Quaternary Science Reviews 34 (2012) 81–92

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

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

Palaeoenvironments in the southern Baltic Sea Basin during Marine Isotope Stage 3: a multi-proxy reconstruction

Johanna Anjar [a,*], Lena Adrielsson [a], Ole Bennike [b], Svante Björck [a], Helena L. Filipsson [a], Jeroen Groeneveld [c], Karen Luise Knudsen [d], Nicolaj Krog Larsen [d], Per Möller [a]

[a] *Department of Geology, Lund University, Sölvegatan 12, SE-22362 Lund, Sweden*
[b] *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark*
[c] *Department of Geosciences, Bremen University, Klagenfurter Strasse, D-28359, Bremen, Germany*
[d] *Department of Geoscience, Aarhus University, Høegh-Guldbergs Gade 2, DK-8000 Aarhus C, Denmark*

ARTICLE INFO

Article history:
Received 21 April 2011
Received in revised form
9 December 2011
Accepted 14 December 2011
Available online 13 January 2012

Keywords:
Scandinavian Ice Sheet
Marine Isotope Stage 3
Baltic Sea Basin
Palaeoenvironment

ABSTRACT

Sediment cores from Kriegers Flak in the southwestern Baltic Sea provide a unique possibility to study the Middle Weichselian history of the Baltic Basin. Three Weichselian interstadial units have been identified and are attributed to Marine Isotope Stage 3 (MIS 3, 60–25 ka). The oldest unit A is characterized by a deglaciation sequence, gradually turning into brackish-water clay. The low-diversity benthic foraminiferal fauna, stable oxygen isotope values and Mg/Ca ratios indicate low temperature and salinity for unit A. A hiatus separates unit A from the overlying unit B, which was deposited in wetlands and shallow lakes between 42 and 36 cal. ka BP. Macrofossil and pollen analyses indicate deposition of unit B in an area dominated by a tree-less open tundra environment, possibly with some birch and pine in sheltered positions. The uppermost unit C is characterized by clay deposition, including redeposition of material from older sediments (unit B). Optically stimulated luminescence (OSL) ages indicate deposition of unit C between 26 and 28.5 ka. Radiocarbon ages of 39 and 40 cal. ka BP for unit C are considered to be too old. The following depositional model is suggested: (I) Isostatic depression of the region after an advance of the Scandinavian Ice Sheet (SIS), most likely the Ristinge ice advance, previously dated to c. 55–50 ka, enabled an inflow of marine waters into the Baltic Basin during the deposition of unit A. (II) Isostatic rebound caused a regression at Kriegers Flak, and a hiatus between units A and B. (III) Wetlands and smaller lakes formed in the uplifted area between 42 and 36 cal. ka BP (unit B). (IV) Deposition of glaciolacustrine clays at Kriegers Flak demonstrates that a growing SIS dammed Kattegat and the Baltic Basin c. 28.5 to 26 ka. The new evidence from Kriegers Flak provides a solid framework for future MIS 3 palaeoenvironmental reconstructions in the circum-Baltic area.

1. Introduction

Marine Isotope Stage 3 (MIS 3, 60–25 ka) was a highly dynamic period with large shifts in temperature and sea level (e.g. Chappell and Shackleton, 1986; Lambeck and Chappell, 2001; Wolff et al., 2010). For Fennoscandia, a relatively warm interstadial climate has been inferred by several studies from Finland (Helmens et al., 2007a; Engels et al., 2008; Bos et al., 2009), Denmark (Bennike et al., 2007) and northern Sweden (Hättestrand and Robertsson, 2010). The Scandinavian Ice Sheet (SIS) was probably periodically substantially reduced or even absent, as indicated by investigations in Sweden (Alexanderson et al., 2010; Wohlfarth, 2010), Finland (Helmens et al., 2000, 2007b; Helmens and Engels, 2010), and coastal western Norway (Mangerud et al., 2009). The warm interstadials were interrupted by cold periods and the SIS reached as far as eastern Denmark between c. 55 and 50 ka and northern Denmark between 29 and 27 ka (Houmark-Nielsen and Kjær, 2003; Larsen et al., 2009). A possible third SIS advance through the Baltic Basin at the end of MIS 3 is under debate (Ukkonen et al., 2007; Houmark-Nielsen, 2010).

The Middle Weichselian history of the Baltic Basin is less well known. This is partly due to the lack of data, as only a few studies of sediment cores record deposits older than the Late Weichselian and Holocene (e.g. Klingberg, 1998; Anjar et al., 2010).

---

* Corresponding author. Tel.: +46 46 222 3992; fax: +46 46 222 4419.
E-mail address: Johanna.Anjar@geol.lu.se (J. Anjar).

0277-3791/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2011.12.009

Middle Weichselian deposits have therefore almost exclusively been studied as glacially dislocated sediments in coastal cliffs (Steinich, 1992; Houmark-Nielsen, 1994; Ludwig, 2006). However, numerous studies of the Late Weichselian and Holocene history of the Baltic Basin have shown that the shallow water depths and shallow inlets of the Baltic Basin make it highly sensitive to variations in the relative sea level (Björck, 1995; Andrén et al., 2011). Kriegers Flak (Fig. 1) is geographically well suited for recording changes in salinity, as well as water depth, because it is situated at relatively shallow water and close to the inlets of the Baltic Basin.

1.1. *Previous studies*

Based on the geotechnical description of nine cores from Kriegers Flak, together with a small number of radiocarbon dates and observations of benthic foraminifera and macrofossils, the general stratigraphy of the Quaternary sediments has previously been outlined (Anjar et al., 2010). The focus was on the interstadial sediments and their connection to the Scandinavian Ice Sheet and possible marine inflows into the Baltic Basin from the North Atlantic. It was found that the lowermost unit A, which consists of clay with benthic foraminifera, was deposited following a deglaciation of the area and in a brackish environment suggesting a marine connection between the Baltic Basin and the Kattegat and further to the North Atlantic. The overlying unit, B, which consists of alternating beds of sand, silt, clay and organic deposits, was interpreted to reflect deposition in wetlands and lakes or ponds. Shell fragments confirmed the lacustrine origin of some of the beds. This unit was radiocarbon dated to 31–35 ^{14}C ka BP. The upper unit C consists of a thick succession of clay and it was tentatively related to a renewed ice advance of the Scandinavian Ice Sheet which dammed the Baltic Basin and led to the formation of a large ice-contact lake (Anjar et al., 2010).

The aim of this study is a detailed palaeoenvironmental reconstruction of the interstadial MIS 3 deposits at Kriegers Flak, using a multi-proxy approach to analyses of three of the sediment cores previously discussed in Anjar et al. (2010). The new dataset includes detailed sedimentological descriptions, analyses of benthic forminifera, macrofossil and pollen contents and measurements of stable oxygen and carbon isotopes. In addition the chronology has been improved by a number of radiocarbon and OSL age determinations. The new results from Kriegers Flak are compared to studies from other areas around the southern Baltic Sea in order to reconstruct the palaeoenvironmental history of the Baltic Basin during the Middle Weichselian.

2. Regional setting

Kriegers Flak is a shallow water area situated at the intersection between the Swedish, Danish and German economical zones in the southwestern Baltic Sea (Fig. 1). The core sites are situated close to the straits that connect the Baltic Basin with the more saline Kattegat. Accordingly, this location is a potentially sensitive area for recording early marine water inflow into the Baltic Basin through the Danish straits, as well as through the previous Esrum/Alnarp valley connection (Fig. 1). It is also situated on the pathway for SIS advances through the Baltic Basin and into Denmark from the east. Such SIS advances have been recorded two times in Denmark during MIS 3, i.e. the Ristinge ice advance c. 55–50 ka and the Klintholm ice advance c. 32 ± 4 ka (Houmark-Nielsen, 2010). In addition, the Kattegat ice stream, which advanced from Norway between 29 and 27 ka, also affected the area by damming the Kattegat and the outlets of the Baltic Basin (Houmark-Nielsen and Kjær, 2003; Larsen et al., 2009). However, the ice margin of the Kattegat advance never reached as far south as Kriegers Flak.

3. Methods

A multi-proxy approach was applied to a sequence of fine-grained marine and lacustrine sediments situated between two diamict sequences in three cores from the northeastern, Swedish, part of Kriegers Flak. The cores are part of a larger set of 40 sediment cores, 15–40 m long (Fig. 2), retrieved from Kriegers Flak as part of geotechnical investigations for a wind turbine park. A general stratigraphy for the northeasternmost part of Kriegers Flak has previously been presented (Fig. 2; Anjar et al., 2010). Three of the cores, C06 (55°3′02″N, 13°7′47″E), D03 (55°2′39″N, 13°9′31″E) and E02 (55°2′44″N, 13°10′31″E), were chosen for detailed studies. Together, these cores include sediments from all units identified between the two-diamict sequences. The sediment cores have been used for geotechnical investigations, and some sections of the cores are therefore missing or poorly preserved. A comparison between our observations and the geotechnical descriptions (made by the company GEO) show good agreement, and the GEO descriptions have therefore been used to reconstruct the missing parts.

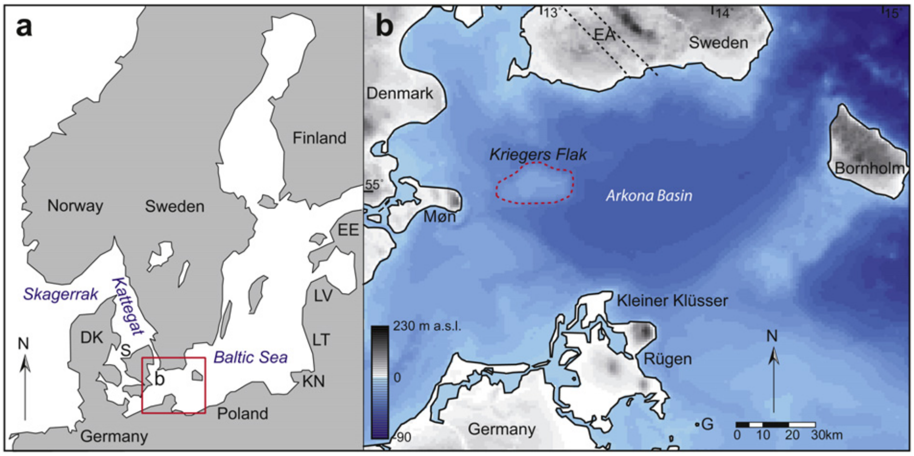


Fig. 1. (a) The Baltic Sea region with localities mentioned in the text: DK – Denmark, EE – Estonia, LT – Lithuania, LV – Latvia, KN – Kaliningrad, S – Sejerø, EA – Esrum/Alnarp valley. (b) The southwestern Baltic Sea region: K – Kleiner Klüsser, G – Greifswalder Oie. Bathymetry from Seifert et al. (2001).

