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Holocene paleoecology along the Blekinge coast, southeast Sweden, and implications for climate and sea-level changes

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Abstract

To investigate the Holocene vegetation history and shoreline displacement along the southeastern Swedish coast, two radiocarbon dated pollen, macrofossil, and mineral magnetic sequences were studied in the western Blekinge coast: Hunnemara Lake and Smygen Bay. Both pollen records show mosaic vegetation with grasslands, heaths and woodlands prior to 11,300 cal. BP. *Pinus*-dominated mixed forest was initially established by 11,000 cal. BP. By 10,000 cal. BP, mixed forest with higher species diversity was fully established. Expansion of broad-leaved trees began at about 8,600 cal. BP, indicating the onset of the mid-Holocene thermal maximum in Scandinavia. Following the *Ulmus* decline ~5,800 cal. BP, the regional forest became much more open due to increased human disturbance. Both basins were isolated during the period of 11,300–11,000 cal. BP, and subsequently in contact with the Ancylus Lake between 10,700 and 9,800 cal. BP. Low abundance of brackish-water diatoms at Smygen suggests that this basin was connected with the Baltic Sea between 9,800 and 8,600 cal. BP, corresponding to the Early Littorina Sea phase. Hunnemara was isolated during this period. The two basins were in turn flooded at 8,600 and 8,300 cal. BP, as a result of global sea-level rise. A sedimentary hiatus (8,300–7,500 cal. BP) was present at Hunnemara, probably caused by a rapid sea-level rise related to global meltwater pulse 3. Aquatic macrofossil and mineral magnetic proxies reveal several minor transgressions at both sites, probably regulated by centennial-scale variations in regional storminess. Hunnemara was isolated from the Baltic Basin by 3,100 cal. BP, concurrent with a lowering of the sea level at Smygen.

Keywords: Pollen, macrofossils, mineral magnetism, Holocene, Baltic Sea, Sweden, Littorina transgression, sea-level change, vegetation history, climate change.

Introduction

In the circum-Baltic areas, postglacial shoreline was primarily controlled by the interplay of isostatic uplift and ice-volume-equivalent global sea-level rise (cf. Mömer, 1979; Lambeck, 1999). The earliest brackish-water condition, known as the Yoldia Sea, occurred locally between 11,300 and 11,100 cal. BP (cf. Björck, 1995), when sea water transgressed into the Baltic Basin through the central Swedish lowland, 250 years after the final drainage of the Baltic Ice Lake (Andrén *et al.*, 2002). However, marine environments within the Baltic Basin were not fully established until 8,500 cal. BP (Björck, 1995; Westman and Sohlenius, 1999; Andrén *et al.*, 2000), as a result of the opening

of the Danish straits and continued rise in global sea level (Fairbanks, 1989; Chappell and Polach, 1991; Bard *et al.*, 1996). In the southeastern Swedish coast, evidence of both beach ridges and lagoon paleoecology generally supports an interval of high sea level during 8,000–5,000 cal. BP (Berglund, 1971; Berglund *et al.*, 2005), corresponding to the Littorina transgression observed elsewhere along the Baltic coast (Eronen, 1974; Digerfeldt, 1975; Christensen, 1995). As crustal rebound of the area slowed down significantly during the middle to late Holocene (*e.g.*, it continues today at a rate of only 0.5 mm/yr; Milne *et al.*, 2001), this sea-level highstand was reached primarily by persistently increased saltwater influx to the Baltic Sea within the context of global sea-level rise.

The pattern of the *Littorina* transgression along the Blekinge coast was well established by Berglund's pioneer study on a suite of isolation basins (Berglund, 1964; 1971). A growing body of evidence generally confirms the idea of a fluctuating mid-Holocene sea level (Christensen, 1995; Clemmensen *et al.*, 2001; Yu *et al.*, 2003; 2004; Berglund *et al.*, 2005), probably caused by coastal storms and tidal cycles (Yu, 2003). However, the detailed history of shoreline displacement prior to the *Littorina* Sea phase, particularly during the transition from the Ancyclus Lake to the *Littorina* Sea, is poorly constrained. Moreover, sea-level rise appears to be rapid around 7,500 cal. BP, evident in the sudden expansion of marine diatoms and appearance of warm-water-demanding dinoflagellates in several basins located above 4.5 m a.s.l. (Yu *et al.*, 2003; 2004). To determine the rate of sea-level rise during this time, more basins below this level should be studied. In this paper, we use radiocarbon dated pollen, macrofossil, and mineral magnetic records from two lagoonal sites to examine the postglacial history of regional vegetation and shoreline displacement in western Blekinge, southeastern Sweden. The results may provide a fresh insight into the regional Holocene climate and sea-level dynamics.

Site description and fieldwork

The Blekinge coast is a bedrock lowland dispersed with granite massifs. This area was widely tectonized by glacial activities, as evidenced by predominantly N-S trending valleys. Such a drainage pattern is prone to the transgression of sea water into the valleys during the mid-Holocene sea-level high. Therefore, continuous sedimentation of gyttja is common in some basins, particularly in those with protected bedrock thresholds. Both temperature and precipitation decrease slightly from the upland to the shore, *e.g.*, at the coast, mean January temperature is around 0°C, and mean July temperature is 16.5°C. Mean annual precipitation is ~600 mm along the coast and ~700 mm in the upland. Westerly to southwesterly winds prevail over the area. 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 to the north.

We studied two sites (Figure 1A). Hunnemara ancient lake (14° 53' E, 56° 10' N) is originally a closed lake with an outflow threshold around 3.0 m a.s.l. (Figure 1B). The lake has been drained, converted to agriculture land and a meadow by local farmers in the nineteenth century, and is now partly used for a garbage dump. An 8.5 m long core was taken near the center of the ancient lake in the summer of 2001, using a Russian peat sampler. All laboratory analyses refer to this master core. Four additional cores were also collected along a NW-SE transect from the shore to the centre of the lake for stratigraphic analysis and correlation. In contrast, Smygen Bay (15° 07' E, 56° 09' N) is a modern lagoon with a submarine bedrock sill 1.0 m below present sea level (Figure 1C). An 11.5 m long sediment sequence was cored using the Russian peat sampler operated on the iced surface in the winter of 2000. Water depth at the coring location was 1.4 m. To ensure a sufficient quantity of sediments for macrofossil analyses, three additional cores were taken from the same coring location in the summer of 2001 from a raft. Separate core segments were correlated on the basis of lithologic boundaries, as well as long-core magnetic-susceptibility scanning.

Methods

Carbon and mineral magnetic measurements

Carbon and mineral magnetic parameters were measured on contiguous subsamples, representing *c.* 2 cm intervals for both of the master cores. Magnetic susceptibility (χ) was determined using a Geofyzika Brno KLY-2 susceptibility bridge. Anhysteretic remanent magnetization (ARM) was imposed along a single axis using a Molspin AF demagnetizer within a 0.1 milliTesla (mT) direct current bias field and a 100 mT peak alternating field. After ARM measurements, each sample was placed in a 1 Tesla (T) magnetic field imposed by a Redcliff BSM-700 pulse magnetizer to induce saturation isothermal remanent magnetization (SIRM). The induced remanence was measured using a Molspin Minispin magnetometer. Back coercivity of remanence was also measured by placing the samples in a reversed weak magnetic field, which was increased by 10 mT steps until a negative value was obtained. IRM_{-100mT} was finally measured by exposing the samples to a reversed field of 100 mT to allow calculation of the S-ratio ($IRM_{-100mT}/SIRM$). All magnetic analyses were performed at room temperature. After the magnetic measurements, the samples were dried overnight at 50°C to calculate mass specific magnetic parameters. Subsamples from the Hunnemara site were desiccated at 105°C and then combusted at 550°C to allow the calculation of loss-on-ignition (LOI). Total organic carbon (TOC) was measured on subsamples from the Smygen site using a Leco RC-412 multiphase carbon analyzer.

Palynological analyses

For both cores, *c.* 1.5 cm³ subsamples for pollen and dinoflagellate analyses were taken at 6–8 cm intervals. Subsamples were processed following the techniques described by Berglund and Jasiewiczowa (1986). At least 500 pollen grains, spores and cysts were counted for each level under $\times 400$ and $\times 1,000$ magnification. Pollen percentages were calculated on the basis of a sum of tree, shrub, and upland herb pollen. Zonation of pollen assemblages was conducted using CONISS in the TILIA computer program, and the pollen diagram was created using TILIA GRAPH (Grimm, 1988). Dinoflagellate cysts were identified following the keys of Rochon *et al.* (1999).

