Hedenström, 2001). However, a consistent difference of the land uplift isobases between the Littorina transgression time and the present day suggests that postglacial crustal rebound in southeastern Sweden was uniform (Ekman, 1996). Therefore, the recorded minor transgressions along the Blekinge coast primarily resulted from the significant reduction in global ice volume (Paper VI). Superimposed on this eustatic pattern, the episodic strengthening of the prevailing westerly winds over the threshold area might have played an important role in the minor transgressions (Papers IV–V; Fig. 3).

The first transgression (L1) occurred between

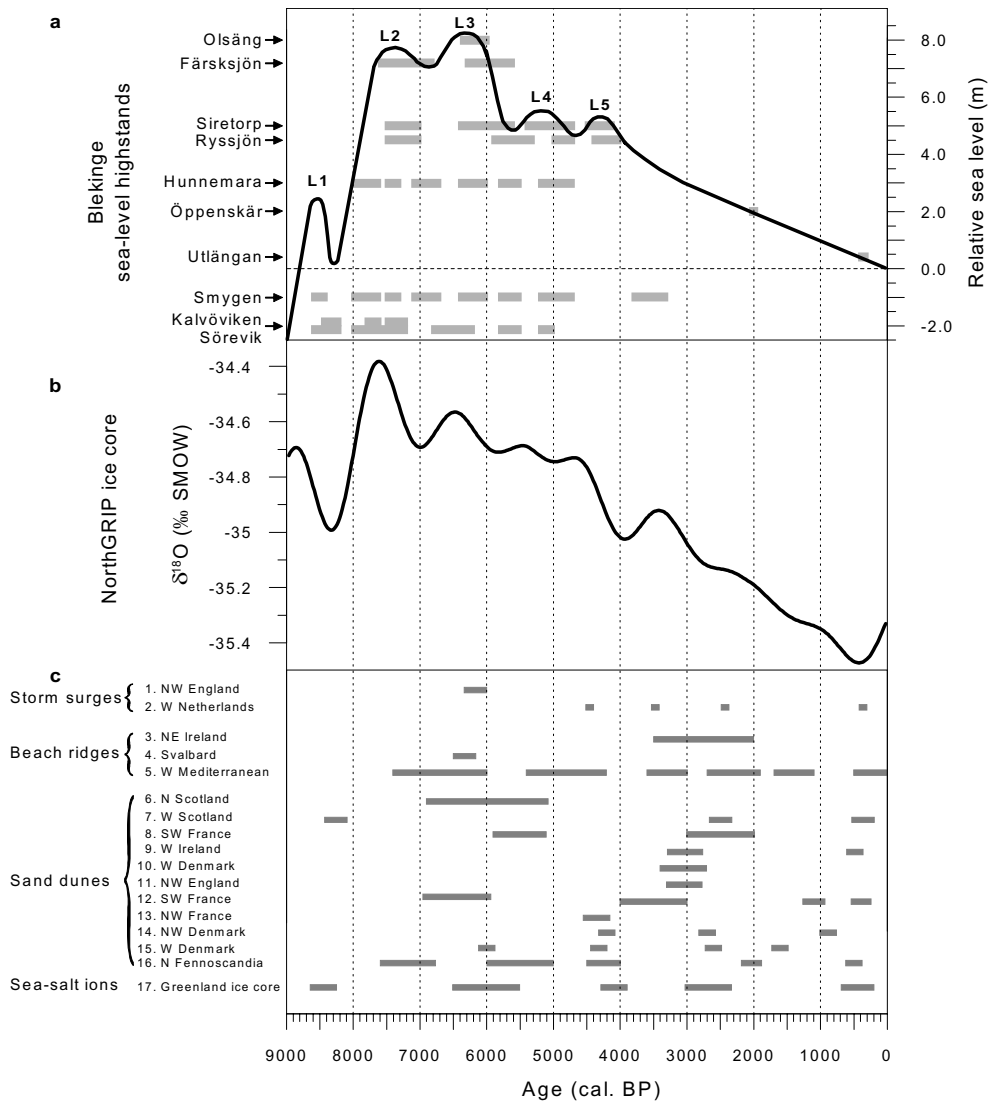


Fig. 3. Baltic shoreline displacement and relevant climate records spanning the Holocene. **(a)** Reconstructed Baltic Sea-level changes along the southeastern Swedish coast using isolation basins as “index points”. Sea-level highstands were determined on the basis of radiocarbon-dated biostratigraphic sequences, such as diatoms, dinoflagellates, seagrasses, stoneworts, as well as mineral magnetic parameters. **(b)** The NorthGRIP ice-core oxygen isotope record (Johnsen *et al.*, 2001). The data set is smoothed using a bandpass filter. **(c)** Storm-induced sediments in the northwestern European coasts. Storm surges are: 1, NW England (Zong and Tooley, 1999), and 2, W Netherlands (Jelgersma *et al.*, 1995). Beach ridge progradations as follows. 3, NE Ireland (Orford *et al.*, 2003). 4, Svalbard (Ziaja and Salvigsen, 1995). 5, W Mediterranean (Goy *et al.*, 2003). Sand dune buildings as follows. 6, N Scotland (Leinert *et al.*, 2000). 7, W Scotland (Wilson, 2002). 8, SW France (Pontee *et al.*, 1998). 9, W Ireland (Wilson and Braley, 1997). 10, W Denmark (Clemmensen *et al.*, 2001a). 11, NW England (Pye *et al.*, 1995). 12, SW France (Clarke *et al.*, 2002). 13, NW France (Haslett *et al.*, 2000). 14, NW Denmark (Clemmensen *et al.*, 2001b). 15, W Denmark (Clemmensen *et al.*, 2001c). 16, N Fennoscandia (Käyhkö *et al.*, 1999). 17. Greenland ice-core sea-salt ions (O’Brien *et al.*, 1995).

8600–8400 cal. BP, as a result of a wider opening of the Great Belt and the newly established connection through the Öresund strait in response to global sea-level rise (Björck, 1995). Sea level rose slowly from -2 m to -1 m (Paper VI) at a rate of 3 mm yr^{-1} , almost the same as the values inferred from far-field sites (Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996). The final drainage of proglacial lakes in northern America may have been