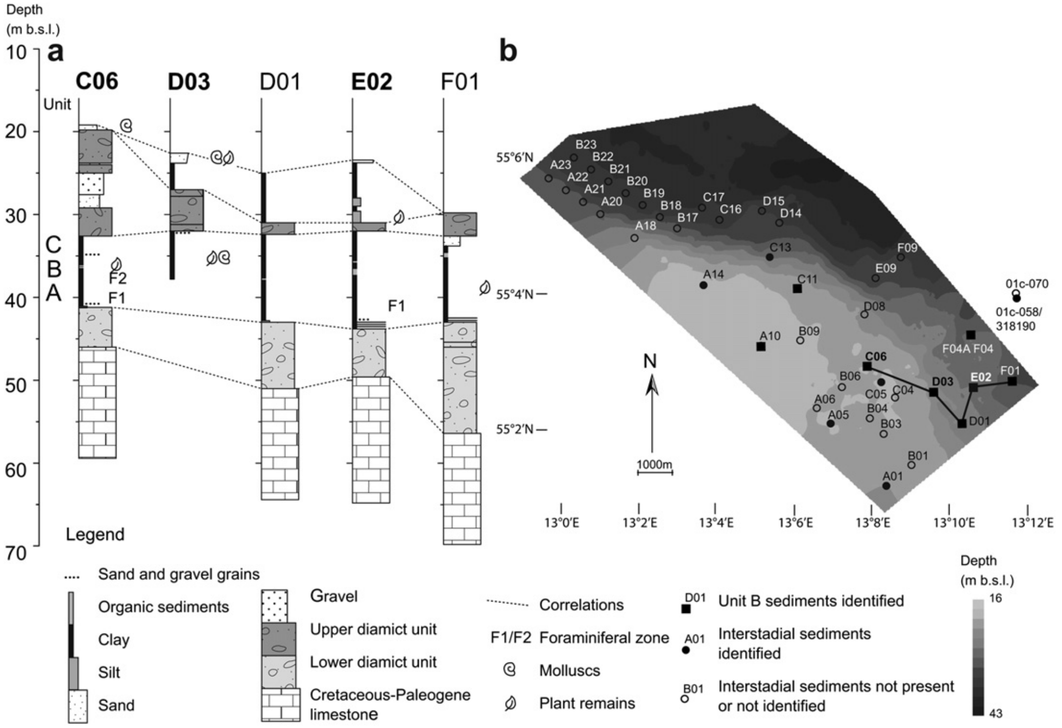


Fig. 2. (a) General litostratigraphy of five sediment cores from Kriegers Flak showing the interstadial sequence. The discussed interval, units A–C, was recorded between two diamict sequences. (b) All the sediment cores described by GEO, Klingberg (1998) and Bennike and Wagner (2010) from the Swedish part of Kriegers Flak. Cores, in which the unit B sediments (black squares) or the interstadial sequence (black circles) have been identified, are indicated.

3.1. Sediment properties

The interstadial sequence was divided into three subunits, A, B and C, following the division of Anjar et al. (2010). The sediments were described based on lithology, structures, colour, and fossil content. The organic carbon content (C_{org}) was measured on 38 samples from unit A. The C_{org} samples were decalcified using HCl and measured using a Costech Elemental Combustion System 4010.

3.2. Core chronology

Radiocarbon determinations on bulk samples of organic sediments (peat and gyttja), macrofossils and mixed samples of benthic foraminiferal tests (200–610 tests each) were performed at Lund University Radiocarbon Dating Laboratory, Sweden. In addition, two samples (1000–1200 foraminiferal tests each) were dated at the ^{14}CHRONO Centre, Queens University, UK. Ages younger than 45 ^{14}C ka BP were calibrated into calendar years (Table 1) using the IntCal09 dataset (Bronk Ramsey, 2009; Reimer et al., 2009).

Six samples were dated using optically stimulated luminescence (OSL) at Sheffield Centre for International Drylands Research luminescence laboratory, UK (Table 2). As the cores had previously been exposed to sunlight, the samples for analysis were extracted from the centre of the core segments and prepared under a subdued red lighting following Bateman and Catt (1996). The samples had dried out, and an estimated moisture content of 30 ± 5% was therefore used. Aliquots with a maximum size range of 90–250 μm were used. The samples were measured on an upgraded Risø TL DA-20 luminescence reader and analyzed using the single aliquot regenerative (SAR) approach as suggested by Murray and Wintle (2000). A preheat temperature of 180 °C for 10 s was selected based on a dose recovery preheat plateau test. Aliquots, in which the ratio between the first and last dose point was larger than ± 10% of unity, were excluded.

3.3. Benthic foraminifera, stable O and C isotopes and Mg/Ca

In the core sections in which foraminifera were identified or expected to occur samples (4-cm slices) were extracted at 5-cm intervals for foraminiferal analyses where the core condition permitted this. In the remaining part of unit A, with the exception of the diamictic parts, samples were taken at 10–15 cm intervals. The samples, each consisting of about 90 g dry sediment, were freeze dried for c. 48 h, and they were subsequently treated with $Na_4P_2O_7$ to disintegrate aggregates and wet sieved on a 63 μm sieve.

A total of 19 samples were chosen for foraminiferal faunal analysis, covering the intervals with abundantly occurring specimens. These samples were dry sieved on 1.0 and 0.1 mm sieves, and the foraminifera in the size fraction 0.1–1 mm were concentrated by floatation in tetrachloroethylene ($\rho = 1.62$ g/cm^3). Results of the use of different size fractions of foraminifera in the Quaternary of NW Europe were discussed by Feyling-Hanssen (1964), who found that most of the adult specimens occurred in the fraction 0.1–1.0 mm and that mainly juvenile individuals and dwarf forms were present in the size fraction <0.1 mm. He stated that only little was gained statistically and stratigraphically by adding the few additional specimens found in the finer fraction. A minimum of 300 specimens in each sample were identified to species level and counted when possible. For samples containing less than 300 specimens, the entire contents were counted, and percentage values were calculated for assemblages with at least 100 specimens following Knudsen (1998).

Table 1
Compilation of radiocarbon dates from Kriegers Flak: (1) This study; (2) Anjar et al., 2010. Calibrated using OxCal 2010 (Bronk Ramsey, 2009).

Borehole	Depth (m b.s.l.)	Latitude (N)	Longitude (E)	Lab no.	Radiocarbon ages (BP)	Calibrated (ka BP)	Dated material	Unit	Reference
Kriegers Flak D03	33.7	55°2′39’’	13°9′31″	LuS 9164	35100 ± 350	40	Amblystegiaceae	Subunit C	1
Kriegers Flak D03	33.7	55°2′39″	13°9′31″	LuS 9163	34100 ± 350	39	Vegetative remains	Subunit C	1
Kriegers Flak C06	36.2	55°3′2″	13°7′47″	LuS 8669	32600 ± 400	37	Moss fragments	Subunit B	2
Kriegers Flak C06	36.3	55°3′2″	13°7′47″	LuS 9162	36700 ± 400	41	Vegetative remains	Subunit B	1
Kriegers Flak D03	34.5	55°2′39″	13°9′31″	LuS 8670	35200 ± 600	40	Bulk	Subunit B	2
Kriegers Flak D03	34.7	55°2′39’’	13°9′31’’	LuS 8830	32100 ± 300	37	Shell fragments	Subunit B	1
Kriegers Flak D03	34.7	55°2′39″	13°9′31″	LuS 9165	45800 ± 2000		*Potamogeton* spp.	Subunit B	1
Kriegers Flak D03	35.8	55°2′39″	13°9′31″	LuS 8831	37650 ± 500	42	Shell fragments	Subunit B	1
Kriegers Flak D01	37.7	55°2′11″	13°10′15″	LuS 7439	35250 ± 500	40	Peat, bulk	Subunit B	2
Kriegers Flak E02	36.8	55°2′44″	13°10′31″	LuS 8454	30800 ± 350	36	Gyttja, bulk	Subunit B	2
Kriegers Flak E02	37.0	55°2′44″	13°10′31″	LuS 7440	33850 ± 600	39	Gyttja, bulk	Subunit B	2
Kriegers Flak C06	37.3	55°3′2″	13°7′47″	LuS 9187	>48000		Foraminifera	Subunit A	1
Kriegers Flak C06	37.3	55°3′2″	13°7′47″	UBA-17028	>54840		Foraminifera	Subunit A	1
Kriegers Flak C06	37.4	55°3′2″	13°7′47″	UBA-17027	>55139		Foraminifera	Subunit A	1
Kriegers Flak C06	37.6	55°3′2″	13°7′47″	LuS 9186	>48000		Foraminifera	Subunit A	1
Kriegers Flak E02	40.8	55°2′44″	13°10′31″	LuS 8927	>39000		Foraminifera	Subunit A	1
Kriegers Flak E02	41.2	55°2′44″	13°10′31″	LuS 8832	>45000		Foraminifera	Subunit A	1
Kriegers Flak E02	41.6	55°2′44″	13°10′31″	LuS 8926	>46000		Foraminifera	Subunit A	1

The two different forms of *Elphidium excavatum* (Terquem), i.e. *E. excavatum* f. *clavata* Cushman and *E. excavatum* f. *selseyensis* (Heron-Allen & Earland)(cf. Feyling-Hanssen, 1972), have not been separated in the analysis, because common occurrences of intermediate forms make it difficult to quantify the two groups.

Stable oxygen and carbon isotope analyses were performed on *E. excavatum* f. *clavata* throughout the marine intervals, on *Haynesina orbiculare* (Brady) in the lowermost part of unit A (cores C06 and E02) and on *E. excavatum* f. *selseyensis* in the uppermost part of unit A (core C06). For these measurements, 20–30 tests were picked from each sample of *E. excavatum* f. *selseyensis* and *H. orbiculare* and 25–50 tests of *E. excavatum* f. *clavata*. All the samples were analyzed at the Stable Isotope Laboratory, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, using a Finnigan Mat 251 mass spectrometer equipped with an automatic carbonate preparation device (Kiel II). Isotope composition is given in the usual δ-notation versus the Vienna Pee Dee Belemnite (V-PDB) standard. The analytical standard deviation is 0.08‰ for δ^{18}O and 0.06‰ for δ^{13}C based on the long-term standard deviation of an internal standard (Solnhofen limestone).

In addition, between 20 and 30 tests of *E. excavatum* f. *selseyensis* and *H. orbiculare,* and 40–50 tests of *E. excavatum* f. *clavata* were selected from each sample when possible for determination of Mg/Ca ratios. The tests were gently crushed, and the shell fragments were cleaned according to the standard cleaning protocol for foraminiferal Mg/Ca analyses (Barker et al., 2003). Before dilution, the samples were centrifuged for 10 min (6000 rpm) to exclude any remaining insoluble particles from the analyses. Samples were diluted with Seralpur water before analysis with an ICP-OES [Perkin Elmer Optima 3300RL with autosampler and ultrasonic nebulizer U-5000 AT (Cetac Technologies Inc.)] at the Department of Geosciences, University of Bremen. The instrumental precision of the ICP-OES was monitored by analysis of an in-house standard solution with a Mg/Ca ratio of 2.93 mmol/mol after every five samples (long-term standard deviation of 0.026 mmol/mol or 0.91%). The analytical precision for Mg/Ca ratios based on three replicate measurements of each sample was 0.15% for *E. excavatum* f. *selseyensis* and *H. orbiculare* and 1.08% for *E. excavatum* f. *clavata*.