Macrofossil analyses

Macrofossils and macroscopic charcoal were identified from contiguous slices of 4 cm in thickness for both cores. Subsamples of 50 cm³ bulk sediments were soaked in a graduated cylinder and then rinsed through a 200 μ m sieve. The residue was examined under a dissecting microscope at $\times 50$ magnification. 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.

Diatom analyses

Subsamples from selected intervals were prepared according to the method described by Battarbee (1986). The prepared samples were dried onto coverslips and mounted in Naphrax™. Identification was carried out under a light microscope at a magnification of $\times 1,000$. In each sample, at least 300 diatom valves, excluding *Fragilaria* spp., were identified and enumerated. Diatom abundance is expressed relative to the sum of all valves, excepting *Fragilaria*. *Fragilaria* abundance is expressed relative to the sum of all counted valves.

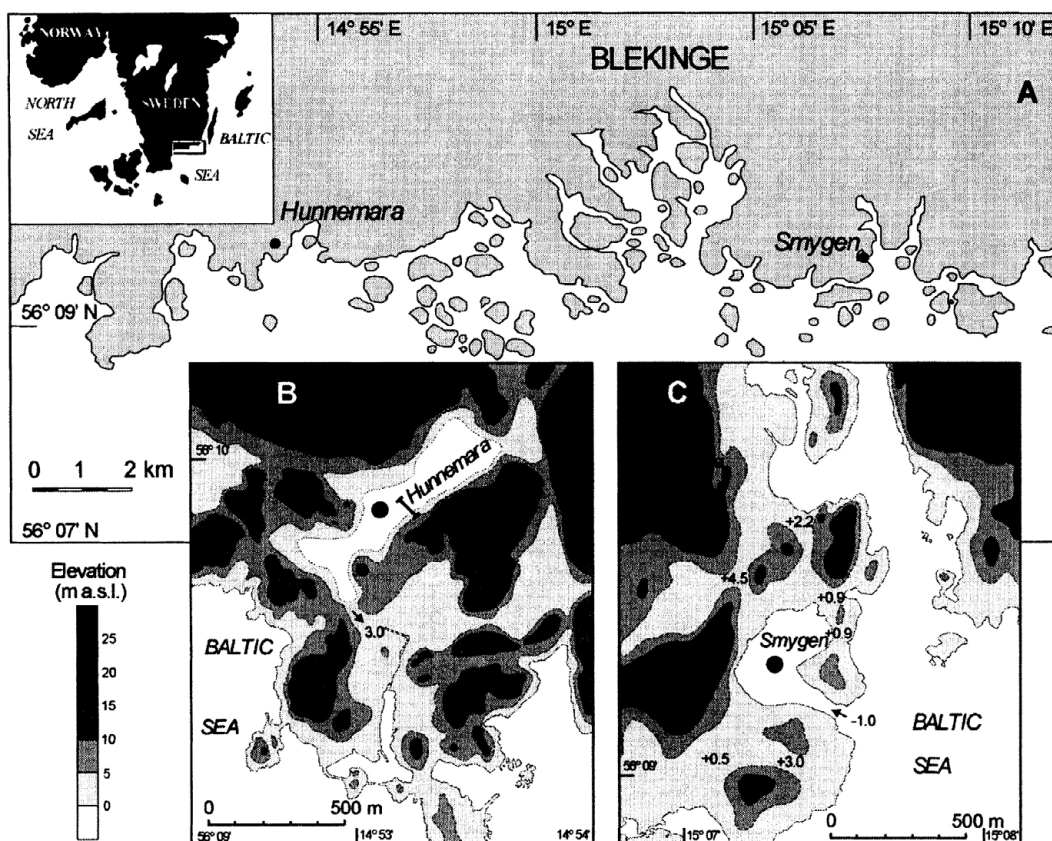


Figure 1 Map showing the geographical location of the study area (A). Topographic maps show the Hunnemara Lake (B) and the Smygen Bay (C) areas. Main coring sites are noted with black dots. The position of the transect at Hunnemara is also marked. The 5 m contour lines, indicated with dashed lines, approximately represent the coastlines of the Littorina Sea. The outline of the former Hunnemara Lake is shown with a dotted line. The elevation of the thresholds is also noted.

Radiocarbon dating

Both bulk sediments and terrigenous plant macrofossils from certain levels were dried and submitted for radiocarbon dating. Radiocarbon dates of brackish-water bulk sediments and seagrass seeds were corrected for reservoir effect by applying the MARINE 98 curve with a regional reservoir age anomaly (AR) of -108 ± 24 years (Berglund, 1971; Stuiver *et al.*, 1998). All dates were converted to calendar ages using the CALIB 4.2 calibration program (Stuiver and Reimer, 1993).

Results and interpretations

Lithostratigraphy and chronology

Hunnemara Lake

Details on the lithology of Hunnemara are given in Table 1. A total of 10 levels were dated. Terrigenous plant macrofossils are scarce in this core. Therefore the chronology is basically controlled by AMS radiocarbon dates on bulk sediments (Table 2). The radiocarbon dates indicate an 800-year-long depositional hiatus at 575 cm, partly corresponding to stratigraphic unit 6 (Figure 2A). Two dates (LuA-5449 and LuA-5450) in the upper half of the core are anomalously old and do not fit into the age-depth model and were thus rejected. The radiocarbon based chronology for the upper half of the core was independently checked by biostratigraphical correlation of regional pollen zones. For example, the significant reduction in *Pinus* pollen accompanied by an increase in *Betula* pollen at 190 cm is also identifiable in other late-Holocene pollen diagrams in Blekinge, which is dated to *c.* 3,800 cal. BP (Berglund, 1966; Sjögren and Björkman, 2000). In addition,

the *Ulmus* decline appears at 480 cm, which is a regional paleoecological event and thus can be used as a time marker horizon. It is dated to 5,900–5,700 cal. BP for the Blekinge area and southern Sweden (Nilsson, 1964; Skog and Regnéll, 1995).

Smygen Bay

At Smygen Bay, the Baltic Ice Lake grey clay (stratigraphic units 1–2) is overlain by fine-detritus gyttja (Table 3). Its lower boundary is dated to 11,120 cal. BP (Table 2). Two dates (LuA-5442 and LuA-5443) on terrigenous macrofossil samples in the lowest part of the core are considered to be too young with respect to the well-dated pollen zones for this region (Berglund, 1966). The age 1,200 cal. BP around 200 cm in the core is assigned by biostratigraphical correlation of significant increases in *Fagus*, *Picea*, and *Juniperus* pollen with those in nearby areas (Sjögren and Björkman, 2000; Figure 2B). Higher sedimentation rates were observed above 550 cm for this core (Figure 2B). According to the age-depth model, the uppermost sediments for the last 1,000 years may have been partly eroded, and thus no firm conclusions can be drawn on the environmental changes during the last millennium.

Diatom assemblages

Hunnemara Lake

Diatom analyses were performed for three levels around 575 cm. Diatom assemblages prior to 8,300 cal. BP were dominated by freshwater plankton, including *Tabellaria flocculosa*, *Aulacoseira subarctica*, *A. alpigena*, *Cyclotella stelligera*, and *C. radiosa*. After 8,300 cal. BP, freshwater taxa disappeared, and the diatom as-

Table 1. Stratigraphy of the Hunnemara core. Terminology for sediment description follows the system of Troels-Smith (1955); cf. Birks and Birks, 1980.

Depth below sediment surface (cm)	Stratigraphic units	Sediment description
0–76	9	Fen peat; dried out due to anthropogenic drainage
76–93	8	Dark-brown fine detritus gyttja with plant remains
93–568	7	Dark grey-green slightly laminated and clayey fine detritus gyttja; very homogenous; <i>Mytilus</i> shells found at 330–331, 350–351, 441–442, and 500–501 cm
568–575	6	Dark-brown coarse detritus gyttja; lower boundary sharp (<0.5 cm)
575–700	5	Dark-brown fine-detritus gyttja; lower boundary gradual (> 1 cm)
700–735	4	Dark green-brown, slightly clayey fine-detritus gyttja; lower boundary very gradual (> 10 cm)
735–770	3	Grey-green clayey gyttja; lower boundary very gradual (>5 cm)
770–784	2	Dark black-green clayey fine detritus gyttja; lower boundary gradual (>3 cm)
784–823	1	Grey clay; lower boundary very sharp (<0.3 cm)

semblages were poorly preserved and dominated by brackish-water and alkaliphilous benthic species, particularly *Mastogloia smithii*, *Rhoicosphenia curvata*, and *Lyrella sulcifera*, as well as moderate percentages of *Epithemia turgida*, *E. sorex*, *M. elliptica*, and *Cocconeis placentula*. Such a floral transition indicates the onset of the Littorina transgression in the basin, which therefore can be placed at the stratigraphic unit 516 boundary.

