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MIS 3 marine and lacustrine sediments at Kriegers Flak, southwestern Baltic Sea

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Sediment cores from the Kriegers Flak area in the southwestern Baltic Sea show a distinct lithological succession, starting with a lower diamict that is overlain by a *c.* 10 m thick clay unit that contains peat, gyttja and other organic remains. On top follows an upper diamict that is inter-layered with sorted sediments and overlain by an upward-coarsening sequence with molluscs. In this paper we focus on the clay unit, which has been subdivided into three subunits: (A) lower clay with benthic foraminifera and with diamict beds in the lower part; (B) thin beds of gyttja and peat, which have been radiocarbon-dated to 31–35 ^{14}C kyr BP (*c.* 36–41 cal. kyr BP); and (C) upper clay unit. Based on the preliminary results we suggest the following depositional model: fine-grained sediments interbedded with diamict in the lower part (subunit A) were deposited in a brackish basin during a retreat of the Scandinavian Ice Sheet, probably during the Middle Weichselian. Around 40 kyr BP the area turned into a wetland with small ponds (subunit B). A transgression, possibly caused by the damming of the Baltic Basin during the Kattegat advance at 29 kyr BP, led to the deposition of massive clay (subunit C). The data presented here provide new information about the paleoenvironmental changes occurring in the Baltic Basin following the Middle Weichselian glaciation.

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Marine Isotope Stage 3 (MIS 3, 60–25 kyr BP) in the Northern Hemisphere is characterized by an interstadial climate punctuated by abrupt climate shifts, the so-called Dansgaard-Oeschger cycles (e.g. Dansgaard *et al.* 1993; Clement & Peterson 2008). The generally warm interstadial climate during MIS 3 resulted in a significantly reduced or completely absent Scandinavian Ice Sheet, as reported from studies in southern Sweden and Bornholm (Kjær *et al.* 2006), northern Sweden (Hättestrand 2008), south and central Sweden and western Finland (Ukkonen *et al.* 2007; Wohlfarth 2009), northern Finland (Helmens *et al.* 2000, 2007) and western Norway (Mangerud *et al.* 2003). These ice-free conditions were interrupted at the beginning and end of MIS 3 by two major ice advances that reached as far as Denmark, namely the Ristinge advance at *c.* 55–50 kyr BP and the Kattegat advance at *c.* 29–27 kyr BP (Houmark-Nielsen 2003, 2007; Houmark-Nielsen & Kjær 2003; Kjær *et al.* 2006; Larsen *et al.* 2009a, b). A third ice advance, the Klintholm advance, has been proposed to have taken place *c.* 35–33 kyr BP (Houmark-Nielsen & Kjær 2003), but the timing of this advance is still under debate (e.g. Ukkonen *et al.* 2007).

The Middle Weichselian history of the southwestern part of the Baltic Basin is largely unknown. Seismic studies reveal a complex pattern of glacially incised valleys in the Arkona Basin, in Hanö Bay (Flodén *et al.* 1997) and in the Gotland Basin (Bjerkéus *et al.* 1994; Flodén *et al.* 1997) (Fig. 1A, B). Marine clay has been described from two cores on the northeastern slope of Kriegers Flak (Klingberg 1998) (Fig. 1B). Radiocarbon dating of benthic foraminifera (*Elphidium excavatum* and *Elphidium albiumbilicatum*) found in this clay gave infinite ages (> 40 kyr BP), and the clay was therefore suggested to be of Late Saalian, Early Eemian or Early Weichselian age (Klingberg 1998). Middle Weichselian sediments have been identified on Møn in southeastern Denmark, on Rügen in northern Germany (Steinich 1992; Houmark-Nielsen 1994; Panzig 1997), and in western Latvia (Saks *et al.* 2007). On Møn, a fining-upward sequence dated to *c.* 50 kyr BP indicates a shift from a glaciofluvial to a glaciolacustrine or lacustrine environment (Houmark-Nielsen 1994). On Rügen, sediments from the same time period have been interpreted as marine clays containing reworked Eemian sediments with benthic foraminifera (Steinich 1992; Panzig 1997), and in western Latvia, marine sand has been OSL-dated to 45–43 kyr BP (Saks *et al.* 2007). It has been suggested that the Baltic Sea was connected to the Kattegat through the Esrum/Alnarp valley during MIS 3 (Fig. 1) (Lagerlund 1987; Andrén & Wannäs 1988; Houmark-Nielsen & Kjær 2003). This valley is presently filled with sediments, but has a bedrock threshold at 60 m below sea level (b.s.l.), which makes an open Esrum/Alnarp valley the lowest threshold between the Baltic Sea basin and the Kattegat strait. Here we present a stratigraphy of Kriegers Flak and discuss the implications for the glacial and palaeoenvironmental history of the southwestern Baltic during MIS 3.