As no species-specific temperature vs Mg/Ca calibrations are available for the species analyzed, we applied alternative calibrations. The use of a general multi-species calibration (Lear et al., 2002) results in unrealistically low temperatures, well below 0 °C. More reliable temperature estimates are obtained by applying the calibration for *Melonis barleeanum* (Kristjánsdóttir et al., 2007). It is notable also, that salinity is likely to have biased the Mg/Ca ratios. Recently, the potential influence of salinity on foraminiferal Mg/Ca has received significant attention (Ferguson et al., 2008; Groeneveld et al., 2008; Kisakürek et al., 2008; Hoogakker et al., 2009; Sadekov et al., 2009; Arbuszewski et al., 2010), and it has been shown that the influence is particularly significant for high salinity conditions (>36 psu) (Ferguson et al., 2008; Hoogakker et al., 2009). However, modern sea-surface salinities in the Kattegat and Baltic Sea are low, decreasing from >20 psu in the northern Kattegat to as low as 6–8 psu at the location of Kriegers Flak (Antonov et al., 2006). Although not very precise, an extrapolation of culturing results of the dependency of salinity on the Mg/Ca in foraminifera (Nürnberg et al., 1996; Kisakürek et al., 2008; Dissard et al., 2010) to Baltic water salinity shows that expected Mg/Ca ratios could be two to three times as low as for open-ocean conditions. Therefore, absolute temperatures are probably difficult to accept as representative. We do, however, present temperatures based on the calibration of *M. barleeanum*, but only changes in temperature (ΔT) are used in the discussion.

Table 2
OSL dates from Kriegers Flak.

Sample	Core	N	Burial depth (m)	K (%)	U (ppm)	Th (ppm)	Rb (ppm)	Moisture (%)	Total dose rate (μGy/a)	De (Gy)	Age (ka)	Unit
Shfd10126	C06	22	19.2	2.6	3.83	11.5	124	30 ± 5	2908 ± 155	208.9 ± 6.3	71.8 ± 4.4	A
Shfd10127	C06	24	22.0	2.5	2.77	8.5	102	30 ± 5	2525 ± 141	218.2 ± 7.4	86.4 ± 5.7	A
Shfd10128	D03	9	10.1	3.3	3.77	17.8	178	30 ± 5	3691 ± 196	105.1 ± 3.5	28.5 ± 1.8	C
Shfd10129	D03	23	11.0	3.2	3.87	17.1	170	30 ± 5	3642 ± 193	94.5 ± 3.4[a]	26.0 ± 1.7	C
Shfd10130	D03	23	12.0	1.4	1.35	5.4	66.3	30 ± 5	1449 ± 78	55.8 ± 2.2[a]	38.5 ± 2.6	B
Shfd10131	D03	24	13.0	2.5	2.55	10.3	112	30 ± 5	2618 ± 143	102.1 ± 3.25	39.0 ± 2.5	B

[a] A finite mixture model based on the lowest component containing more than 10% of the data was used for the determination.

3.4. Macrofossils and pollen

A total of 25 sediment samples were available for macrofossil analysis (Table 3). The total weight of the samples was 3.6 kg. The dried-out samples (c. 100 g) were soaked in water with NaOH and subsequently wet sieved on a series of 0.4, 0.2 and 0.1 mm sieves. A dissecting microscope was used to analyse the residue left on the sieves, and selected material was dried for AMS radiocarbon dating.

The calcareous clay gyttja of unit B in the E02 core was sampled and analyzed for its pollen content. Preparation of the samples followed standard methods using HCl, NaOH, HF and acetolysis (e.g. Moore et al., 1991). *Lycopodium* spore tablets were added to the 1 cm^3 large samples prior to preparation to allow calculations of pollen concentrations (pollen/cm^3) (Stockmarr, 1971). Preservation of the pollen grains was generally rather poor, but a total sum of at least 300 pollen grains was reached in each sample. The percentages were calculated from total terrestrial pollen. Pollen identification was completed on a light microscope with x400 magnification. In addition to pollen, different algae such as colonies of *Pediastrum* and *Botryococcus*, dinoflagellates and spores of aquatic plants were also counted. The percentages of those were calculated on the basis of the sum of pollen grains + the sum of, e.g., *Pediastrum*.

4. Results

4.1. Unit A

4.1.1. Description

Unit A directly overlies the lower diamict succession, which is followed by a thin silt bed in core C06 and by laminated clay in E02. The lower metres of unit A consist of sandy, silty clay in C06 and of alternating beds of diamict and reddish clay in E02. In C06, the sand content decreases upwards, whereas a gradual thinning of the diamict beds is seen in E02, from decimetre thick diamict bands in the lowermost part to thin laminae in the upper part. The clay beds in E02 are centimetre thick throughout. The upper part of the unit consists of massive, compact clay with minor colour variations seen as grey and reddish beds. A few outsized clasts are found scattered in the clay.

Foraminifera have been identified in two intervals of unit A (Fig. 3), which are defined as two assemblage zones, designated zones F1 and F2. The lower foraminiferal zone (zone F1) is completely dominated by *H. orbiculare* and *E. excavatum* f. *clavata,* and only a few additional taxa are found in low numbers, i.e. *Cassidulina reniforme* Nørvang, *Elphidium albiumbilicatum* (Weiss), *Elphidium asklundi* Brotzen, *Oolina melo* (d'Orbigny), Polymorphinidae, *Quinqueloculina seminulum* (Linné) and *Scutuloris tegminis* Loeblich and Tappan. The upper zone (zone F2) is totally dominated by *E. albiumbilicatum* and *E. excavatum* f. *selseyensis,* with some *E. excavatum* f. *clavata* and rare occurrences of *H. orbiculare* in the assemblages.

The number of specimens is generally high in both zones. The foraminiferal tests are well preserved in zone F1, but some chemical etching of the test surfaces is observed in zone F2. One and a half metres of clay with only a few scattered foraminiferal specimens separate the two fossiliferous intervals (Fig. 3).

In the lower part of unit A (zone F1), a decreasing trend in $\delta^{18}O$ values is seen in both cores and for both analyzed species, *E. excavatum* f. *clavata* and *H. orbiculare* (Fig. 3). The $\delta^{18}O$ values change from $-3.16‰$ in the lower part of zone F1 to $-7.28‰$ in the upper part. In the upper part of unit A (zone F2), the $\delta^{18}O$ values fluctuate between -10.71 and $-12.22‰$ for *E. excavatum* f. *selseysenis* and between -10.33 and $-10.94‰$ for *E. excavatum* f. *clavata* (Fig. 3).

The $\delta^{13}C$ values in the lower part of unit A (zone F1) vary between -3.85 and $-2.73‰$ for *E. excavatum* f. *clavata* and between -1.46 and $-0.47‰$ for *H. orbiculare* (Fig. 3). In zone F2, the $\delta^{13}C$ values measured on *E. excavatum* f. *clavata* and *E. excavatum* f. *selseysensis* are relatively stable. The $\delta^{13}C$ values from the two forms of *E. excavatum* differ with approximately 1.2‰, but the same general pattern is seen for both records.

Mg/Ca ratios for *E. excavatum* f. *clavata* vary between 0.72 and 1.06 mmol/mol with the higher ratios seen in zone F1. For *E. excavatum* f. *selseyensis,* Mg/Ca varies between 0.52 and 0.96 mmol/mol and for *H. orbiculare* between 0.54 and 0.74 mmol/mol (Fig. 3). When using the calibration of *M. barleeanum* (Kristjánsdóttir et al., 2007), this translates into temperatures between 0.7 and 3.5 °C for *E. excavatum* f. *clavata*, between -1.7 and 2.8 °C for *E. excavatum* f. *selseyensis,* and between -1.5 and 0.9 °C for *H. orbiculare*.

4.1.2. Interpretation

The coarse sediments and repeated diamict beds in the lowermost part of unit A are interpreted as a deglaciation sequence deposited in an ice-contact subaquatic setting, which was gradually replaced by a more ice-distal environment. The foraminiferal contents in zone F1 (lower part of unit A, above the diamict beds) indicate deposition in a glacier-distal environment with slightly reduced salinity. A restricted environment is suggested by the low number of species. *E. excavatum* f. *clavata* is an opportunistic taxon that typically occurs in relatively shallow waters with highly fluctuating environmental conditions. In glacier-proximal environments, it is found to be a dominant taxon together with *C. reniforme* (cf. Hald et al., 1994; Hald and Korsun, 1997), but this latter species is almost absent in the present assemblages. *H. orbiculare,* on the other hand, does not occur in the vicinity of melting glaciers (e.g. Hald and Korsun, 1997), and the dominance of that species would indicate a glacier-distal environment during deposition of zone F1. There is no faunal indication of any change in temperature or salinity through zone F1.

In modern assemblages, *H. orbiculare* occurs over a salinity range from *c.* 22 to >26 psu and it prefers depths of >10 m (Murray, 1991; Steinsund, 1994). The modern temperature range in the Barents Sea is between <−1 and +1 °C (Steinsund, 1994), but *H. orbiculare* can adapt to temperatures as high as 20 °C (Murray, 1991), and it is one of the dominant species in Eemian interglacial deposits in the western Baltic Sea (cf. Kristensen et al., 2000; Kristensen and Knudsen, 2006).

The dominance of only two species in zone F2 (upper part of unit A) is also evidence of deposition in an extremely restricted environment. The high frequency of the boreal *E. excavatum* f. *selseyensis* (cf. Feyling-Hanssen, 1972), together with *E. albiumbilicatum,* indicates higher temperatures than for zone F1 and deposition in shallow, brackish coastal surface waters. *E. excavatum* f. *selseyensis* is tolerant to large salinity and temperature fluctuations. At present, *E. albiumbilicatum* is common in shallow waters in boreal and subarctic environments, and its distribution is assumed to be determined by salinity (Alve, 1995; Alve and Murray, 1999). It has been found at a salinity as low as 3 psu in the Baltic Sea (Rottgardt, 1952). The modern distribution and environmental preferences for *E. albiumbilicatum* in the Arctic is uncertain.

The occurrence of the generally arctic *E. excavatum* f. *clavata* together with the boreal *E. excavatum* f. *selseyensis* in zone F2 may indicate fluctuating environmental conditions in a boundary area between arctic and subarctic climatic regimes. However, it is possible that the two forms actually lived together, but reproduced during different seasons, the dominant boreal forma *selseyensis* during summers and the arctic forma *clavata* during a colder season. In the present Baltic Sea, *E. excavatum* f. *clavata* is

Table 3
Macrofossils identified in units B and C in core C06 and D03.