Smygen Bay

Four levels between 1,120 and 1,020 cm (stratigraphic unit 7) were analyzed. At 9,500 cal. BP (1,120 cm), the diatom assemblage was dominated by freshwater plankton, including *Cyclotella* spp. (*C. rossii*, *C. radiosa*, *C. ocellata*) and *Aulacoseira* spp. (*A. subarctica*, *A. islandica*). From 9,000 cal. BP, planktonic species decreased and benthic taxa, including *Fragilaria* spp., *Amphora pediculus*, and a diverse group of freshwater species in the

genera *Achnanthes* and *Navicula* increased, indicating that the lake level was gradually lowering. By 8,600 cal. BP (1040 cm), benthic taxa, including *Fragilaria brevistriata*, *F. pinnata*, *Amphora pediculus*, *Navicula* spp., and *Achnanthes* spp., were dominant. The very low abundance (<3%) of brackish-water diatoms implies that the basin was weakly connected with the Baltic Sea during the period 9,500–8,600 cal. BP, corresponding to the Early Littorina Sea phase (Berglund *et al.*, 2005).

Carbon and mineral magnetism

Hunnemara Lake

Logs of magnetic parameters and loss-on-ignition (LOI) from Hunnemara are presented in Figure 3. Apart from the clay in stratigraphic unit 1, which displays very low values throughout (3.5–5.9%), the organic sediments generally have LOI values between 20% and 40%, with variations inversely related to the mix-

Table 2 Radiocarbon dates from the Hunnemara Lake and the Smygen Bay, southeastern Sweden

Lab. ID	Depth (cm)	Materials dated	Weight (mg)	$\delta^{13}\text{C}$ (‰)	^{14}C age (yr BP)	2 σ calibrated age range (yr BP)
Hunnemara						
LuA-5448	89.5	Bulk sediments	> 100	–23.0	2,935 \pm 80	3,100 (3,330–2,870)
LuA-5449*	180.0	Bulk sediments	> 100	–16.9	4,575 \pm 95	4,870 (5,250–4,600)
LuA-5450*	274.5	Bulk sediments	> 100	–18.7	4,850 \pm 90	5,290 (5,550–4,950)
LuA-545 1	376.0	Bulk sediments	> 100	–17.1	4,800 \pm 95	5,270 (5,500–4,900)
LuA-5445	436.0	<i>Ruppia</i> and <i>Zannichellia</i> seeds	8	–10.3	4,875 \pm 90	5,310 (5,550–5,000)
LuA-5452	508.0	Bulk sediments	> 100	–16.2	5,455 \pm 90	5,920 (6,170–5,720)
LuA-5453	567.5	Bulk sediments	> 100	–18.1	6,415 \pm 90	7,010 (7,230–6,780)
LuA-5454	601.5	Bulk sediments	> 100	–30.1	7,860 \pm 95	8,620 (9,000–8,450)
LuA-5455	674.5	Bulk sediments	> 100	–30.8	8,220 \pm 110	9,200 (9,500–8,800)
LuA-5456	783.0	Bulk sediments	> 100	—	9,890 \pm 100	11,230 (11,950–11,100)
Smygen						
LuA-5278	276	<i>Betula</i> leaves and seeds	3	—	2,820 \pm 110	2,910 (3,250–2,750)
LuA-5277	402	<i>Betula</i> leaves and twigs	5	—	2,920 \pm 95	3,080 (3,340–2,850)
LuA-5276	526	<i>Betula</i> leaves and seeds	3	—	3,090 \pm 105	3,280 (3,550–2,970)
LuA-5133	594	<i>Betula</i> seeds; <i>Pinus</i> needles	5	—	3,950 \pm 85	4,420 (4,790–4,090)
LuA-5132	671	<i>Betula</i> seeds; <i>Pinus</i> needles	6	—	4,555 \pm 105	5,300 (5,570–4,870)
LuA-5131	787	<i>Betula</i> leaves; <i>Pinus</i> needles	13	—	5,645 \pm 85	6,430 (6,640–6,290)
LuA-5146	895	<i>Betula</i> seeds; <i>Pinus</i> needles	9	—	6,020 \pm 95	6,820 (7,170–6,650)
LuA-5130	1024	<i>Alnus</i> and <i>Betula</i> seeds	3	—	7,310 \pm 100	8,120 (8,340–7,940)
LuA-5442*	1042	<i>Ainus</i> seeds; <i>Pinus</i> needles	4	—	7,220 \pm 90	7,990 (8,200–7,830)
LuA-5446	1120	Bulk sediments	> 100	–26.9	8,475 \pm 95	9,510 (9,700–9,100)
LuA-5443*	1178	<i>Betula</i> seeds; <i>Pinus</i> needles	5	—	8,225 \pm 95	9,200 (9,470–9,000)
LuA-5447	1226	Bulk sediments	> 100	–30.9	9,650 \pm 95	11,120 (11,250–10,650)

*Dates rejected as anomalous.

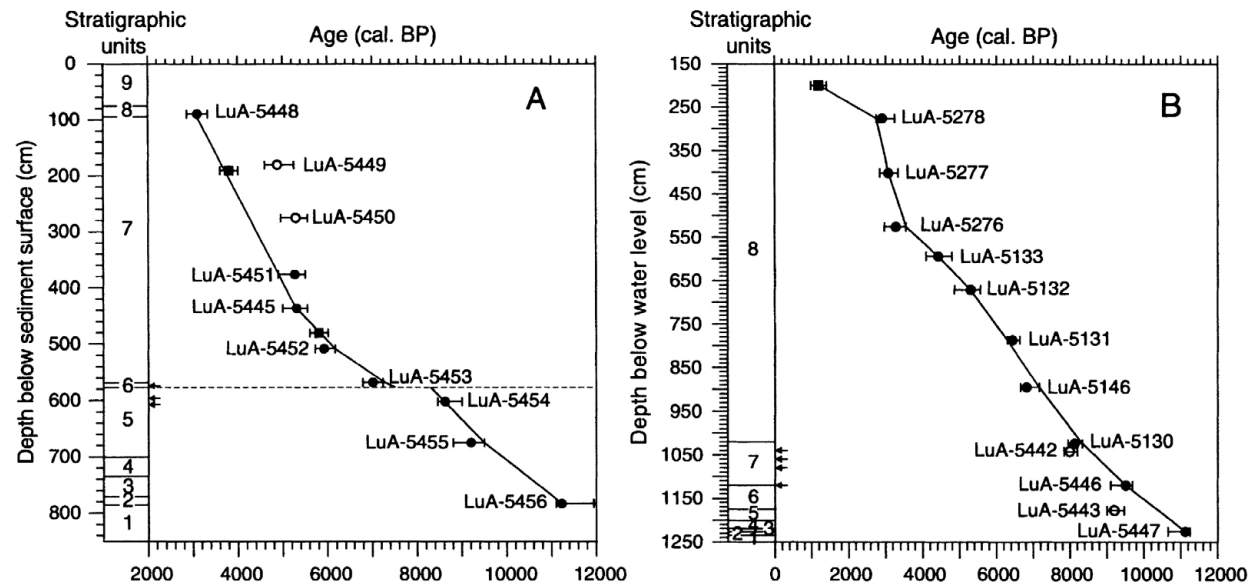


Figure 2. Age-depth relationship for Hunnemara (A) and Smygen (B), based on calibrated radiocarbon dates (solid cycles) and biostratigraphical dates (solid squares). All of the calibrated dates are plotted with 20 standard deviation and biostratigraphical dates with confidence intervals. Open cycle denotes date excluded from the age-depth model. Dashed line in (A) shows the depositional hiatus. Arrows indicate levels for diatom analyses. Stratigraphic units according to Tables 1 and 3.

ture of minerogenic materials. Around 85 cm, corresponding to 3100 cal. BP, there is a quite rapid shift to values over 40%.