responsible for this sea-level rise as well as the subsequent “8.2-kyr” cold event (Barber *et al.*, 1999). A short regression following this modest sea-level rise (Fig. 3) was probably caused by local meteorological conditions, as the high pressure over the Baltic Sea may have been intensified as a result of regional cooling, which triggered strong outflow of seawater from the Baltic Basin (Berglund *et al.*, in press). The second one (L2) occurred between

8100–7600 cal. BP (Papers I–III), at an accelerated rate of $\sim 15 \text{ mm yr}^{-1}$ (Paper VI). A synchronous transgression also was observed along the southwestern Swedish and the Danish Baltic coasts (Mörner, 1969; Digerfeldt, 1975; Christensen, 1995). Significantly increased salinity during this time also was recorded along the central Baltic coast (Persson, 1973; Hyvärinen, 1980; Risberg *et al.*, 1991; Korhola, 1995; Eronen *et al.*, 2001), and no transgressive sea-level rise occurred north of Stockholm (Robertsson and Persson, 1989), which determines the north limit of this transgression. As a continuation of L2, transgression L3 has the same geographical extent as L2. A beach ridge located at 8 m a.s.l. in Olsäng suggests that this transgression might have corresponded to the highest Holocene sea level along the Blekinge coast (Paper III). Gradual isolation of the elevated basins indicates that sea level along the Blekinge coast fell from 6500 cal. BP (Paper VI), as a result of the deceleration of global sea-level rise (Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996) and the continued rebound in Scandinavia (Påsse, 1996). However, superimposed upon this trend, episodic rises may have occurred, as revealed by two minor transgressions (L4–L5). It is difficult to say whether or not these two events were caused by ice-volume changes, as the resolution of far-field coral records covering the second half of the Holocene is very low. Thus, high-resolution sea-level changes during the last 6000 years need to be quantified. Moreover, these two minor transgressions positively correlate to the periods of beach-ridge progradations and dune build-ups in the northwestern European coasts (Fig. 3c), suggesting a possible forcing of submillennial-scale variations in regional storminess. Sea-level highstands corresponding to these two transgressions were not recorded in the north Baltic, implying that a modest rise of sea level may have been overshadowed by the higher land uplift rate.