Sample no.	Depth (m b.s.l.)	*Salix polaris* (VP)	*Carex* sp. 2-sided (VP)	*Carex* sp. 3-sided (VP)	*Juncus* sp.(VP)	*Distichium* sp. (B)	*Bryum* sp. (B)	*Cenococcum geophilum* (F)	Carabidae? (Co)	Staphylinidae (Co)	Amblystegiaceae (B)	*Scorpidium revolvens* (B)	*Calliergon* sp. (B)	*Aulacomnium palustre* (B)	*Sphagnum* sp. (B)	*Nitella* sp. (A)	*Chara* sp. (A)	*Ranunculus* sect. *Batrachium* sp. (B)
14205	32.20	–	–	–	–	1	–	–	–	–	r	–	–	–	–	–	–	–
14204	32.58	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
14215	33.19	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
14214	33.28	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
14213	33.38	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
14211	33.68	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
14227	33.68	–	–	–	–	3	–	–	–	–	c	–	–	–	–	–	–	–
14226	33.73	–	–	–	–	–	–	–	–	–	c	–	–	–	–	–	–	–
14225	34.29	–	–	–	–	1	–	–	–	–	r	–	–	–	–	–	–	–
14224	34.40	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
14223	34.51	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
14221	34.74	–	18	2	–	–	–	–	1	–	c	20	–	–	–	–	–	4
14236	35.35	–	–	–	–	–	–	2	–	2	r	–	–	–	–	–	–	1
14235	35.48	–	–	–	2	–	–	2	–	–	r	–	–	–	1	3	–	–
14234	35.68	–	–	–	–	2	–	–	–	–	c	–	–	–	–	–	–	–
14233	35.78	–	–	–	1	–	–	6	–	–	r	–	–	–	–	–	–	–
34514	35.68	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
34512	35.88	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
34510	36.15	–	–	–	–	–	–	–	–	–	c	–	–	–	–	–	–	–
3451b	36.20	2	–	–	–	–	1	–	–	–	c	c	c	1	–	–	–	–
3459	36.28	–	–	–	–	–	–	–	1	–	r	–	–	–	–	–	–	–
3458	36.34	–	1	–	–	–	–	4	1	1	r	–	–	–	–	30	1	–
3456	36.45	–	–	–	–	–	–	–	–	–	r	–	–	–	–	2	–	–
3454	36.58	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–
3451a	36.68	–	–	–	–	–	–	–	–	–	r	–	–	–	–	–	–	–

A: Algae, B: Bryopsida, Br: Bryozoa, Co: Coleoptera, Cr: Crustacea, F: Fungi, M: Mollusca, T: Trichoptera, VP: vascular plants.

a dominant taxon, which is adapted to the deep, relatively stable, often oxygen-depleted basins, whereas the forma *selseyensis* is much more frequent above the halocline (cf. Lutze, 1965, 1974). Fluctuations in the position of the halocline may, thus, also result in mixing of the two forms of *E. excavatum*, as found in zone F2.

The 1.2‰ offset in the $\delta^{13}C$ values recorded for *E. excavatum* f. *clavata* and *E. excavatum* f. *selseyensis* could be explained by seasonal or microhabitat effects or by a fluctuating halocline. However, the overall similar patterns of the $\delta^{18}O$ and $\delta^{13}C$ records for *E. excavatum* f. *selyseyensis* and *E. excavatum* f. *clavata* would seem to indicate that the offset is more likely a result of species-specific vital effects. The fact that the two different forms of *E. excavatum* are often not separated may cause a problem in using $\delta^{18}O$ and $\delta^{13}C$ for palaeoenvironmental reconstructions.

The $\delta^{18}O$ values are generally low in unit A (Fig. 3), indicating relatively low salinity, high impact of glacial $\delta^{18}O$-depleted meltwater, or high temperature. Given the environmental indication of the assemblages, it is likely that the major part of the $\delta^{18}O$ signal in the foraminiferal tests can be related to the $\delta^{18}O$ composition of the water ($\delta^{18}O_W$) and thereby indirectly to salinity. The trend from relatively heavy values in the lower part of zone F1 to lighter values in zone F2 suggests that either the temperature increased or $\delta^{18}O_W$ decreased upwards. The combined patterns for the $\delta^{18}O$ and $\delta^{13}C$ curves would suggest a change in $\delta^{18}O_W$. This is further supported by the Mg/Ca record, which shows fairly stable values not indicative of any substantial temperature increase. Such a decrease in $\delta^{18}O_W$ could partly be caused by variations in the $\delta^{18}O$ composition of e.g. the meltwater, but the substantial decrease recorded here most likely indicates relatively less marine influence and a decrease in salinity during this time period. The almost barren interval between zone F1 and F2 could indicate a time interval with even lower salinity. The upper part of unit A (zone F2) is characterized by low $\delta^{18}O$ values displaying little variability in the order of less than $\pm 1‰$, which indicates only minor changes in temperature and salinity.

In summary, the zone F2 assemblages indicate highly variable conditions with a generally higher temperature and lower salinity than zone F1. The assemblages of zones F1 and F2 were probably both influenced by glacial meltwater, but not in a glacier-proximal position.

4.2. Unit B

4.2.1. Description

Unit B is a heterogeneous unit with alternating beds of sand, silt and clay inter-bedded with organic-rich beds, ranging in thickness from a millimetre up to 40 cm. The results of the macrofossil analyses are presented in Table 3. A few of the samples contained well-preserved fossil remains, but many contained only small fragments of leaves of brown mosses (Amblystegiaceae). Well preserved moss stems with leaves were found in a few samples. Brown mosses can grow submerged on lake bottoms, but such plants have widely spaced leaves. However, the specimens from Kriegers Flak had densely spaced leaves and thus represent terrestrial wetland mosses. Some of the brown mosses were identified as *Scorpidium revolvens*, which is a wetland species.

All the other non-aquatic species may also represent wetlands. Non-aquatic taxa comprise dwarf willow (*Salix polaris*; two leaf fragments), *Carex* spp. (21 achenes), *Juncus* sp. (3 seeds), the bryophyte *Distichium* sp. (3 small stem fragments with leaves), the soil fungus *Cenococcum geophilum* (14 sclerotia), rove beetles (Staphylinidae, 3 elytra), the bryophyte *Aulacomnium palustre* (1 leaf) and *Sphagnum* sp. (1 leaf). The assemblage of freshwater taxa is thus fairly rich, with at least 21 species. Macrolimnophytes comprise the charophyte algae *Nitella* sp. (40 oospores) and *Chara* sp. (1 oospore) and the vascular plants *Ranunculus* sect. *Batrachium* sp. (5 achenes), *Potamogeton perfoliatus* (4 achenes) and *Potamogeton filiformis* (35 achenes). These taxa are mainly found in shallow water.

Invertebrates comprise the tadpole shrimp *Lepidurus* cf. *arcticus* (8 mandibles and 2 segments from the abdomen), the water fleas *Chydorus sphaericus* (*c.* 400 shells and head shields) and *Daphnia pulex* (7 ephippia), the ostracodes *Cytherissa lacustris* (42 carapaces), *Limnocythere* cf. *sanctipatricii* (1 shell) and *Ilyocypris* sp. (4 shells). Three species of molluscs were found: the gastropods *Valvata cristata* (1 shell) and *Lymnaea peregra* (9 shells) and the small bivalve *Pisidium* sp. (3 shells). Two species of bryozoans were recovered: *Cristatella mucedo* (11 statoblasts) and *Fredericella indica* (12 statoblasts). Insects are represented by non-biting midge larvae (Chironomidae, 28 head capsules), remains of caddis fly larvae (Trichoptera, including two frontocypeal apotomes from *Grensia praeterita*). Two exoskeletons of oribatid mites may represent mites

Potamogeton perfoliatus (VP)	*Potamogeton filiformis* (VP)	*Lepidurus* cf. arcticus (Cr)	*Chydorus sphaericus* (Cr)	*Daphnia pulex* tp. (Cl)	*Cytherissa lacustris* (Cr)	*Limnocythere* cf. *sanctipatricii* (Cr)	*Ilyocypris* sp. (Cr)	Chironomidae indet.	Trichoptera indet.	*Grensia praeterita* (T)	Oribatida indet.	*Valvata cristata* (M)	*Lymnaea peregra* (M)	*Pisidium* sp. (M)	*Cristatella mucedo* (Br)	*Fredericella indica* (Br)	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	D03 unit C
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	D03 unit B
–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	2	–	–	–	–	–	–	–	–	
4	34	6	–	2	–	–	–	–	–	–	–	–	1	–	–	–	
–	–	–	1	–	27	–	4	4	–	–	1	–	–	–	–	–	
–	–	1	3	–	7	–	–	9	–	1	–	–	–	–	–	–	
–	–	–	–	–	8	–	–	5	–	–	–	1	–	2	–	–	
–	–	–	–	2	–	1	–	–	–	–	1	–	–	1	–	–	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	C06 unit B
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	2	1	–	–	–	1	–	–	–	–	–	–	–	–	
–	–	–	1	1	–	–	–	4	–	–	1	–	–	–	–	1	
–	–	–	1	1	–	–	–	–	–	–	–	–	8	–	4	–	
–	1	2	400	–	–	–	–	3	–	–	–	–	–	–	7	10	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	
–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	

living in soil or a species of lacustrine oribatid mites (*Limnozetes* sp. or *Hydrozetes* sp.).