Magnetic concentrations (*i.e.*, χ , SIRM, and χ_{ARM}) display a few peaks and troughs on a generally decreasing pattern from the clay in the bottom of the core to around 675 cm (9,500 cal. BP). It can also be noted that at 85 cm (3,100 cal. BP) χ_{ARM} values drop to very low values. Like in Smygen, $(B_0)_{CR}$ values generally range from 30 to 50 mT, which indicate a very uniform magnetic mineralogy dominated by detrital magnetite in a range of grain sizes. The higher $(B_0)_{CR}$ values (60–70 mT) in the interval from 675 to 576 cm (9,500–8,300 cal. BP) are an exception to this general pattern.

Smygen Bay

Logs of magnetic parameters and total organic carbon (TOC) from Smygen are presented in Figure 4. A very well-defined TOC peak reaches almost 40% in the fine-detritus gyttja layer (stratigraphic unit 3). In the lower part of the homogeneous fine-detritus gyttja (stratigraphic unit 8), TOC values stabilize around 15%.

Magnetic parameters χ and SIRM reflect, in general, the inverse relation compared with TOC. The peak values in the clay (stratigraphic unit 1) are followed by a significant drop to very low values around the fine-detritus gyttja layer (stratigraphic unit 3). Within the fine-detritus gyttja in stratigraphic unit 8, there is

very little variation, and values are generally very low. Between c. 1,050 and 650 cm (8,600–5,000 cal. BP), χ_{ARM} is highly variable, which points to variations in the distribution of finer-grain-size magnetite. The very low concentrations above 650 cm have resulted in a large scatter in the magnetic ratios and in the $(B_0)_{CR}$ values, which corrupts the records. The magnetic mineralogy is dominated by coarse-grained detrital magnetite as reflected by the $(B_0)_{CR}$ values, generally from 30 to 50 mT.

Our interpretation of magnetostratigraphy in terms of basin status is indicated in Figures 3 and 4. Identification of minor transgressions L1–L6 is mainly based on magnetic parameter $\chi_{ARM}/SIRM$ (Berglund *et al.*, 2005).

Pollen assemblages

Hunnemara Lake

A total of five local pollen assemblage zones (LPAZs) are defined (Figure 5).

LPAZ 1 (11,800–11,000 cal. BP; 820–770 cm). This zone is divided into two subzones. Subzone 1a (11,800–11,300 cal. BP; 820–790 cm) is dominated by *Pinus* (65%). *Betula* and shrub pollen constitute only 35%. The late-glacial steppe communities, including *Artemisia*, *Aster*, *Rumex*, and *Poaceae*, were still present, suggesting open woodland vegetation. *Betula* pollen increased to 40%, together with a large reduction in *Pinus* (30%) throughout subzone

Table 3. Stratigraphy of the Smygen core

Depth below water level (cm)	Stratigraphic units	Sediment description
150–1020	8	Dark clayey fine-detritus gyttja, very homogeneous
1020–1120	7	Lighter brown-green clayey fine-detritus gyttja
1120–1175	6	Green-grey clayey gyttja, tinged with FeS
1175–1203	5	Light green-grey clayey gyttja
1203–1220	4	Light brown-grey clayey gyttja; 1203–1206: brown-grey clayey gyttja with moss leaves at 1205–1206 cm; 1206–1216: light green-grey clayey gyttja
1220–1228	3	Dark brown fine-detritus gyttja (the isolation layer)
1228–1236	2	Grey gyttja clay; 1228–1230: light green-grey clayey gyttja
1236–1250	1	Grey clay; 1236–1237: grey silty sand with gravel

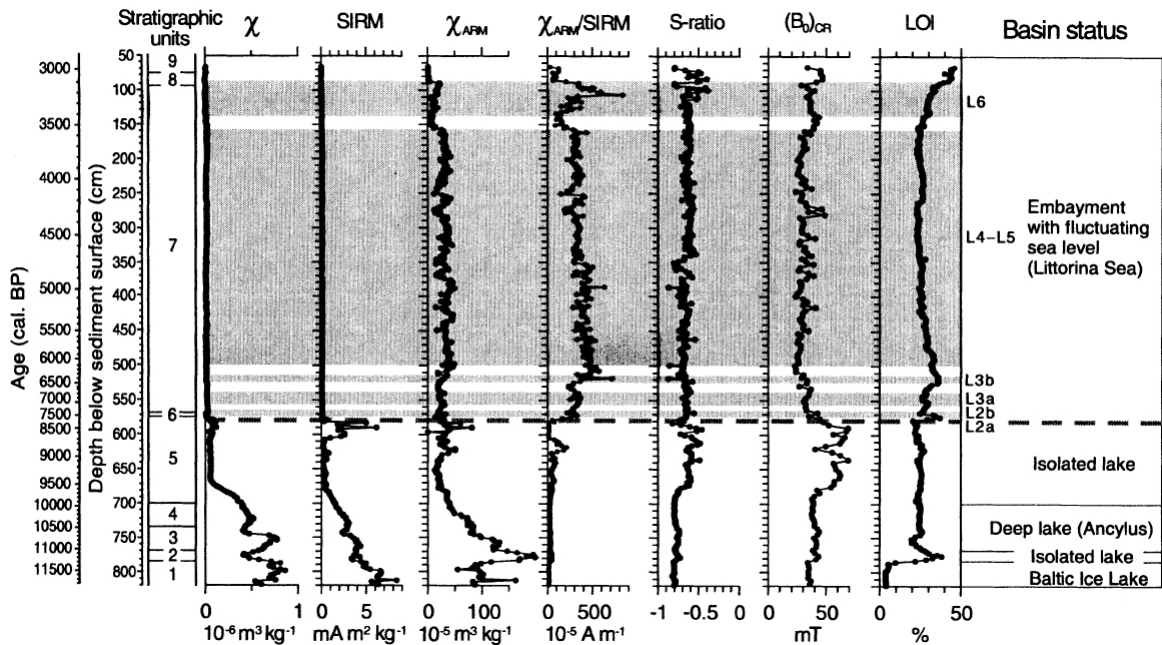


Figure 3. Loss-on-ignition (LOI) and mineral magnetic stratigraphy of Hunnemara. Stratigraphic units according to Table 1. Dashed line shows the depositional hiatus.

1b (11,300–11,000 cal. BP; 790–770 cm), indicating the initial establishment of *Betula*-dominated forests within the lake area.

LPAZ 2 (11,000–10,500 cal. BP; 770–735 cm). *Pinus* pollen expanded, accompanied by a gradual decrease in *Betula* throughout this zone. *Corylus* arrived locally around 11,000 cal. BP. Late-glacial plants reduced significantly, as a result of immigration and competition of new species, probably implying the initial amelioration of regional climate.

LPAZ 3 (10,500–8,600 cal. BP; 735–600 cm). Values of *Pinus* pollen decreased, while *Betula* and *Corylus* remained nearly constant throughout the zone. *Alnus* occurred locally and gradually

expanded together with *Ulmus*. Upland herbs were present in small amounts. The catchment was densely vegetated by a mixed forest. Freshwater herbs included *Myriophyllum alterniflorum* and *Nymphaea alba*. Wetland herbs and ferns were also common along the shore of the lake.