Atmospheric forcing versus tidal actions

The large-scale rise of Baltic Sea level was ascribed to the partial collapse of the Antarctic Ice Sheet (Paper VI). However, concomitant changes of sea-level proxies and Greenland ice-core sea-salt ions along with cosmogenic nuclides suggest that centennial-scale fluctuations could be linked to solar forcing in the 210-yr Suess band. The modest variations in solar activities may affect sea-level fluctuations by changing the regional storminess (Suursaar *et al.*, 2003), probably through a system similar to the dipole oscillation of modern North Atlantic

atmosphere (Papers IV–V), as it governs Baltic sea-level fluctuations today (Andersson, 2001). Observed NAO indices exhibit intermittent oscillation with temporarily active and passive phases, probably driven by atmospheric noise (Visbeck, 2002), whereas reconstructed NAO phases based on Greenland ice-core snow accumulation during the last 350 years demonstrate centennial-scale fluctuations in the 88-yr Gleissberg frequency band (Appenzeller *et al.*, 1998). Long-term behavior of the NAO is still unclear. Thus, extending the NAO phases to the whole Holocene is of particular importance for understanding paleoatmospheric dynamics in the North Atlantic realm.

The modern Baltic Sea is almost tideless (Ekman and Stigebrandt, 1990). However, mollusc faunal assemblages reveal an increase of tidal actions in the Kattegat Sea during the Littorina Sea stage (Petersen, 1993). Thus, periodical fluctuations of mid-Holocene Baltic Sea level also may have been produced by tidal actions related to lunar cycles, particularly when the connection of the Baltic basin with the Kattegat Sea was wider (Paper IV). The recorded centennial-scale cycles can be the whole-number multiples of the lunar perigee cycle or the lunar full nodal cycles, or sometimes can be thought to be the difference tone between the lunar and the solar cycles (Berger and von Rad, 2002). Periodical variations in the tidally induced vertical mixing also exert considerable influence on sea surface temperatures (Keeling and Whorf, 1997), which may affect the overlying atmosphere and thus regional climate.

Conclusions

- The Littorina transgression/regression in southeastern Sweden covers the time span 8500–3000 cal. BP. It can be ascribed to the accelerated rise of global sea level, overprinting the slow isostatic uplift in southern Scandinavia during the middle Holocene.
- Within the Littorina Sea stage, five minor transgressions and regressions are recorded by multiple stratigraphic sequences from four sites in the Blekinge coast: L1 8500–8200, L2 7800–6900, L3 6400–5600, L4 5300–4700, and L5 4500–4100 cal. BP. These minor transgressions/regressions, lasting 500–1000 years in the study sites, occurred almost synchronously at least between 8000–5500 cal. BP across the southern Baltic Sea.