Methods

In this study we use sediment descriptions (provided by the company GEO) of nine geotechnical drill-cores from a wind-turbine project at Kriegers Flak, 30 km south of Trelleborg (Figs 1B, 2). In addition, we performed more

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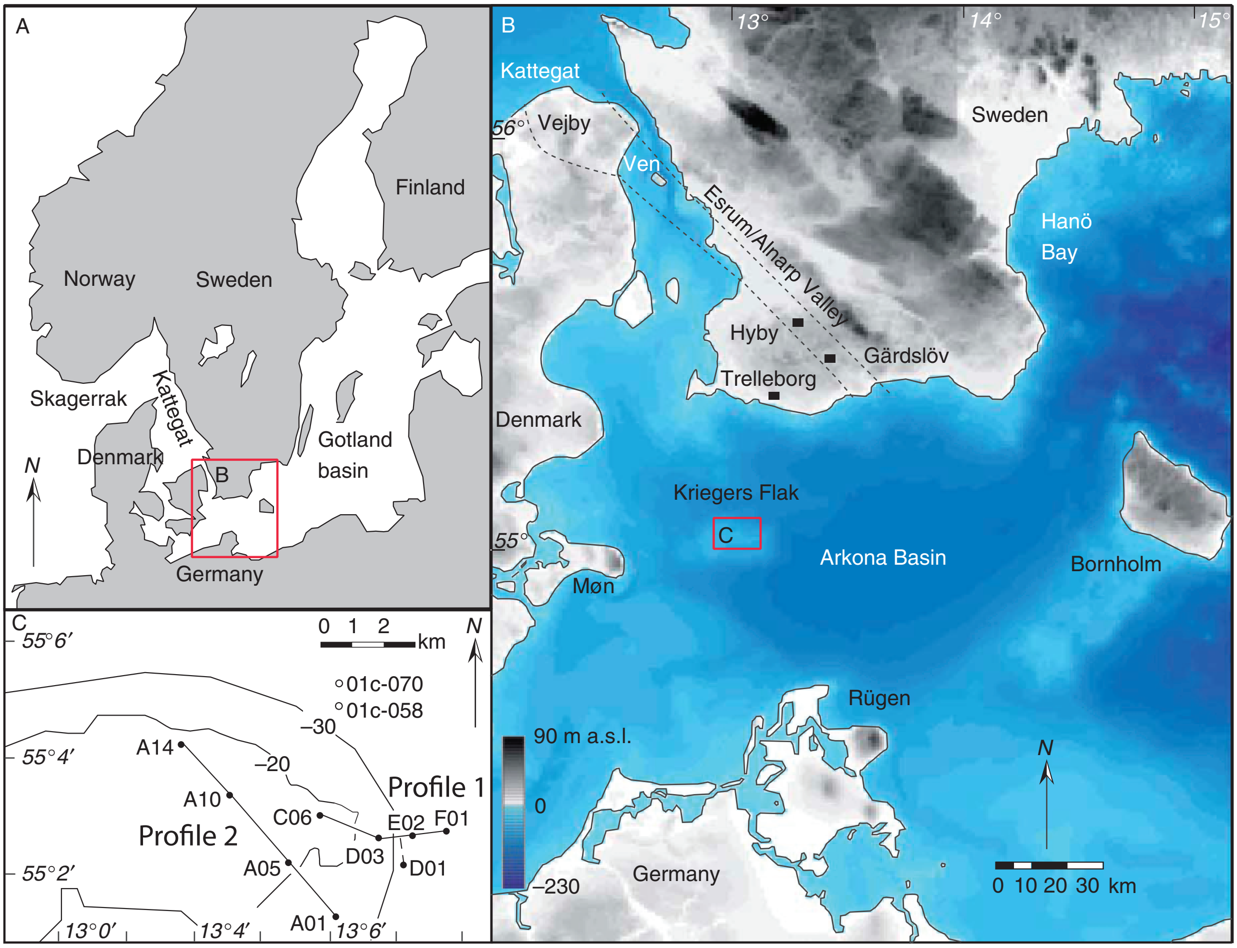

Fig. 1. A. Overview map of the Baltic Sea region. B. Localities mentioned in the text. Bathymetry from Seifert *et al.* (2001). C. Locations of the cores from Kriegers Flak investigated in this study and of the cores from Klingberg (1998).

detailed studies on core E02 (Figs 2, 3) in order to confirm the interpretations made by GEO. Four samples were taken from E02 to search for benthic foraminifera, and another four from core D03 to search for shell fragments. These sediment samples were washed over a 63-μm screen, treated with sodiumdiphosphate ($Na_4P_2O_7$) during sieving to disintegrate sediment aggregates, dried at room temperature and surveyed for their foraminiferal and macrofossil content. Four bulk radiocarbon dates from cores D03, D01 and E02, one radiocarbon date on moss fragments from core C06 and a compilation of published (Esrum/Alnarp valley; Miller 1977) and unpublished (Hanö Bay; Björck & Dennegård 1988 and Björck *et al.* 1990) radiocarbon dates (Table 1) provide a chronological framework. The radiocarbon dates presented here were calibrated according to Fairbanks *et al.* (2005; http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm).