LPAZ 4 (8,600–5,800 cal. BP; 600–480 cm). This zone is marked by continued decreases in *Pinus* pollen, as well as the occurrence of *Quercus* and expansion of *Tilia*. Rapid rises of *Quercus* and *Ranunculus*, as well as the marine dinoflagellates *Spiniferites* spp. and *Operculodinium centrocarpum*, at 7,500 cal. BP point to a hiatus. Noteworthy is the expansion of *Ranunculus* pol-

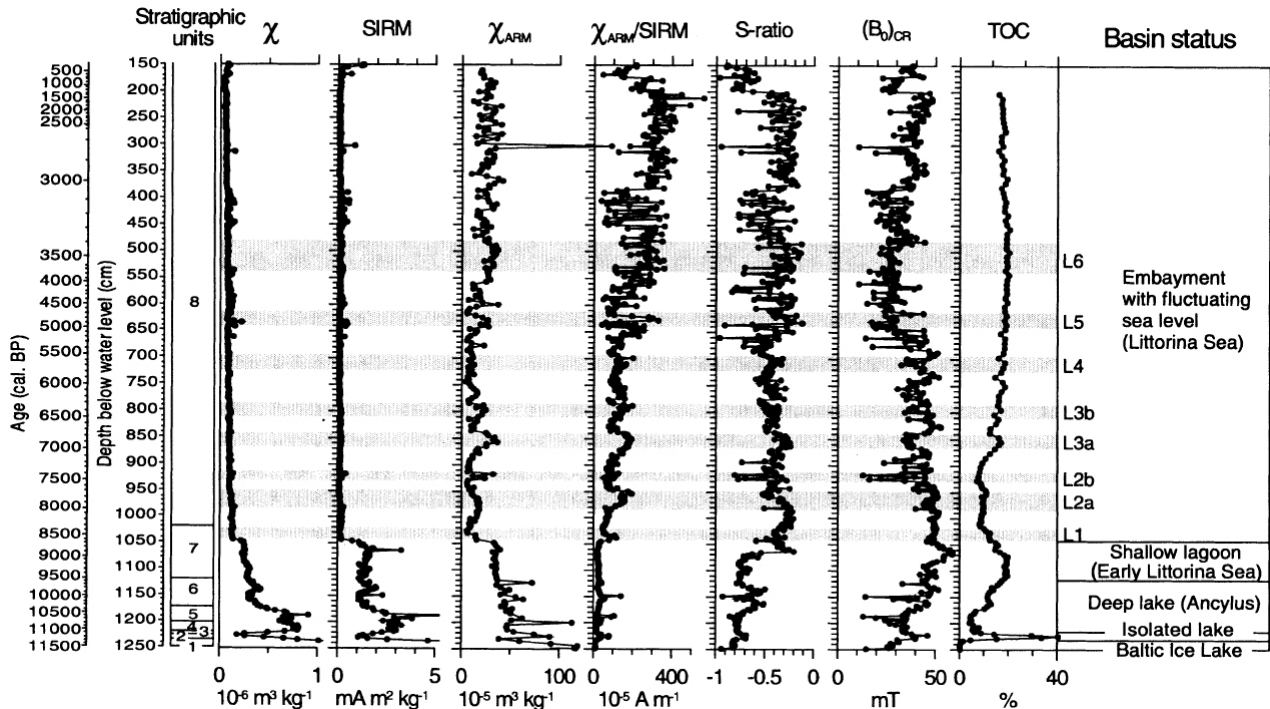


Figure 4. Total organic carbon (TOC) and mineral magnetic stratigraphy of Smygen. Stratigraphic units according to Table 3.

len from this zone onwards, probably derived from aquatic *Batrachium* species favored by brackish conditions. Brackish-water diatoms occurred at 8,300 cal. BP, suggesting the inception of the Littorina transgression in the basin. This caused a long-term destructive erosion between 8,300 and 7,500 cal. BP.

LPAZ 5 (5,800–3,000 cal. BP; 480–70 cm). This zone comprises two subzones. *Pinus* continued to decrease as *Quercus* expanded moderately, and other tree species remained almost constant throughout subzone 5a (5,800–3,700 cal. BP; 480–190 cm). A slight expansion of upland herbs after the *Ulmus* decline event at the beginning of the zone suggests an opening of the mixed forest. Subzone 5b (3,700–3,000 cal. BP; 90–70 cm) is marked by a rapid decrease in *Pinus* pollen and a gradual increase in *Betula*. Significant reduction of *Ulmus* pollen, along with rises in Poaceae (>40 µm), around 3,700 cal. BP suggests increased human impact within the catchment. Dinoflagellates vanished around 3,100 cal. BP, indicating the isolation of the basin from the Baltic Sea.

Smygen Bay

The diagram is divided into eight LPAZs (Figure 6).

LPAZ 1 (11,500–11,000 cal. BP; 1,250–1,220 cm). This pollen assemblage zone, subdivided into two subzones, is quite similar to LPAZ 1 of Hunnemara. Pollen assemblages of subzone 1a (11,500–11,300 cal. BP; 1,250–1,235 cm) are dominated by *Pinus* (50%) and *Betula* (20%). Subzone 1b (11,300–11,000 cal. BP; 1,235–1,220 cm) is marked by a substantial reduction in *Pinus* pollen and an increase of *Betula* pollen. The presence of the late-glacial dwarf shrub and steppe communities suggests open woodlands within the catchment.

LPAZ 2 (11,000–10,500 cal. BP; 1,220–1,175 cm). At the beginning of the zone, *Pinus* pollen increased rapidly to 60%. *Corylus* also rose, whereas *Betula* pollen declined to 20%. Late-glacial steppe plants almost disappeared. Increased percentages of Poaceae pollen and Polypodiaceae spores suggest that lush meadows were also present in this area.

LPAZ 3 (10,500–8,600 cal. BP; 1,175–1,050 cm). This zone is correlated to LPAZ 3 of Hunnemara. A gradual decrease in *Pinus* pollen and expansion of *Alnus*, *Ulmus*, and *Tilia* suggest major compositional shift in the catchment vegetation. Aquatic and wetland herbs were rare. *Ranunculus/Batrachium* aquatics expanded from the middle of this zone onwards.

LPAZ 4 (8,600–5,800 cal. BP; 1,050–730 cm). This zone consists of two phases. Subzone 4a (8,600–7,000 cal. BP; 1,050–870 cm) is marked by an expansion of *Quercus* and a gradual decline in *Pinus* pollen. Upland herbs were sparsely present, indicating a dramatic increase of forests. The occurrence of the marine dinoflagellate *O. centrocarpum* at the lower boundary of the zone suggests an initial establishment of brackish-water conditions in the basin. *Pinus* pollen continued to decrease, whereas *Quercus* pollen slightly increased throughout subzone 4b (7,000–5,800 cal. BP; 870–730 cm). The warmth-demanding dinoflagellate *Spiniferites* spp. expanded, and *Operculodinium centrocarpum* increased to 10%, suggesting that brackish-water conditions were fully established in the basin.

LPAZ 5 (5,800–3,700 cal. BP; 730–540 cm). The *Ulmus* decline occurred at the beginning of the zone, concurrent with that recorded in Hunnemara. The forests became more open after 5,800 cal. BP, which is shown by increases of Poaceae and other upland herbaceous pollen above this level.

LPAZ 6 (3,700–2,500 cal. BP; 540–260 cm). This zone is marked by occurrences of *Carpinus* and other human-induced

plants, such as Poaceae (>40 µm) and *Plantago lanceolata*. The dramatic reduction of *Ulmus* pollen indicates increasing human disturbance within the catchment forests from 3,700 cal. BP.

LPAZ 7 (2,500–1,200 cal. BP; 260–200 cm). *Betula* increased to 30% across the lower boundary of the zone. Nonarborescent pollen, including *Artemisia*, *Thalictrum*, and Poaceae, also increased, suggesting an opening of the forests within the catchment due to increased human impact. Dinoflagellates decreased significantly from 2,500 cal. BP, implying a dramatic lowering of the sea level, although the lagoon was still connected with the Baltic Sea.

LPAZ 8 (1,200–500 cal. BP; 200–160 cm). This zone is marked by a substantial expansion of *Fagus*, *Picea*, and *Juniperus*, together with a reduction in *Quercus* pollen. Increases in Poaceae and *Plantago lanceolata* pollen imply continued human impact within the catchment forests.

Macrofossil assemblages

Hunnemara Lake

Macrofossil data are presented in Figure 7. Four local macrofossil assemblage zones (LMAZs) are recognized visually.

LMAZ I (11,800–10,500 cal. BP; 820–735 cm). This zone is divided into two subzones. Tree and shrub macrofossils were scarce throughout subzone Ia (11,800–11,300 cal. BP; 820–790 cm). Isolated occurrences of tree birch macrofossils indicate that open woodlands were present within the catchment. Plant macrofossil assemblages of subzone Ib (11,300–10,500 cal. BP; 790–770 cm) are dominated by *Betula*, *Pinus*, and *Salix*. Upland herb macrofossils were absent. Wetland herb macrofossils were notably rare. Presence of moss twigs and the statoblasts of *Cristatella mucedo* suggests that the shore of the lake may have been covered partly by moss communities. The intermittent occurrence of charcoal implies that fires were not frequent.