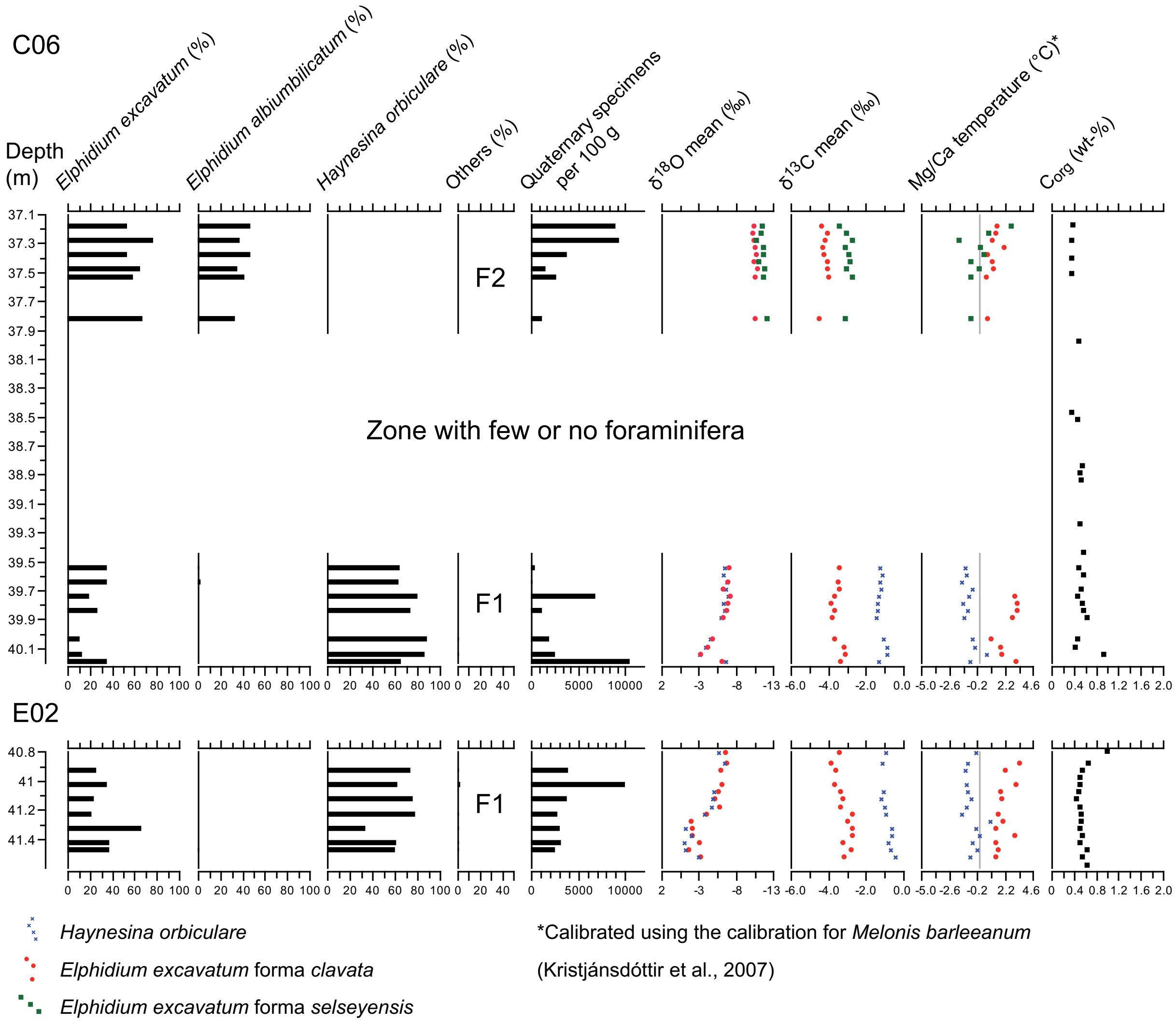
The two samples analyzed for pollen at 36.9–36.89 m and 36.87–36.86 m below sea level in core E02 show fairly consistent pollen spectra with only 30–40% tree pollen and low total pollen concentrations (40000–77000 grains/cm^3). *Betula* (13–19%) and *Pinus* (12–15%) grains dominate among the tree pollen grains, but grains of *Corylus*, *Tilia*, *Alnus*, *Ulmus*, *Quercus*, *Populus* and *Picea* were also found, of which *Picea* grains are most common, 3–4%. With the exception of abundant well-preserved *Pinus* grains, most of the tree pollen grains are heavily corroded and often badly preserved. It is therefore likely that many of them have been reworked from older deposits. With values of 27–30%, pollen grains of Cyperaceae (sedge) are the most abundant pollen type in the two samples. Other rather common non-arboreal pollen grains are Poaceae, *Salix*, *Artemisia*, Caryophyllaceae and *Rumex*. Among the other microfossils found, it is noteworthy that colonies of the freshwater algae *Pediastrum* (green algae) reach values of 30–40%. Up to 2% (marine) dinoflagellates were also found, possibly reworked, as well as a few spores of *Equisetum* and Polypodiaceae (ferns).

4.2.2. Interpretation

Unit B is interpreted as terrestrial and lacustrine sediments deposited in wetlands and shallow lakes. The organic deposition was repeatedly interrupted by clastic sediment influx, probably from sediment-laden small streams and gravity flows. In the macrofossil samples all the non-aquatic species may represent wetland environments. As mentioned above, brown mosses dominate most of the assemblages, and they likely grew in mires. *S. polaris*, the only woody plant represented, is found on raw soils characterized by cryoturbation, in late snow beds, and in mires. *Distichium* shows broad ecological and climatic amplitude, but it is particularly common in the far north. Hence, in northern Greenland it is by far the most common moss (Holmen, 1960). Both *S. polaris* and *Distichium* sp. are calciphilous, showing that the raw soils were carbonate rich, which reflects the observation that tills in the region are rich in fragments of chalk from the pre-Quaternary bedrock. *S. polaris* was probably the first woody plant that arrived to the region after the last deglaciation, and it dominates some early lateglacial fossil assemblages (Korsager et al., 2003). *Distichium* is also a pioneer species that arrived shortly after the last deglaciation. Overall, the macroscopical remains of non-aquatic plants indicate a tree-less, open landscape with tundra-like vegetation. The plants probably colonised small areas with relatively stable soils, and the plants themselves helped to stabilize the soil further.

Although the amassed diversity of freshwater species is fairly high, the freshwater flora and fauna point to extremely difficult living conditions. For example, it is unusual to find a lake deposit with so few remains of chironomids or cladocerans. Holocene lake deposits from non-glacial lakes in the Arctic often contain hundreds of head capsules of chironomid larvae per ml sediment, and thousands of cladoceran remains per ml. In contrast, sediments from glacial lakes may be almost devoid of invertebrate remains. The extremely low numbers in the Kriegers Flak deposit suggest that huge quantities of clay were washed into the lake(s) from the surrounding terrain, making the water highly turbid. During some intervals the rate of in-wash may have decreased, allowing a richer flora and fauna to spread.

Most of the represented invertebrates are benthic, living at the bottom of lakes. *Daphnia* is planktonic, but occurs in small water bodies. Bryozoans live on firm objects, on Kriegers Flak probably on macrolimnophytes. *G. praeterita* inhabits tundra lakes and ponds (Wiggins and Parker, 1997). All taxa can be classified as pioneer species. Most of them have been reported from both early lateglacial and interstadial deposits from the region (Bennike and Jensen, 1995; Jensen et al., 1997). *C. lacustris* is found on muddy substrates of large cold-water lakes. It is quite common in deposits from the southwestern part of the Baltic Ice Lake (Jensen et al., 1997) and in lateglacial deposits from the region. It is typical of oligotrophic or mesotrophic conditions. This is consistent with the pollen data. The high values of green algae and sedges are evidence of a freshwater environment rich in wetlands, whereas the other pollen types indicate an open and rather tree-less environment. Possibly birch and especially pine trees occurred occasionally in sheltered sites around, e.g. lake basins. However, the lack of tree macrofossils indicates that the pollen of *Betula* and *Pinus* might be long-distance transported. Light-demanding herbs and shrubs were common and the environment could probably be characterized as an open tundra-like landscape rich in wetlands.



*Calibrated using the calibration for *Melonis barleeanum* (Kristjánsdóttir et al., 2007)

Fig. 3. Benthic foraminiferal fauna in zones F1 and F2 in (cores C06 and E02). The reconstructed Mg/Ca temperatures should not be considered as absolute temperatures because of the uncertainties related to the calibration and palaeosalinity (see also text).

4.3. Unit C

4.3.1. Description

Unit C consists primarily of compact massive grey clay with a few silt laminae. On raw surfaces the clay shows a spotted texture. A thin diamict bed is followed by clay with scattered sand- and gravel-sized clasts in the lowermost metre of this unit in core C06, and scattered clasts of coarse sand and gravel also occur in the uppermost part. Fewer macrofossils occur in unit C than in the underlying unit, and most samples contained only fragments of leaves of brown mosses (Amblystegiaceae). A few small stem fragments of *Distichium* sp. was found in two of the samples (Table 3).

4.3.2. Interpretation

Unit C is interpreted as glaciolacustrine clay. The clayey sediments indicate an increase in water depth and flooding of Kriegers Flak. This is supported by the spotted texture of the clay, which is interpreted as a result of redeposition of previously deposited clay. The macrofossils identified in this unit are therefore likely to be redeposited as well. The thin diamict bed and the coarse sand and gravel identified in the uppermost and lowermost part of the unit might indicate an increased glacial influence.

4.4. Chronology

The sediments have been dated by a combination of radiocarbon and OSL dating (Fig. 4; Tables 1 and 2). Seven radiocarbon dates on foraminifera from both zones F1 and F2 in unit A gave non-finite ages of more than 55 ^{14}C ka BP (Table 1). Two OSL samples yielded ages of 86.4 ± 5.7 and 71.8 ± 4.4 ka, respectively. The sediments sampled for OSL dating were deposited subaqueously and may not have been completely bleached, and an overestimation of the ages can therefore not be excluded. For the older dates, an additional uncertainty should be considered because of an insufficient thickness of the sampled bed. However, both OSL samples showed good luminescence characteristics with roughly normal distributions. The OSL dates indicate an Early Weichselian age for zone A, but since the sediments in unit A indicate a deglaciation phase and no Early Weichselian ice advances are known from the southwestern Baltic Sea area, we suggest that these ages most likely overestimate the actual age. An early Middle Weichselian age on the other hand would allow us to correlate these sediments with the deglaciation of the Ristinge advance, the oldest known Weichselian ice advance reaching eastern Denmark (Houmark-Nielsen, 2010).

In unit B, eight radiocarbon ages have been determined on bulk material, shell fragments of freshwater molluscs and plant

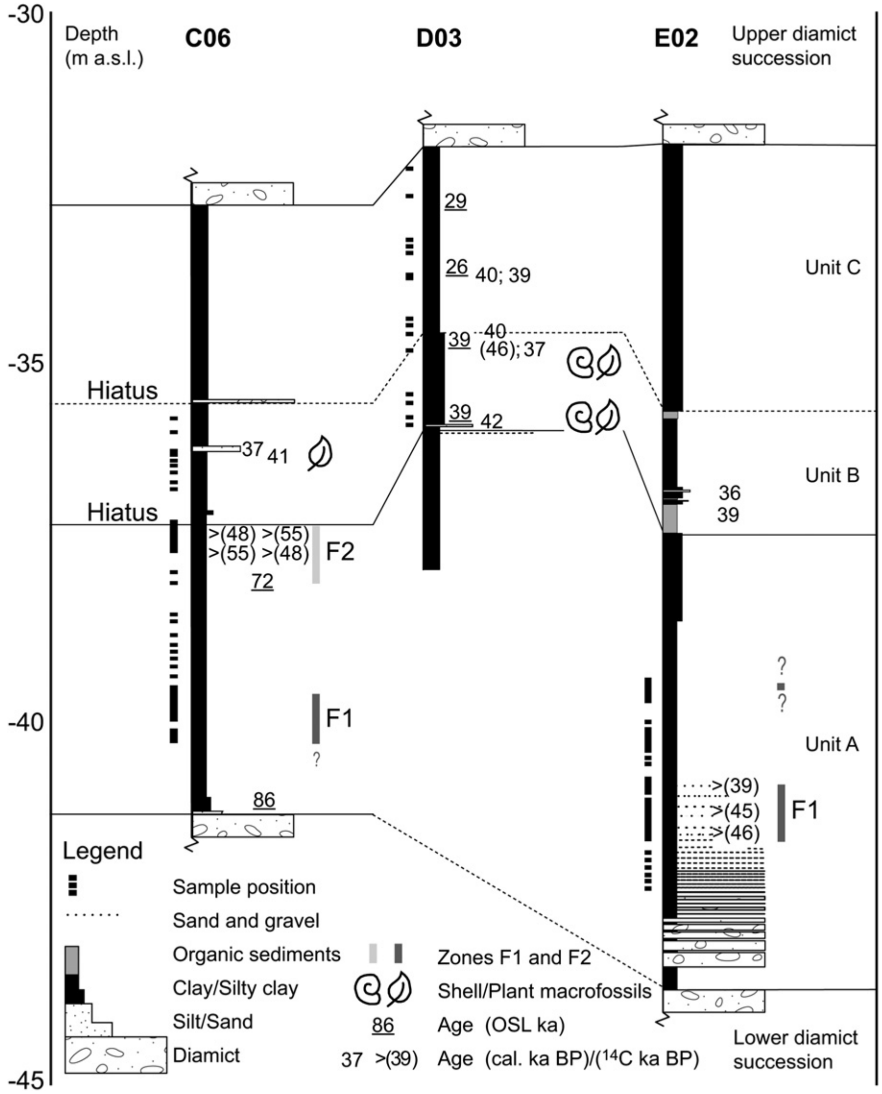


Fig. 4. Detailed lithological logs for units A–C. Sample positions mark the levels of samples extracted for foraminiferal or macrofossil analyses.

macrofossils. Seven of these gave ages ranging from 36 to 42 cal. ka BP, whereas the last one, performed on achenes of *P. filiformis* and *P. perfoliatus*, gave an age of 45.8 ^{14}C ka BP. Two OSL samples resulted in ages of 38.5 ± 2.6 and 39.0 ± 2.5 ka. The radiocarbon age outlier (45.8 ^{14}C ka BP) was determined on a water plant and may have inherited an anomalously old signal by uptake of bicarbonates in the water. An age of 36–42 cal. ka is therefore suggested for unit B.