- The first transgression (L1), characterized by a slight sea-level rise between 8600–8400 cal. BP, may be linked to the flood of the proglacial lakes in North America. The most pronounced transgression (L2) occurred between 8000–7600 cal. BP, when Baltic Sea level rose by *c.* 8 m in 500 years, at an accelerated rate of $\sim 15 \text{ mm yr}^{-1}$. It is almost concurrent with the rapid flooding in the Black Sea and elsewhere, suggesting a global meltwater pulse probably triggered by the partial collapse of the Antarctic Ice Sheet.
- The younger minor transgressions L3 (6400–5600), L4 (5300–4700) and L5 (4500–4100 cal. BP) were possibly caused by ice-volume changes in combination with submillennial-scale variations in regional storminess. Beach-ridge progradations, storm surges, dune buildings in the north-western European coasts along with sea-salt ion concentrations in Greenland ice cores are correlated with these events, suggesting a possible connection between Baltic Sea level and North Atlantic climate.
- Centennial-scale sea-level fluctuations have been identified by palaeobotanical and mineral magnetic stratigraphy, and show good coherence with ice-core sea-salt ions and cosmogenic nuclides in some time windows. The modest changes in solar radiance may have an impact on Baltic Sea level by changing the regional storminess, probably through a system similar to the dipole oscillation of the North Atlantic atmosphere (i.e. NAO). In addition, tidal actions related to lunar cycles may exert another important influence on Baltic Sea level during the middle Holocene.
- The global and regional North Atlantic climate is reflected in sea-level changes along the south-eastern Swedish Baltic coast with regional centennial-scale storminess variations overprinting global millennial-scale ice-volume changes.
- Sea-level fluctuations have exerted large influences on Neolithic cultures in the Blekinge coast. Discontinuities of coastal settlements are correlated to beach-ridge buildings and transgression periods, whereas Neolithic cultural layers correspond to regression periods, indicating more favorable conditions for coastal settlements.

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Svensk sammanfattning

Östersjöns Littorinatransgression i sydöstra Sverige och dess relation till klimatfluktuationer under mellersta Holocen

Den seneglaciala och Holocena strandförskjutningen i Östersjön har sin grund i samspelet mellan den isostatiska landhöjningen och den eustatiska havsyteförändringen, vilka är orsakade av den senaste inlandsisens tillväxt och avsmältning. Detta samspel ledde till relativa förändringar av vattenytan i världshaven och har medfört att den nuvarande Östersjön tidvis varit isolerad från världshavet, nämligen under Baltiska Issjöns tid (från inlandsisens avsmältning fram till ca 11 500 år före nutid) och under Ancylussjöns tid (10 700–9800 år före nutid). Däremellan har det funnits en kontakt till världshavet, nämligen under Yoldiahavets tid (11500–10700 år före nutid) och under Littorinahavets tid (i vidsträckt bemärkelse 9800 år före nutid fram till idag; i strikt bemärkelse 8500 till 3000 år före nutid). Det nuvarande Östersjöstadiet från 3000 år före nutid fram till idag, ibland kallat Limnea havet eller Sen Littorina tid, under vilken det alltså finns en kontakt med världshavet, är således en direkt fortsättning av Littorinahavet.

Littorinahavets historia inleddes således ca 9800 före nutid med ett brackvattenstadium benämnt det Tidiga Littorinahavet. Då var förbindelsen med Nordsjön koncentrerad till Stora Bält. Genom att den globala havsytestigningen var större än den isostatiska komponenten öppnades också kontakten till världshavet genom Öresund ca 8500 år före nutid och det Egentliga Littorinahavet uppstod, med större vattendjup och högre salinitet. Detta stadium som varade fram till ca 3000 år före nutid karakteriseras av en succesiv höjning av havsytan fram till ca 6000 år före nutid följt av en vattenståndssänkning. Denna s.k. Littorinatransgression omfattar således tiden 8500–3000 år före nutid. Dess förlopp och orsaker har varit mycket omdiskuterade av forskare i Danmark, Sverige och Finland. Den förhärskande finska uppfattningen har varit, att transgressionen är *en* långvarig havsytestigning, medan danska och svenska geologer hävdar, att *flera* mindre transgressioner förekommit under tiden 8500–4000 år före nutid. De senare har oftast sett orsaken till dessa i globala, eustatiska transgressioner. Min avhandling syftar till att klarlägga denna problemställning genom att dokumentera havsyteförändringar i kustnära bassänger med stor kronologisk och stratigrafisk precision, och att

analysera orsakerna till desamma, särskilt relationerna till klimat och oceanografi inom det nordatlantiska området.