LMAZ II (10,500–8,300 cal. BP; 735–575 cm). Concentrations of both *Betula* and *Pinus* macrofossils increased, suggesting the full establishment of a mixed birch/pine forest within the catchment. Isolated occurrences of *Alnus glutinosa* seeds at the lower boundary of the zone indicate that this species arrived in the area around 10,500 cal. BP, confirming the pollen results. The low macrofossil concentrations of wetland herbs, as well as a significant reduction of *Cristatella mucedo*, indicate that the lake level became higher.

LMAZ III (8,300–3,100 cal. BP; 575–90 cm). Concentrations of terrestrial macrofossils declined substantially. Both *Betula* and *Pinus* were sparse. The occurrence of the sea grasses *Zannichellia palustris*, *Ruppia maritima*, and *Najas marina*, as well as brackish-water stoneworts *Chara* and *Nitella*, indicates that brackish conditions prevailed. Charcoal may have been transported from coastal Neolithic settlements by wave erosion.

LMAZ IV (3,100–3,000 cal. BP; 90–70 cm). Both sea grasses and stoneworts vanished around 3,100 cal. BP, indicating the isolation of the basin from the Baltic Sea.

Smygen Bay

The macrofossil record is subdivided into five LMAZs (Figure 8).

LMAZ I (11,500–10,500 cal. BP; 1,250–1,175 cm). This zone comprises two subzones. Macrofossils of trees and shrubs were absent throughout subzone Ia (11,500–11,300 cal. BP; 1,250–1,235 cm), suggesting treeless vegetation in the catchment. Subzone Ib (11,300–10,500 cal. BP; 1,235–1,175 cm) is marked by the occurrence of *Betula* seeds and *Pinus* needles, indicating that

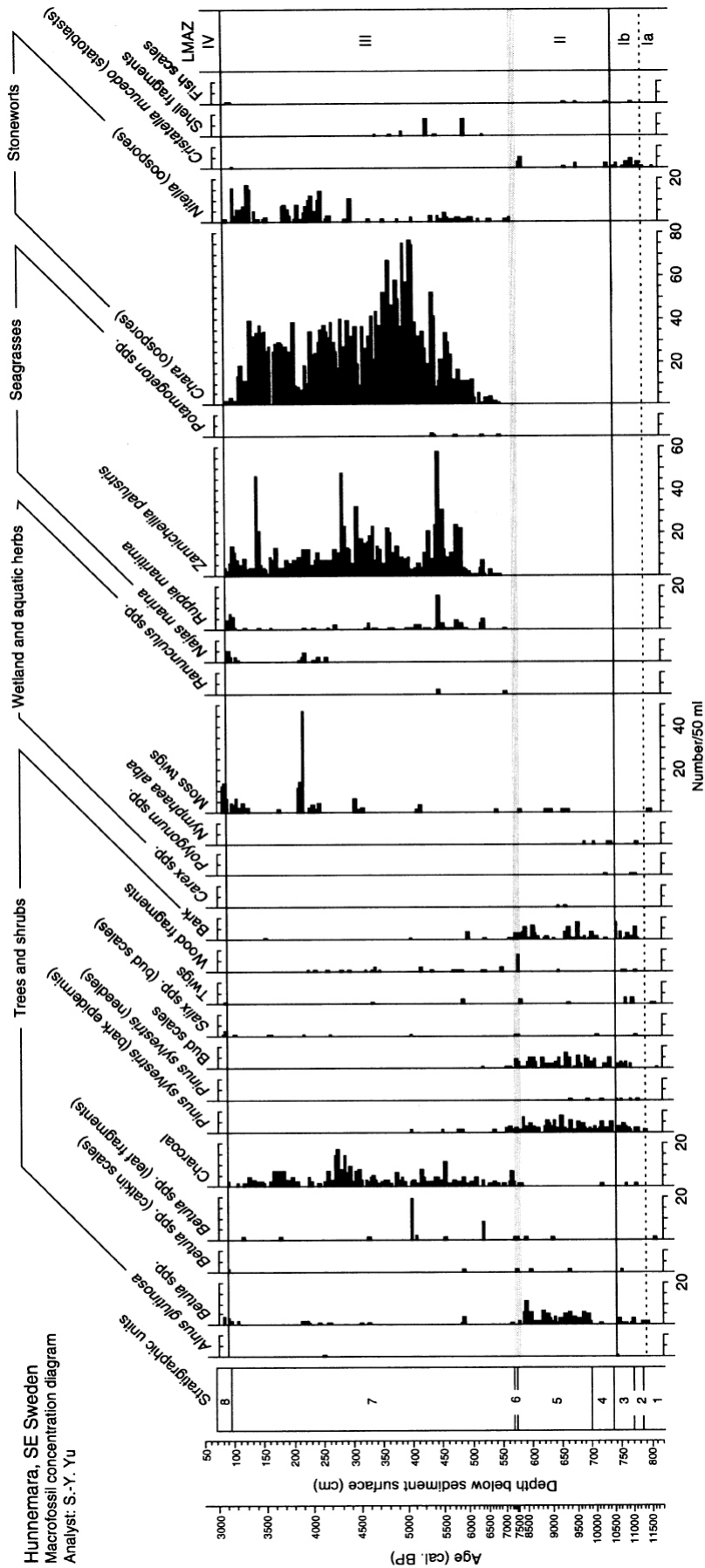


Figure 7. Macrofossil concentration diagram of Hunnemara. All finds are seeds or fruits unless otherwise indicated. Shaded band indicates the depositional hiatus. Stratigraphic units according to Table 1.

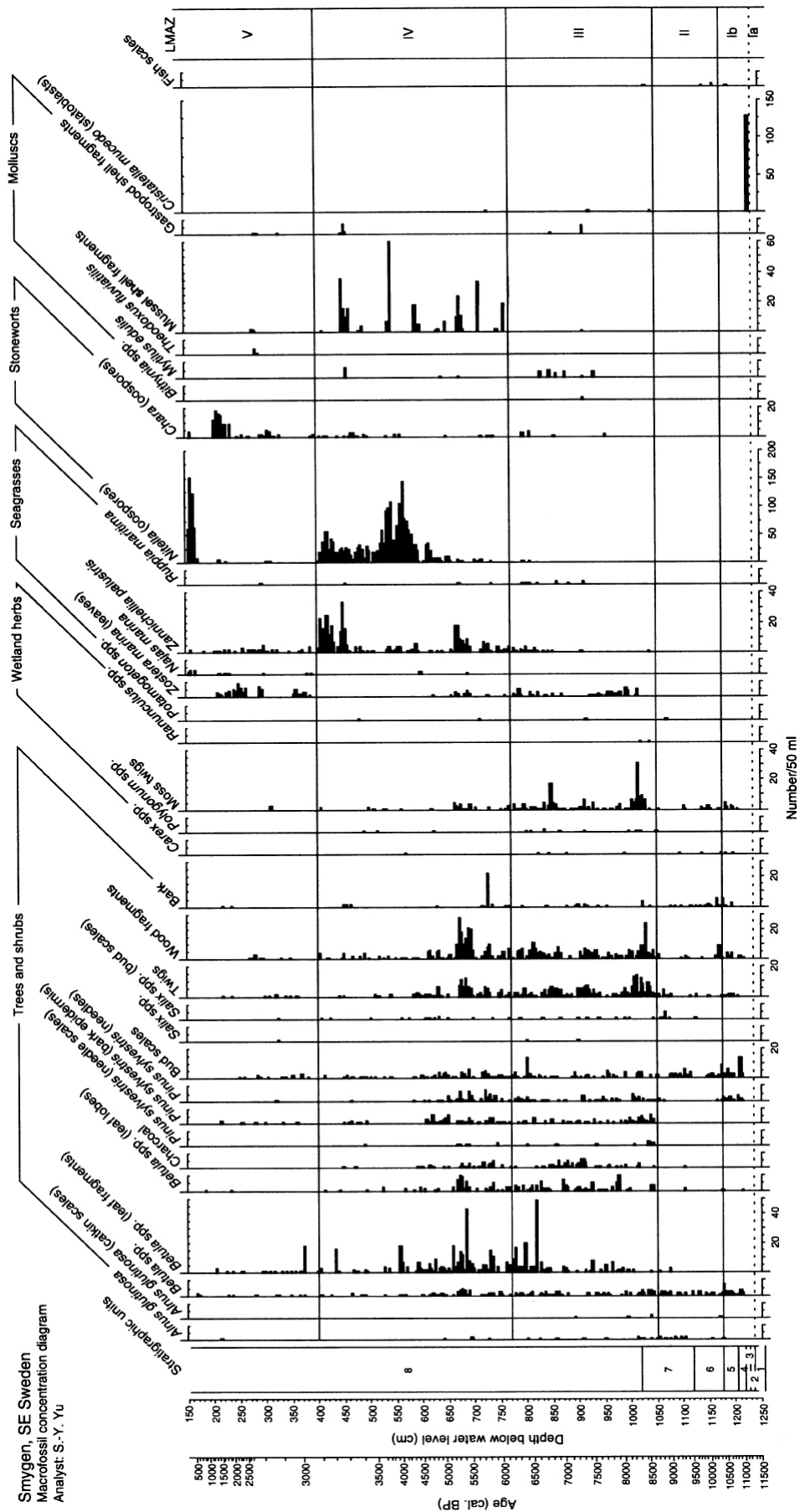


Figure 8. Macrofossil concentration diagram of Smygen. All finds are seeds or fruits unless otherwise indicated. Stratigraphic units according to Table 3.

mixed woodlands established locally after 11,300 cal. BP. The shore of the lake may have been sparsely covered by moss communities, evident as abundant statoblasts of *Cristatella mucedo*, a moss animal that inhabits very shallow waters.