Radiocarbon ages of macrofossils from unit C gave 39 and 40 cal. ka BP. This is in contrast to two OSL ages from this unit of 28.5 ± 1.8 and 26.0 ± 1.7 ka. Because of the indication of redeposition of sediments from unit B into unit C, we suggest that the radiocarbon ages from unit C should be considered maximum ages. The substantially younger OSL ages are therefore considered more reliable.

In summary, the available data lead us to suggest that the marine unit A was deposited after the Middle Weichselian Ristinge ice advance at around 50 ka, unit B was deposited between 42 and 36 ka and unit C between 28.5 and 26 ka (Fig. 4).

5. Discussion

This study provides a well-dated chronology for Middle Weichselian climatic and palaeoenvironmental changes in the southwestern Baltic Basin. The oldest part of the studied succession directly overlies a diamict and was most likely deposited during the Middle Weichselian deglaciation of the SIS (Ristinge advance), which has been OSL dated to c. 50 ka (Fig. 5; Larsen et al., 2009; Houmark-Nielsen, 2010). Glacial isostatic subsidence of the thresholds between the Baltic Basin and Kattegat enabled sea water to enter the Baltic Basin despite the relatively low global sea level (Chappell et al., 1996; Cutler et al., 2003; Peltier and Fairbanks, 2006), and a low-diversity, brackish-water foraminiferal fauna became established (zone F1).

A benthic foraminiferal fauna similar to that in the upper foraminiferal zone (zone F2) has previously been described from Kriegers Flak by Klingberg (1998). Radiocarbon ages of the foraminifera gave non-finite ages (Klingberg, 1998), and amino-acid analysis indicated a Late Saalian or Early Weichselian age, although younger ages could not be excluded (Bennike and Wagner, 2010). Both the faunal composition and the δ^{18}O data from zone F2 indicate higher bottom-water temperatures compared to zone F1 but this is not seen in the Mg/Ca ratios (Fig. 3). The δ^{18}O record is, however, complicated by the strong influence of δ^{18}O-depleted meltwater from an ice sheet, as also noted by Klingberg (1998), and the Mg/Ca ratios might be influenced by salinity variations. The

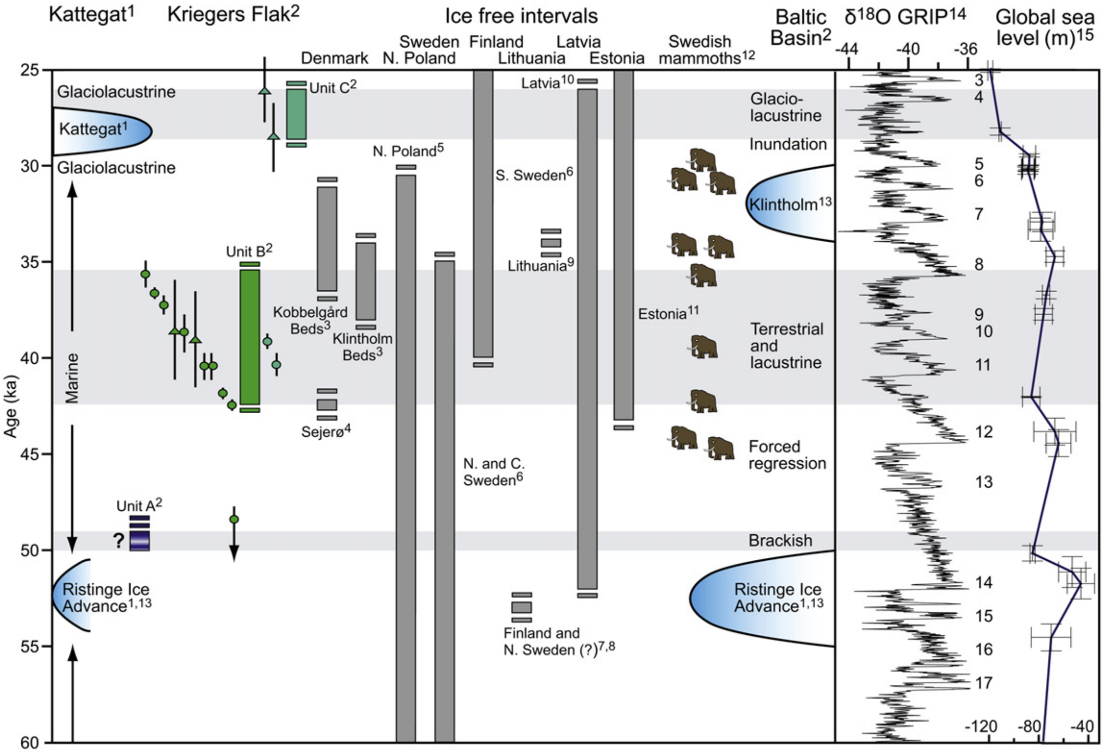


Fig. 5. Schematic summary of Middle Weichselian ice advances, ice-free intervals and mammoth remains from the circum-Baltic region compared with the GRIP δ^{18}O data and the global sea-level curve. For Kriegers Flak, all finite radiocarbon (circles) and OSL dates (triangles) are shown as well. For the other areas, the dating resolution is highly variable, and the ages suggested in the different studies have therefore been taken at face value. 1 – Larsen et al. (2009), 2 – This study, 3 – Houmark-Nielsen and Kjær (2003), 4 – Bennike et al. (2007), 5 – Wysota et al. (2002), 6 – Wohlfarth (2010), 7 – Helmens and Engels (2010), 8 – Hättestrand and Robertsson (2010), 9 – Satkunas et al. (2009), 10 – Saks et al. (2010), 11 – Kalm (2006), 12 – Ukkonen et al. (2007, 2011), 13 – Houmark-Nielsen (2010), 14 – GRIP Members (1993), 15 – Chappell et al. (1996), Cutler et al. (2003), Peltier and Fairbanks (2006).

decrease in salinity inferred from zone F1 to zone F2 in unit A could be a result of either increased freshwater input or decreased marine inflow. A lower water depth in the sill area and thereby reduced marine influence is expected because of the isostatic rebound following the Ristinge advance.

Marine sediments have also been identified at several locations around the German Baltic Sea coast, but few reliable dates and an uncertain biostratigraphy make it difficult to correlate with any of these. Radiocarbon dating at Kleiner Klüsser gave ages of 36 and 29 ^{14}C ka BP (Steinich, 1992; Panzig, 1997), but the stratigraphical position of these sediments is still problematic (Ludwig, 2006). At Greifswalder Oie (Fig. 1), glacially dislocated brackish-marine clay has been attributed to the Early to Middle Weichselian by Obst and Ansorge (2010). An Early Weichselian or Late Saalian age has occasionally been assumed for marine sediments because of the previous lack of evidence for a marine influence during the Middle Weichselian (Klingberg, 1998). However, the present results indicate that sea water did enter the Baltic Basin during the Middle Weichselian. This result is, however, not in agreement with the model by Lambeck et al. (2010), which suggested that the thresholds of the Baltic Basin were situated above the relative sea level during this period.

A subsequent forced-regression of the area turned Kriegers Flak into an island or a peninsula. Erosion and non-deposition connected to this regression could explain the hiatus found between units A and B. Unit B was deposited in wetlands and shallow lakes between 42 and 36 ka cal. BP. The macrofossil record for unit B includes the arctic species *S. polaris* and *Grensia praeterita*, indicating an arctic climate. Living *G. praeterita* has been recorded from Alaska, northern Yukon, the Canadian Northwest Territories, Greenland, and northern Eurasia (Stoltze, 1981; Wiggins and Parker, 1997). The species has also been recorded from an interstadial deposit on Sejerø in Denmark, dated to c. 41.5 cal. ka BP (Bennike et al., 2007).

The most warmth demanding species identified in unit B are probably *C. mucedo* and *C. lacustris*. The northern geographical range limit of *C. mucedo* seems to coincide with the present arctic tree line. This would correspond to a mean July temperature around 10 °C (Lacourt, 1968). However, in Greenland the species is probably living somewhat further north (Bennike et al., 2004), and we suggest that the occurrence of *C. mucedo* indicates a mean July temperature above 8 °C. *C. lacustris* is presently found across Europe, and in Canada it is found in the boreal zone (Delorme, 1970). It has been discovered in lakes on Svalbard (Sywula et al., 1994), but this is apparently the only record from the Arctic. Hence, its geographical range may be similar to that of *C. mucedo*. The co-occurrence of arctic species and more thermophilous species may indicate a mean July temperature around 10 °C for unit B. This is similar to the value suggested for the Sejerø deposit, which is likely of the same age as unit B of the Kriegers Flak deposits.

The other recorded bryozoan species, *F. indica*, is rarely recorded as a fossil, probably because the statoblasts are in-distinctive. However, it has been found in Middle Weichselian interstadial deposits in Sweden (Helmens et al., 2007a). It is common in Holocene lake deposits from SW Greenland and in early lateglacial deposits from Denmark (Bennike, unpublished data). In Norway, it is presently common in the northern part of the country (Økland and Økland, 2005).