Results

Out of 40 geotechnical drill-cores from Kriegers Flak we chose nine cores from the eastern part because they contain a *c.* 10 m thick sequence consisting mainly of clay beneath a diamict unit (Figs 1C, 2). The sediments in these cores consist of a 3–16 m thick lower diamict unit, which directly overlies the Cretaceous–Paleogene bedrock in most of the cores. Above follows a 2.8–14.5 m thick clay unit, which is overlain by a 1–17 m thick unit consisting of diamict beds inter-layered with sorted sediments. The uppermost sediments consist of a 0.4–7 m thick upward-coarsening sequence with molluscs. The genetic interpretation of the lower and upper diamict units and of the uppermost sorted sediments will be presented elsewhere. Here, we focus on the clay unit with its interstadial sediments.

The interstadial sediments

Description. – The clay unit consists of silty clay, in places interbedded with layers of sand, silt and organic sediments (Figs 2, 3). It has been subdivided into three subunits, A–C.

Subunit A is 2–6 m thick and consists mainly of massive clay, except for the lowermost part, where the clay

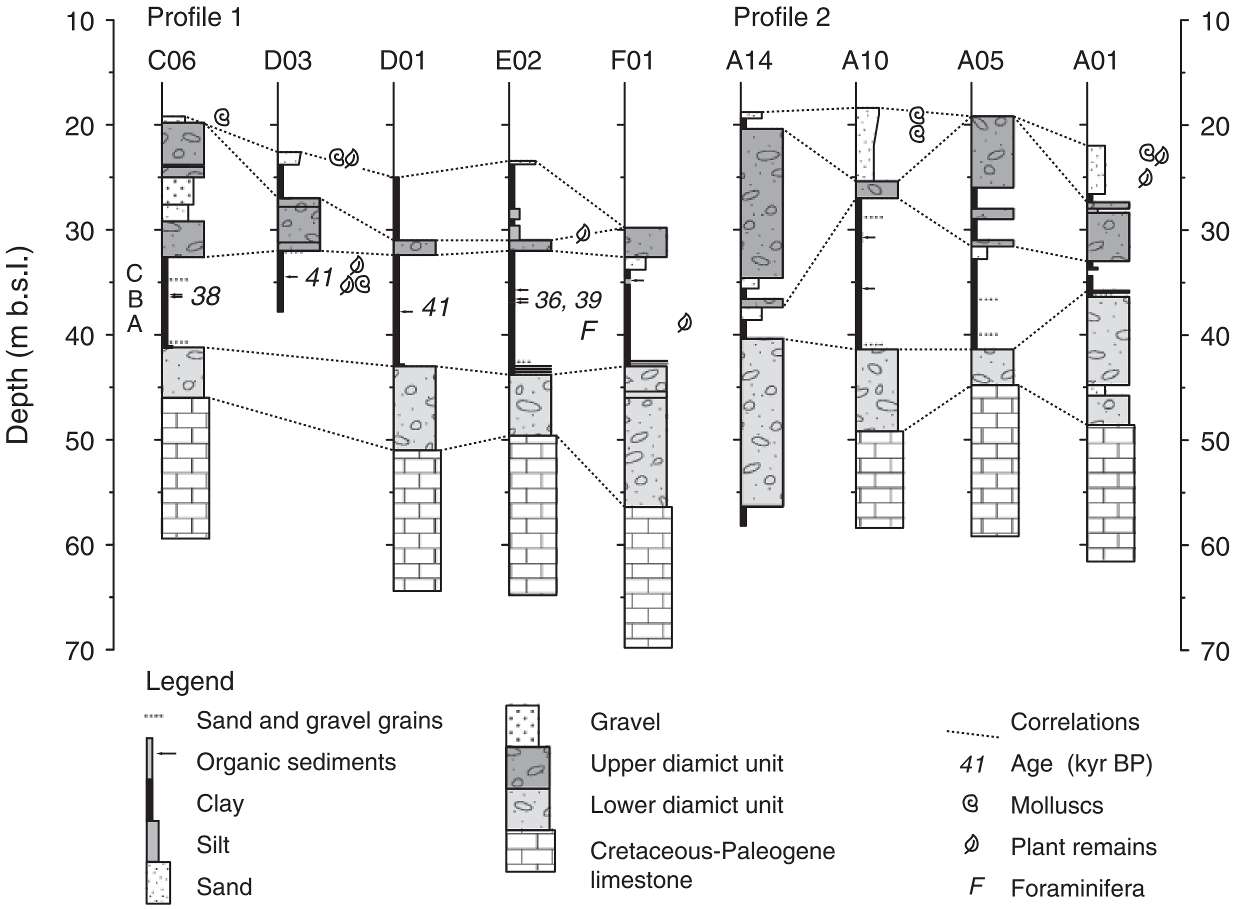

Fig. 2. Lithostratigraphic logs of the sediment cores from Kriegers Flak. Subunits A–C with clays, gyttja and peat were recorded between two diamict units.