LMAZ II (10,500–8,600 cal. BP; 1,175–1,050 cm). At the lower zone border, concentrations of *Betula* macrofossils show a maximum, and *Pinus* gradually decrease. Seeds of *Alnus glutinosa* are found at the lower boundary of the zone. Wetland herb macrofossils were scarce. The isolated occurrence of charcoal suggests that fires were very rare.

LMAZ III (8,600–6,100 cal. BP; 1,050–770 cm). The occurrence of sea grasses *Zannichellia palustris* and *Zostera marina* around 8,600 cal. BP marks the beginning of the Littorina transgression in the basin. A distinct peak of wood and moss twigs indicates low water level and shore erosion around 8,300 cal. BP. Water level may have been high during this period, indicated by generally low concentrations of aquatic herbs growing near the shore.

LMAZ IV (6,100–3,100 cal. BP; 770–400 cm). Concentrations of *Nitella* oospores increased gradually, suggesting that the lagoon became more and more sheltered in response to the lowering of sea level. Low sea level with agitated environments may have occurred occasionally, as indicated by peaks of mussel shell-fragments, wood, and *Zannichellia* fruits, particularly around 5,500, 4,000–3,600 and 3,300–3,100 cal. BP.

LMAZ V (3,100–1,200 cal. BP; 400–160 cm). A significant reduction in both sea grass and stonewort macrofossils at the beginning of the zone indicates a gradual lowering of the sea level, corresponding to the final isolation of the Hunnemara basin.

Correlation between the Hunnemara and Smygen sites

All litho- and biostratigraphic sequences of both sites are correlated and presented in Figure 9. A close correlation between the two sites exists prior to c. 3,000 cal. BP, suggesting that coastal landscape developments were controlled by both Baltic evolution and regional climate changes (Gustafsson and Nordberg, 2002), particularly during the early Holocene. The two basins were in turn flooded at 8,600 and 8,300 cal. BP, evidently recording a step-like rise of postglacial sea level. Superimposed upon a general rising trend, sea level at both sites exhibited significant fluctuations. The ratio of magnetic parameters χ_{ARM} to SIRM is a promising indicator of oxic conditions of deep water related to sea-level fluctuations (Berglund *et al.*, 2005). A series of well-defined maxima of χ_{ARM} /SIRM ratios at both sites reveals six periods of higher sea level (Figures 3 and 4), which are generally confirmed by the minima of *Zannichellia* and broad peaks of *Chara* (Figures 7 and 8), a stonewort growing in relatively deep waters (Luther, 1951; Blindow and Krause, 1990).

Discussion

Coastal vegetation history and controls of climate and soil conditions

The coastal forest history is well documented by both pollen and plant macrofossil assemblages at these two sites. Pollen assemblages at both sites are similar, suggesting the identical vegetational development in these two watersheds during the early to middle Holocene. The regional vegetation prior to 11,300 cal. BP was mosaic. Grasslands were widespread, and scattered heaths and *Betula*-dominated open woodlands occurred, indicating an ameliorating regional climate after the Younger Dryas cold re-

versal. Absence of *Pinus* macrofossils suggests that the air-borne *Pinus* pollen may have been transported to this area from the north European continent. Following the Preboreal warming, soil conditions improved, shown as increasing organic content and decreasing magnetic concentrations at both sites. A *Betula*-dominated mixed forest with *Ulmus* and *Corylus* was initially established between 11,300 and 10,500 cal. BP. The late-glacial steppe communities disappeared after 10,500 cal. BP, and the regional forest became more closed, although open heaths and meadows were still present on scree slopes and along shores. The regional forest was dominated by *Pinus* between 10,500 and 8,600 cal. BP. However, there was a minor difference in forest composition between these two sites during this period. For example, at Smygen, *Pinus* reduced slightly along with a moderate rise of *Corylus*. A peak in organic carbon content at Smygen implies that more fertile soils may have caused this. From 8,600 cal. BP, *Quercus* and *Tilia* expanded gradually, together with a dramatic decline in *Pinus* stands. The forests were still dominated by *Pinus* until 7,000 cal. BP. Such a successive expansion of broad-leaved trees is a strong indication of the mid-Holocene thermal maximum (Seppä and Birks, 2001; 2002). The major tree pollen remained almost constant between 7,000 and 5,800 cal. BP, suggesting that the regional forests reached a climax status (Berglund, 1966), in response to the mid-Holocene thermal maximum in Scandinavia (Fries, 1965; Korhola *et al.*, 2000). The *Ulmus* decline occurred around 5,900 cal. BP as elsewhere in northwest Europe (Peglar and Birks, 1993; cf. Parker *et al.*, 2002). Recently, discussion of the mechanism behind this event has been framed within a series of human impact and mid-Holocene climatic events over the North Atlantic sector (cf. Berglund, 2003). After 5,800 cal. BP, the regional forests were dominated by broad-leaved trees and became extremely unstable. Occurrences of human-induced plants suggest intensified human impact on the regional forests following the *Ulmus* decline.

Aquatic ecosystem dynamics and shoreline displacement

The history of the aquatic ecosystem development is reconstructed based on both macrofossils and pollen from local sources and the mineral magnetic analysis. Both basins may have been isolated from the Baltic Ice Lake during its draining around 11,550 cal. BP (Andrén *et al.*, 2002). Both aquatic micro- and macrofossils were scarce at the two sites, accompanied by extremely low carbon content prior to 11,300 cal. BP. This indicates oligotrophic conditions with low productivity during the transition from the Baltic Ice Lake to the Yoldia Sea. High concentrations of magnetic minerals at both sites suggest intense erosion of the sparsely vegetated shores. A peak of *Pediastrum* at Hunnemara between 11,300 and 11,000 cal. BP indicates a clear and oligotrophic lake, probably with high water level (Jankovská and Komárek, 2000). However, *Pediastrum* was almost absent at Smygen, whereas ferns, mosses and *Cristatella mucedo* were abundant, suggesting that the lake level was extremely low. Both lake basins were still isolated from the weakly brackish-water Yoldia Sea during this time, when global sea level was c. –45 m (Lambeck and Chappell, 2001). The isolated status during this period is further reflected in the peak of LOI/TOC values and the drop in magnetic concentrations. This period was followed by a flooding in the Baltic basin through the central Swedish lowland, probably as a result of rapid sea-level rise in response to melt-water pulse 1B (Fairbanks, 1989; Bard *et al.*, 1996; Hanebuth *et al.*, 2000). This pulse may have slowed down the North Atlantic