The pollen record gives a similar indication and suggests vegetation resembling a forest tundra rich in wetlands. This can be compared with pollen data from slightly younger sediments from northwestern Lithuania, radiocarbon dated to c. 33–34 cal. ka BP, which indicate a cold and wet climate and an open landscape, whereas wood fragments indicate presence of some trees or shrubs (Satkunas et al., 2009). Ice-free periods of roughly the same age are also found in other areas around the present Baltic Sea. In Latvia, lacustrine sands indicate the existence of a large freshwater lake in the Baltic Basin between 52 and 26 ka (Saks et al., 2010), and Kalm (2006) suggested that Estonia was ice-free at least between 43.2 and 26.8 ka. In southwestern Estonia, lacustrine sediments were deposited between 37 ka (OSL) and 44.4 ^{14}C ka BP (Rattas et al., 2010), whereas glaciofluvial and glaciolacustrine sediments from Møn, Denmark, have been dated at 34–38 ka (Bennike et al., 1994; Houmark-Nielsen and Kjær, 2003). In addition, Sweden (Ukkonen et al., 2007; Wohlfarth, 2010) and northern Poland (Wysota et al., 2002) seem to have experienced ice-free conditions (Fig. 5) during this time period. In contrast, southwestern Norway experienced an ice advance (Skjonghelleren ice advance) reaching beyond the coast around 41 ka (Mangerud et al., 2009).

Deposition of glaciolacustrine clays at Kriegers Flak c. 28.5–26 ka (unit C) supports the previous assumption that the SIS during the Kattegat advance dammed Kattegat and the Baltic Basin (Houmark-Nielsen and Kjær, 2003; Larsen et al., 2009). The hiatus found between units B and C corresponds in time with the Klintholm advance (cf. Houmark-Nielsen, 2010), possibly signifying glacial erosion, but it could also be explained by non-deposition or erosion connected with the damming of the Baltic Basin.

6. Conclusions

The Middle Weichselian palaeoenvironmental history of the southwestern Baltic Basin was reconstructed based on sediment cores and dates from Kriegers Flak and previously published dates from around the Baltic Sea. We suggest the following scenario:

(1) Following the deglaciation of the SIS during the Middle Weichselian (Ristinge ice advance), isostatic depression allowed sea water to enter the Baltic Basin. A low-diversity, benthic foraminiferal fauna indicative of cold brackish-water conditions was established.
(2) A forced regression, probably caused by a combination of isostatic rebound and a falling global sea level, led to a period of non-deposition and erosion at Kriegers Flak.
(3) Between 42 and 36 cal. ka BP, sedimentation occurred in shallow lakes and wetlands on Kriegers Flak. The vegetation was tundra-like, or forest tundra-like, possibly with birch and pine in sheltered locations. A mean July temperature of c. 10 °C is suggested.
(4) From 28.5 to 26 ka, the SIS dammed Kattegat and Baltic Basin and a thick succession of glaciolacustrine clay was deposited at Kriegers Flak.

Our results provide a well-dated reconstruction of Middle Weichselian palaeoenvironmental history at Kriegers Flak providing a solid framework for future research around the circum-Baltic Basin.

Acknowledgement

We are grateful to Göran Loman and Vattenfall A/S, Sweden, who allowed us to analyze the cores retrieved by them during their survey of Kriegers Flak. We would also like to thank Andreas Mackensen, Alfred Wegener Institute für Polar- und Meeresforschung, Germany, for conducting the stable carbon and oxygen isotope analyses and Åsa Wallin, Lund University, Sweden, for the C_{org} measurements. An anonymous reviewer provided a constructive and helpful review. Financial support was provided by Kungliga Fysiografiska Sällskapet i Lund and the Crafoord Foundation, Sweden.

References

Alexanderson, H., Johnsen, T., Murray, A.S., 2010. Re-dating the Pilgrimstad Interstadial with OSL: a warmer climate and a smaller ice sheet during the Swedish Middle Weichselian (MIS 3)? Boreas 39, 367–376.

Alve, E., 1995. Benthic foraminiferal distribution and recolonization of formerly anoxic environments in Drammensfjord, southern Norway. Marine Micropaleontology 25, 169–186.

Alve, E., Murray, J.W., 1999. Marginal marine environments of the Skagerrak and Kattegat: a baseline study of living (stained) benthic foraminiferal ecology. Palaeogeography, Palaeoclimatology, Palaeoecology 146, 171–193.

Andrén, T., Björck, S., Andrén, E., Conley, D., Lambeck, K., Zillén, L., Anjar, J., 2011. The development of the Baltic Sea basin during the last 130 ka. In: Harff, J., Björck, S., Hoth, P. (Eds.), The Baltic Sea Basin as a Natural Laboratory. Springer-Verlag, Berlin, Heidelberg, pp. 75–97.

Anjar, J., Larsen, N.K., Björck, S., Adrielsson, L., Filipsson, H.L., 2010. MIS 3 marine and lacustrine sediments at Kriegers Flak, southwestern Baltic Sea. Boreas 39, 360–366.

Antonov, J.I., Locarnini, R.A., Boyer, T.P., Mishonov, A.V., Garcia, H.E., 2006. World Ocean Atlas 2005. In: Levitus, S. (Ed.), NOAA Atlas NESDIS 62. Salinity, vol. 2. U.S. Governement Printing Office, Washington D.C, p. 182.

Arbuszewski, J., deMenocal, P., Kaplan, A., Farmer, E.C., 2010. On the fidelity of shell-derived $\delta^{18}O_{seawater}$ estimates. Earth and Planetary Science Letters 300, 185–196.

Barker, S., Greaves, M., Elderfield, H., 2003. A study of cleaning procedures used for foraminiferal Mg/Ca paleothermometry. Geochemistry Geophysics Geosystems 4. doi:10.1029/2003GC000559.

Bateman, M.D., Catt, J.A., 1996. An absolute chronology for the raised beach deposits at Sewerby, E. Yorkshire, England. Journal of Quaternary Science 11, 389–395.

Bennike, O., Jensen, J.B., 1995. Near-shore Baltic Ice Lake deposits in Fakse Bugt, southeast Denmark. Boreas 24, 185–195.

Bennike, O., Wagner, B., 2010. Amino acid analysis of pre-Holocene foraminifera from Kriegers Flak in the Baltic Sea. Geological Survey of Denmark and Greenland, Bulletin 20, 35–38.

Bennike, O., Houmark-Nielsen, M., Böcher, J., Heiberg, E.O., 1994. A multi-disciplinary macrofossil study of Middle Weichselian sediments at Kobbelgård, Møn, Denmark. Palaeogeography, Palaeoclimatology, Palaeoecology 111, 1–15.

Bennike, O., Brodersen, K.P., Jeppesen, E., Walker, I.R., 2004. Aquatic invertebrates and high latitude paleolimnology. In: Pienitz, R., Douglas, M.S.V., Smol, J.P. (Eds.), Long-term Environmental Change in Arctic and Antarctic Lakes. Springer, Berlin, pp. 159–186.

Bennike, O., Houmark-Nielsen, M., Wiberg-Larsen, P., 2007. A Middle Weichselian interstadial lake deposit on Sejerø, Denmark: macrofossil studies and dating. Journal of Quaternary Science 22, 647–651.

Björck, S., 1995. A review of the history of the Baltic Sea, 13.0–8.0 ka BP. Quaternary International 27, 19–40.

Bos, J.A.A., Helmens, K.F., Bohncke, S.J.P., Seppä, H., Birks, H.J.B., 2009. Flora, vegetation and climate at Sokli, northeastern Fennoscandia, during the Weichselian Middle Pleniglacial. Boreas 38, 335–348.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.

Chappell, J., Shackleton, N.J., 1986. Oxygen isotopes and sea level. Nature 324, 137–140.

Chappell, J., Omura, A., Esat, T., McCulloch, M., Pandolfi, J., Ota, Y., Pillans, B., 1996. Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. Earth and Planetary Science Letters 141, 227–236.

Cutler, K.B., Edwards, R.L., Taylor, F.W., Cheng, H., Adkins, J., Gallup, C.D., Cutler, P.M., Burr, G.S., Bloom, A.L., 2003. Rapid sea-level fall and deep-ocean temperature change since the last interglacial period. Earth and Planetary Science Letters 206, 253–271.

Delorme, L.D., 1970. Freshwater ostracodes of Canada. Part IV. Families Ilyocyprididae, Notodromadidae, Darwinulidae, Cytherideidae, and Entocytheridae. Canadian Journal of Zoology 48, 1251–1259.

Dissard, D., Nehrke, G., Reichart, G.J., Bijma, J., 2010. The impact of salinity on the Mg/Ca and Sr/Ca ratio in the benthic foraminifera *Ammonia tepida*: results from culture experiments. Geochimica et Cosmochimica Acta 74, 928–940.

Engels, S., Bohncke, S.J.P., Bos, J.A.A., Brooks, S.J., Heiri, O., Helmens, K.F., 2008. Chironomid-based palaeotemperature estimates for northeast Finland during Oxygen Isotope Stage 3. Journal of Paleolimnology 40, 49–61.

Ferguson, J.E., Henderson, G.M., Kucera, M., Rickaby, R.E.M., 2008. Systematic change of foraminiferal Mg/Ca ratios across a strong salinity gradient. Earth and Planetary Science Letters 265, 153–166.

Feyling-Hanssen, R.W., 1964. Foraminifera in Late Quaternary deposits from the Oslofjord area. Norges Geologiske Undersøgelse 225, 1–383.

Feyling-Hanssen, R.W., 1972. The foraminifer *Elphidium excavatum* (Terquem) and its variant forms. Micropaleontology 18, 337–354.

GRIP Members, 1993. Climate instability during the last interglacial period recorded in the GRIP ice core. Nature 364, 203–207.

Groeneveld, J., Nürnberg, D., Tiedemann, R., Reichart, G.J., Steph, S., Reuning, L., Crudeli, D., Mason, P., 2008. Foraminiferal Mg/Ca increase in the Caribbean during the Pliocene: Western Atlantic warm Pool formation, salinity influence, or diagenetic overprint? Geochemistry Geophysics Geosystems 9, Q01P23. doi:10.1029/2006GC001564.

Hald, M., Korsun, S., 1997. Distribution of modern benthic foraminifera from fjords of Svalbard, European Arctic. Journal of Foraminiferal Research 27, 101–122.

Hald, M., Steinsund, P.I., Dokken, T., Korsun, S., Polyak, L., Aspeli, R., 1994. Recent and Late Quaternary Distribution of *Elphidium excavatum* f. *clavatum* in Arctic Seas. Cushman Foundation Special Publication 32, 141–153 pp.

Hättestrand, M., Robertsson, A.-M., 2010. Weichselian interstadials at Riipiharju, northern Sweden – interpretation of vegetation and climate from fossil and modern pollen records. Boreas 39, 296–311.

Helmens, K.F., Engels, S., 2010. Ice-free conditions in eastern Fennoscandia during early Marine Isotope Stage 3: lacustrine records. Boreas 39, 399–409.

Helmens, K.F., Räsänen, M.E., Johansson, P.W., Jungner, H., Korjonen, K., 2000. The Last Interglacial–Glacial cycle in NE Fennoscandia: a nearly continuous record from Sokli (Finnish Lapland). Quaternary Science Reviews 19, 1605–1623.

Helmens, K.F., Bos, J.A.A., Engels, S., Van Meerbeeck, C.J., Bohncke, S.J.P., Renssen, H., Heiri, O., Brooks, S.J., Seppä, H., Birks, H.J.B., Wohlfarth, B., 2007a. Present-day temperatures in northern Scandinavia during the last glaciation. Geology 35, 987–990.