Som undersökningsområde har jag valt Blekinges kust, eftersom de geologiska förutsättningarna utefter hela kusten är likformiga samtidigt som hela området ligger på samma isobas och är obetydligt påverkat av isostasi sedan mellersta Holocen. Landskapets relief har gett goda förutsättningar för en kontinuerlig sedimentation i många bassänger (under 10 m ö.h.) längs kusten i vilka dessa vattenståndsförändringar registrerats och som indirekt kan återspeglas i olika geofysiska, fysikaliska och biologiska parametrar (s.k. "proxy records"). Jag har provtagit och analyserat fyra lagerföljder (sjöar, havsvikar) och kombinerat olika stratigrafiska metoder: transektborrningar, mineralmagnetisk analys, pollen- och dinoflagellatanalys, diatoméanalys, makrofossilanalys för att i detalj studera havsyteförändringarna under Littorinaskedet baserat på dessa "proxy records". Kronologin har fastlagts genom ett stort antal kol-14 dateringar. Resultaten från dessa fyra lokaler har jämförts med varandra och kompletterats med tidigare publicerade undersökningar från ytterligare nio lokaler utefter Blekingekusten.

En detaljerad strandförskjutningskurva presenteras för perioden 8500–3000 år före nutid. Den komplexa Littorinatransgressionen omfattar fem mindre transgressionsvågor benämnda L1–L5, med den maximala nivån på 8.0 m ö.h. som inträffande ca 6000 år före nutid. Transgressionerna L2 och L3 är synkrona vid jämförelse med motsvarande i Öresundsområdet och vid Finska vikens södra kust, dvs utefter en väst–östlig transekt med en Littorinanivå på 5–9 m ö.h. Mineralmagnetisk stratigrafi och fluktuationer av vissa brackvattenväxter (*Ruppia*, *Zannichellia*, *Chara*) förekomst korreleras med iskäror från Grönland avseende havssaltjoner och kosmogena isotoper. Ett samband kan också påvisas med förekomsten av eoliska dyner i Nordvästeuropa. Detta tolkas så att det finns ett samband mellan solinstrålning, lufttrycksförhållande och stormfrekvens kring Nordatlanten, vilket påverkar klimat och havsyteförändringar i Östersjön. Informationen om strandförskjutningen under sen Holocen är bristfällig i detta område men en långsam och regelbunden regression antas för tiden efter 3000 år före nutid, dvs under Sen Littorinatid.

Huvudslutsatserna i min avhandling kan sammanfattas sålunda:

- Littorinatransgressionen 8500–3000 år före nutid är komplex och omfattar minst fem mindre

transgressionsvågor: L1 (8500–8200), L2 (7800–6900), L3 (6400–5600), L4 (5300–4700) och L5 (4500–4100) år före nutid. Under transgressionen L3 når Östersjön sin högsta nivå i Blekinge, ca 8 m ö.h. Dessa transgressionsvågor är troligtvis synkrona i södra Östersjön och kan knytas till globala/regionala klimatvariationer. De är inte möjliga att identifiera norr om Mellansverige och norr om Finska viken på grund av den större landhöjningen i dessa områden.

- Transgressionsvågorna L1 och L2 är samtida med omfattande issjötappningar i Nordamerika respektive isavsmältning i Antarktis. Dessa processer kan ha påverkat världshavets nivå och därmed orsakat transgressioner i Östersjön.
- Transgressionsvågorna L3–L5 kan delvis förklaras av global isavsmältning men sambandet med stormfrekvenser i det nordatlantiska området antyder att den nordatlantiska atmosfärsoscillationen påverkat havsytan i Östersjön – högre medelvattenyta under oceaniska och stormiga lågtrycksperioder, lägre medelvattenyta under kontinentala och lugnare högtrycksperioder.
- De neolitiska kustbosättningarna har påverkats av klimat och vattenstånd, vilket gett gynnsammare förutsättningar för strandnära boende under regressionsperioder.

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