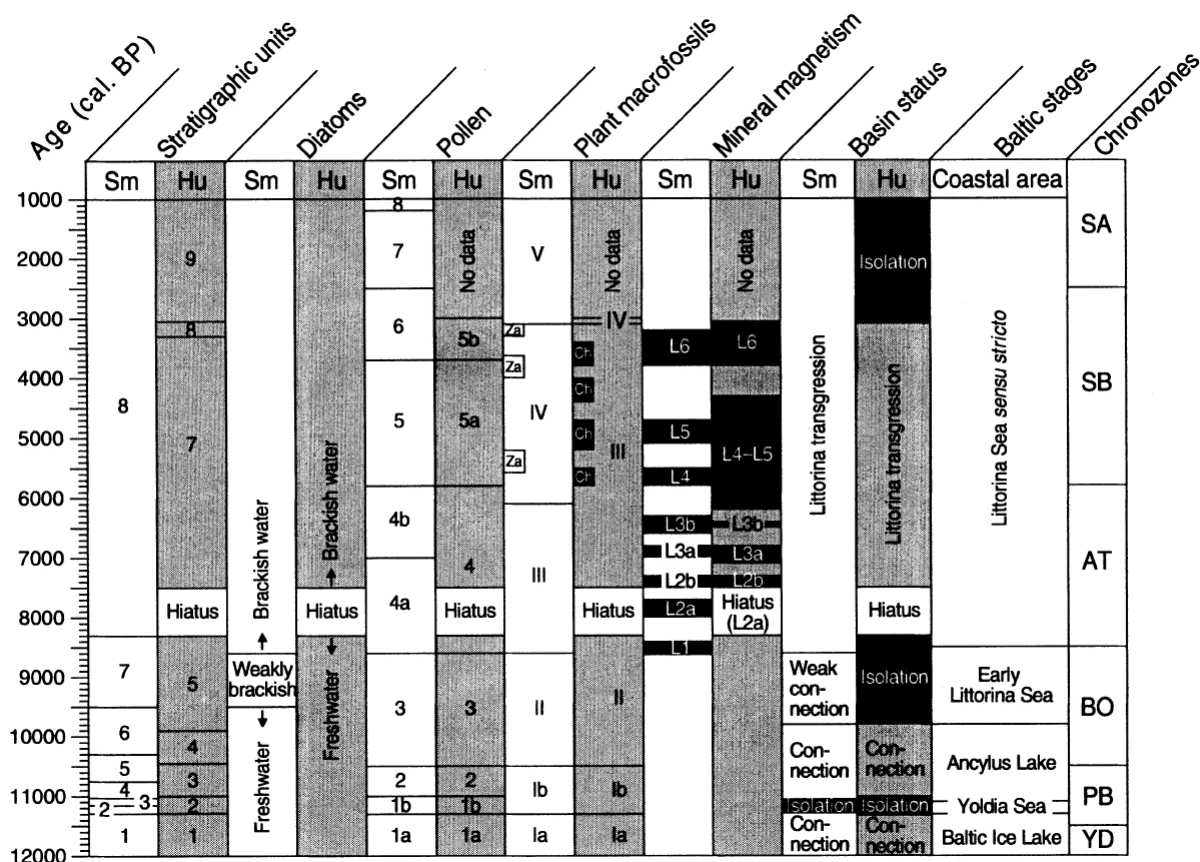


Figure 9. Stratigraphic correlation between Hunnemara (Hu) and Smygen (Sm) based on diatom, pollen, plant macrofossil and mineral magnetic analyses. Ch = Chara; Za = Zannichellia; SA = Subatlantic; SB = Subboreal; AT = Atlantic; BO = Boreal; PB = Preboreal; YD = Younger Dryas.

deep water formation and thus produced an episodic cooling, referred to as the Preboreal Oscillation (Björck *et al.*, 1996; 1997; Clark *et al.*, 2001; Fisher *et al.*, 2002). However, our biostratigraphical data fail to reveal the detailed response of both terrestrial and aquatic ecosystems to this cold reversal due to coarse time resolution. Moreover, the depletion of $\delta^{13}\text{C}$ suggests that the sediments were dominated by inwashed terrigenous organic materials (Boutton, 1991). Thus, rich organic content cannot always be interpreted as high lake productivity. Both basins may have been connected with the Ancyclus Lake during 11,000–9,800 cal. BP. Low organic content implies low production and little input of terrigenous organic materials to the basins when the catchment was well covered with dense forests. However, meltwater from remaining glaciers may have been another source of the high minerogenic content of the Ancyclus sediments. Substantial lowering of the Ancyclus lake level around 9,800 cal. BP eventually led to the second isolation of the Hunnemara basin. The extremely low abundance of brackish-water diatoms in Smygen between 9,500 and 8,600 cal. BP suggests a weak contact of this basin with the Baltic Sea. Occurrences of brackish-water stone-worts, dinoflagellates, diatoms, and sea grasses mark the beginning of the Littorina transgression *sensu stricto* in the two basins, dated to 8,600 cal. BP in Smygen and to 8,300 cal. BP in Hunnemara. The warm-water dinoflagellate *Spiniferites* spp. increased from 7,500 cal. BP at both sites, indicating the onset of the mid-Holocene hypsithermal interval in the Baltic and the neighboring seas (Koç *et al.*, 1993; Calvo *et al.*, 2002; Birks and Koç, 2002). This event is almost concurrent with the terrestrial warming revealed as the expansion of broad-leaved trees in Scandinavia

(Seppä and Birks, 2001; 2002; Heikkilä and Seppä, 2003). The modern distribution of *Operculodinium centrocarpum* is congruent with the North Atlantic Drift Current (Harland, 1983; Rochon *et al.*, 1999). Thus, this species immigrated into the Baltic Sea as a result of enforced saltwater inflow driven by the westerly winds when a NAO-like pattern of atmospheric activities prevailed over the Danish straits (Yu, 2003). High $\delta^{13}\text{C}$ values suggest that the organic materials of sediments were mainly from brackish-water plants, as well as local shore vegetation (Boutton, 1991). A rapid reduction of the *O. centrocarpum* percentages from 5,000 cal. BP indicates decreased water exchange between the Baltic and the Kattegat Sea (Westman and Sohlenius, 1999). Disappearances of dinoflagellates, sea grasses and stoneworts as well as a drop in the χ_{ARM} /SIRM and an increase in LOI values from 3,100 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 as a substantial reduction in the abundance of dinoflagellates, sea grasses, and stoneworts. Thresholds between hills surrounding the bay also were eroded when sea level was lowered.

Hiatus in litho- and biostratigraphic records and rapid flooding

A hiatus between 601.5 and 567.5 cm at Hunnemara is shown by radiocarbon dates (between 8,300 and 7,500 cal. BP). The rise of the $\delta^{13}\text{C}$ values from -30.1% to -18.1% indicates a rapid transition from a freshwater lake to an embayment. Similar stratigraphic gaps have been found in other bays along the Blekinge coast (Berglund, personal communication). The steep rises of

Quercus and dinoflagellates confirm the existence of the hiatus, which can be ascribed to a rapid sea-level rise (Berglund *et al.*, 2005). This rapid sea-level rise can probably be correlated to meltwater pulse 3 documented in the Caribbean-Atlantic coral records (Blanchon and Shaw, 1995). According to the 5 m contour line (Figure 1), which approximately represents the coastline of the Baltic Sea during the time of the Littorina transgression, the Smygen Bay was part of an open sea, surrounded by several small islands, whereas Hunnemara was a lagoon with a narrow inlet. In accordance with the law of mass conservation in fluid dynamics, strong and fast currents through this narrow passage were established. Diatoms were brackish taxa, and most valves were broken in stratigraphic unit 6 at Hunnemara, suggesting that the materials may have been redeposited following the destructive erosion.

Multiwave transgression and regional atmospheric activities

The mid-Holocene Baltic sea-level highstand, in terms of the Littorina transgression, can be primarily ascribed to the substantial drawdown of global ice volume (Peltier, 2002). Our magnetic and macrofossil proxies reveal several minor transgressions (Figure 9). The small-scale fluctuations superimposed upon the ice-volume equivalent sea-level rise were probably related to variations in regional meteorological conditions (Ekman, 1999), particularly the prevailing wind pattern over the Danish straits (Plag and Tsimplis, 1999). Atmospheric activities in high latitudes of the Northern Hemisphere are predominated by the North Hemisphere annular mode (NAM), which governs the intensity of mid-latitude zonal flow and storm tracks (Thompson and Wallace, 2001). The NAO is a manifestation of the NAM over the North Atlantic sector (cf. Viles and Goudie, 2003), which has been demonstrated to be the conductor of Baltic sea-level fluctuations today (Andersson, 2002). As the NAO is the lowest frequency of atmospheric activities known from instrumental data, it can be used for a template of centennial- to submillennial-scale changes in regional pressure cells. Other factors, *e.g.*, tidal cycles and storms, may be involved in this quasi-periodical pattern of relative sea-level fluctuations (Yu, 2003).

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