Helmens, K.F., Johansson, P.W., Räsänen, M.E., Alexanderson, H., Eskola, K.O., 2007b. Ice-free intervals continuing into Marine Isotope Stage 3 at Sokli in the central area of the Fennoscandian glaciations. Bulletin of the Geological Society of Finland 79, 17–39.

Holmen, K., 1960. The mosses of Peary Land, North Greenland. Meddelelser om Grønland 163, 96.

Hoogakker, B.A.A., Klinkhammer, G.P., Elderfield, H., Rohling, E.J., Hayward, C., 2009. Mg/Ca paleothermometry in high salinity environments. Earth and Planetary Science Letters 284, 583–589.

Houmark-Nielsen, M., 1994. Late Pleistocene stratigraphy, glaciation, chronology and Middle Weichselian environmental history from Klintholm, Møn, Denmark. Bulletin of the Geological Society of Denmark 41, 181–202.

Houmark-Nielsen, M., 2010. Extent, age and dynamics of Marine Isotope Stage 3 glaciations in the southwestern Baltic Basin. Boreas 39, 343–359.

Houmark-Nielsen, M., Kjær, K.H., 2003. Southwest Scandinavia, 40–15 kyr BP: palaeogeography and environmental change. Journal of Quaternary Science 18, 769–786.

Jensen, J.B., Bennike, O., Witkowski, A., Lemke, W., Kuijpers, A., 1997. The Baltic Ice Lake in the southwestern Baltic: sequence-, chrono- and biostratigraphy. Boreas 26, 217–236.

Kalm, V., 2006. Pleistocene chronostratigraphy in Estonia, southeastern sector of the Scandinavian glaciation. Quaternary Science Reviews 25, 960–975.

Kisakürek, B., Eisenhauer, A., Böhm, F., Garbe-Schönberg, D., Erez, J., 2008. Controls on shell Mg/Ca and Sr/Ca in cultured planktonic foraminifera, *Globigerinoides ruber* (white). Earth and Planetary Science Letters 273, 260–269. doi:10.1016/j.epsl.2008.06.026.

Klingberg, F., 1998. A Late Pleistocene marine clay succession at Kriegers Flak, westernmost Baltic, southern Scandinavia. Journal of Quaternary Science 13, 245–253.

Knudsen, K.L., 1998. Foraminiferer i Kvartær stratigrafi: laboratorie-og fremstillingsteknik samt udvalgte eksempler. Geologisk Tidsskrift 3, 1–25.

Korsager, B., Bennike, O., Houmark-Nielsen, M., 2003. *Salix polaris* leaves dated at 14.3 ka BP from northern Jylland, Denmark. Bulletin of the Geological Society of Denmark 50, 151–155.

Kristensen, P., Knudsen, K.L., 2006. Palaeoenvironments of a complete Eemian sequence at Mommark, southern Denmark: foraminifera, ostracods and stable isotopes. Boreas 35, 349–366.

Kristensen, P., Gibbard, P., Knudsen, K.L., Ehlers, J., 2000. Last interglacial stratigraphy at Ristinge Klint, South Denmark. Boreas 29, 103–116.

Kristjánsdóttir, G.B., Lea, D.W., Jennings, A.E., Pak, D.K., Belanger, C., 2007. New spatial Mg/Ca-temperature calibrations for three Arctic, benthic foraminifera and reconstruction of north Iceland shelf temperature for the past 4000 years. Geochemistry Geophysics Geosystems 8, Q03P21. doi:10.1029/2006GC001425.

Lacourt, A.W., 1968. A monograph of the freshwater Bryozoa – Phylactolaemata. Zoologische Verhandelingen 93, 159.

Lambeck, K., Chappell, J., 2001. Sea level change through the Last Glacial cycle. Science 292, 679–686.

Lambeck, K., Purcell, A., Zhao, J., Svensson, N.-O., 2010. The Scandinavian Ice Sheet: from MIS 4 to the end of the Last Glacial Maximum. Boreas 39, 410–435.

Larsen, N.K., Knudsen, K.L., Krohn, C.F., Kronborg, C., Murray, A.S., Nielsen, O.B., 2009. Late Quaternary ice sheet, lake and sea history of southwest Scandinavia – a synthesis. Boreas 38, 732–761.

Lear, C.H., Rosenthal, Y., Slowey, N., 2002. Benthic foraminiferal Mg/Ca-paleothermometry: a revised core-top calibration. Geochimica Cosmochimica et Acta 66, 3375–3387.

Ludwig, A.O., 2006. Cyprinenton und I1-Folge im Pleistozän von Nordost-Rügen und der Insel Hiddensee (südwestliche Ostsee). Zettschrift für Geologische Wissenschaften 34, 349–377.

Lutze, G.F., 1965. Zur Foraminiferenfauna der Ostsee. Meyniana 15, 75–142.

Lutze, G.F., 1974. Foraminiferen der Kieler Bucht (Westlicher Ostsee): 1. "Hausgartengebiet" des Sonderforschungsbereiches 95 der Universität Kiel. Meyniana 26, 9–22.

Mangerud, J., Gulliksen, S., Larsen, E., 2009. ^{14}C-dated fluctuations of the western flank of the Scandinavian Ice Sheet 45–25 kyr BP compared with Bølling–Younger Dryas fluctuations and Dansgaard–Oeschger events in Greenland. Boreas 39, 328–342.

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis, Second ed. Blackwell Scientific, Oxford.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.

Murray, J.W., 1991. Ecology and Palaeoecology of Benthic Foraminifera. Longman Scientific and Technical, Harlow.

Nürnberg, D., Bijma, J., Hemleben, C., 1996. Assessing the reliability of magnesium in foraminiferal calcite as a proxy for water mass temperatures. Geochimica Cosmochimica et Acta 60, 803–814.

Obst, K., Ansorge, J., 2010. Die Greifswalder Oie – ein einzigartiges Vorkommen von präpleistozänen Schollen und Geschieben in einer hoch deformierten quartären Abfolge. In: Lampen, R., Lorenz, S. (Eds.), Eiszeitlandschaften in Mecklenburg-Vorpommern. Geozon Science Media, Greifswald, pp. 132–158.

Økland, J., Økland, K.A., 2005. Freshwater bryozoans (Bryozoa) of Norway V: review and comparative discussion of the distribution and ecology of the 10 species recorded. Hydrobiologia 534, 31–55.

Panzig, W.-A., 1997. The Klüsser site (NW Wittow). In: Piotrowski, J.A. (Ed.), Excursion Guide from Field Symposium on Glacial Geology at the Baltic Sea Coast in Northern Germany. The Peribaltic Group, INQUA commission on Glaciation, Kiel, Germany, pp. 55–59.

Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Reviews 25, 3322–3337.

Rattas, M., Kalm, V., Kihno, K., Liivrand, E., Tinn, O., Tänavsuu-Milkeviciene, K., Sakson, M., 2010. Chronology of Late Saalian and Middle Weichselian episodes of ice-free lacustrine sedimentation recorded in the Arumetsa section, southwestern Estonia. Estonian Journal of Earth Sciences 59, 125–140.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51, 1111–1150.

Rottgardt, D., 1952. Mikropaläontologische wichtige Bestandteile rezenter brakischer Sedimente an den Küsten Schleswig-Holstein. Meyniana 1, 169–228.

Sadekov, A., Eggins, S.M., De Deckker, P., Ninnemann, U., Kuhnt, W., Bassinot, F., 2009. Surface and subsurface seawater temperature reconstruction using Mg/Ca microanalysis of planktonic foraminifera *Globigerinoides ruber, Globigerinoides sacculifer*, and *Pulleniatina obliquiloculata*. Paleoceanography 24, PA3201. doi:10.1029/2008PA001664.

Saks, T., Kalvans, A., Zelcs, V., 2010. OSL dating of Middle Weichselian age shallow basin sediments in Western Latvia, Eastern Baltic. Quaternary Science Reviews. doi:10.1016/j.quascirev.2010.11.004.

Satkunas, J., Grigiene, A., Jusiene, A., Damusyte, A., Mazeika, J., 2009. Middle Weichselian palaeolacustrine basin in the Venta river valley and vicinity (northwest Lithuania), exemplified by the Purvai outcrop. Quaternary International 207, 14–25.

Seifert, T., Tauber, F., Kayser, B., 2001. A high resolution spherical grid topography of the Baltic Sea. Proceedings of the Baltic Sea Science Congress 25–29 November 2001, poster 147. Stockholm, Sweden.

Steinich, G., 1992. Die stratigraphische Einordnung der Rügen-Warmzeit. Zeitschrift für Geologische Wissenschaften 20, 125–154.

Steinsund, P.I., 1994. Benthic foraminifera in surface sediments of the Barents and Kara seas: modern and late Quaternary applications. PhD thesis, Institute of Biology and Geology, Department of Geology, University of Tromsø, Tromsø, Norway.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13, 615–621.

Stoltze, M., 1981. Grønlandske vårfluers udbredelse og indvandringshistorie. Unpublished report. Zoological Museum, Copenhagen, 16 pp.

Sywula, T., Namiotko, T., Sell, J., Witkowski, A., Zajackowski, M., 1994. Crustacean species new to Spitsbergen with notes on the polymorphism and the subfossil preservation of *Cytherissa lacustris* (G. O. Sars). Polar Research 13, 233–235.

Ukkonen, P., Arppe, L., Houmark-Nielsen, M., Kjær, K.H., Karhu, J.A., 2007. MIS 3 mammoth remains from Sweden – implications for faunal history and glaciation chronology. Quaternary Science Reviews 26, 3081–3098.

Ukkonen, P., Aaris-Sørensen, K., Arppe, L., Clark, P.U., Daugnora, L., Lister, A.M., Lõugas, L., Seppä, H., Sommer, R.S., Stuart, A.J., Woital, P., Zupinš, I., 2011. Woolly mammoth (*Mammuth primigenius* Blum.) and its environment in northern Europe during the last glaciation. Quaternary Science Reviews 30, 693–712.

Wiggins, G.B., Parker, C.R., 1997. Caddisflies (Trichoptera) of the Yukon, with analysis of the Beringian and Holarctic species of North America. In: Danks, H.V., Downes, J.A. (Eds.), Insects of the Yukon. Biological Survey of Canada (Terrestrial Arthropods), Ottawa, pp. 787–866.

Wohlfarth, B., 2010. Ice-free conditions in Sweden during Marine Oxygen Isotope Stage 3? Boreas 39, 377–398.

Wolff, E.W., Chappellaz, J., Blunier, T., Rasmussen, S.O., Svensson, A., 2010. Millennial-scale variability during the last glacial: the ice core record. Quaternary Science Reviews 29, 2828–2838.

Wysota, W., Lankauf, K.R., Szmańda, J., Chruścińska, A., Oczkowski, H.L., Przegiętka, K.R., 2002. Chronology of the Vistulian (Weichselian) glacial events in the lower Vistula region, middle-north Poland. Geochronometria 21, 137–142.