contains grains of sand and gravel and is inter-layered with centimetre-thin diamict beds. Well-preserved benthic foraminifera were identified at 40 m b.s.l. in E02, and initial investigations indicate a low-diversity foraminifera fauna.

Subunit B is 0.07–4.5 m thick and consists of clay inter-layered with beds of organic sediments that were identified in the middle parts of five of the investigated cores (A10, C06, D01, E02 and F01) between 30 and 38 m b.s.l. In D01, a 7 cm thick peat layer was dated to *c*. 41 cal. kyr BP, and in C06 moss fragments were dated to 38 cal. kyr BP (Table 1). E02 contains three organic beds consisting of brown, calcareous clay gyttja, and the lowermost beds were radiocarbon-dated to *c*. 39 and 36 cal. kyr BP, respectively (Fig. 3, Table 1). In core D03, subunit B consists of 1.5 m of clay and sandy clay with fragile limnic shell fragments identified as *Sphaerium* sp., *Pisidium* sp., *Valvata piscinalis* and *Lymnaea pereger*. The identifications are, however, uncertain owing to the highly fragmented appearance of these shells. An organic-rich laminae situated above the shell-rich interval at 34.5 m b.s.l. was radiocarbon dated to 41 cal. kyr BP (Fig. 3, Table 1).

Subunit C is the uppermost part of the clay succession and overlies the organic beds of subunit B. It is 2–5 m thick and consists of massive clay, but its uppermost part contains some sand and gravel.

Interpretation. – The clays of subunit A indicate deposition in a low-energy environment and probably also a low organic production. Diamict beds and dispersed grains of sand and gravel in the lower part are interpreted as debris flows and ice-rafted debris, indicating proximity to an ice margin. Benthic foraminifera were not found in the lower part but appear further up. The low diversity of the foraminiferal assemblage suggests brackish conditions during at least parts of the deposition period.

The calcareous clay gyttja of subunit B (in core E02) and the limnic shell fragments (in core D03) reflect deposition in a lacustrine environment, whereas the peat and moss fragments (recovered in cores D01 and C06, respectively), which seem to be contemporaneous with the clay gyttja, point to a terrestrial setting. The preservation of fragile limnic shell fragments in D03 indicates that they have not been redeposited. The

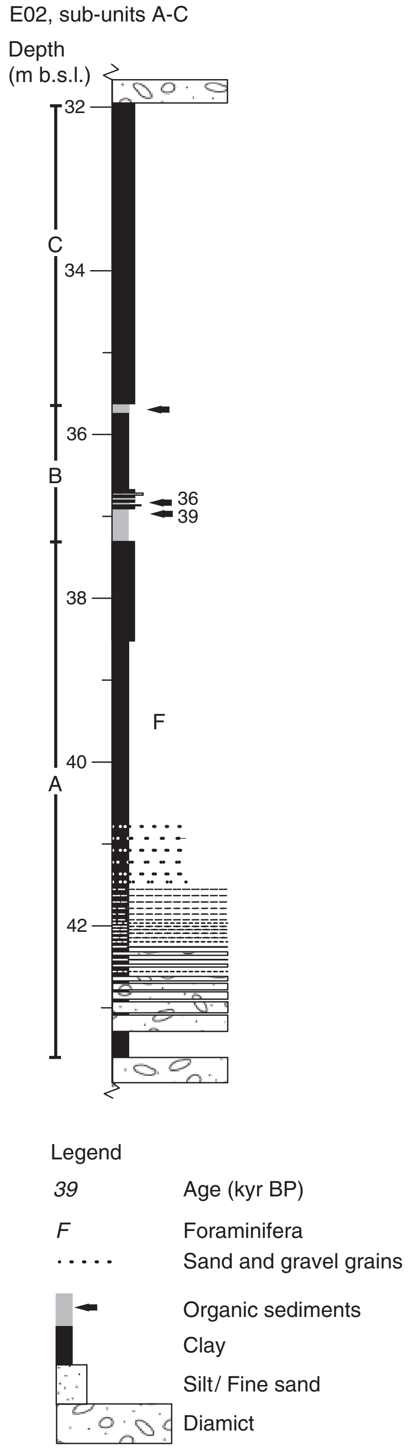

Fig. 3. Detailed lithological log of subunits A–C in core E02.

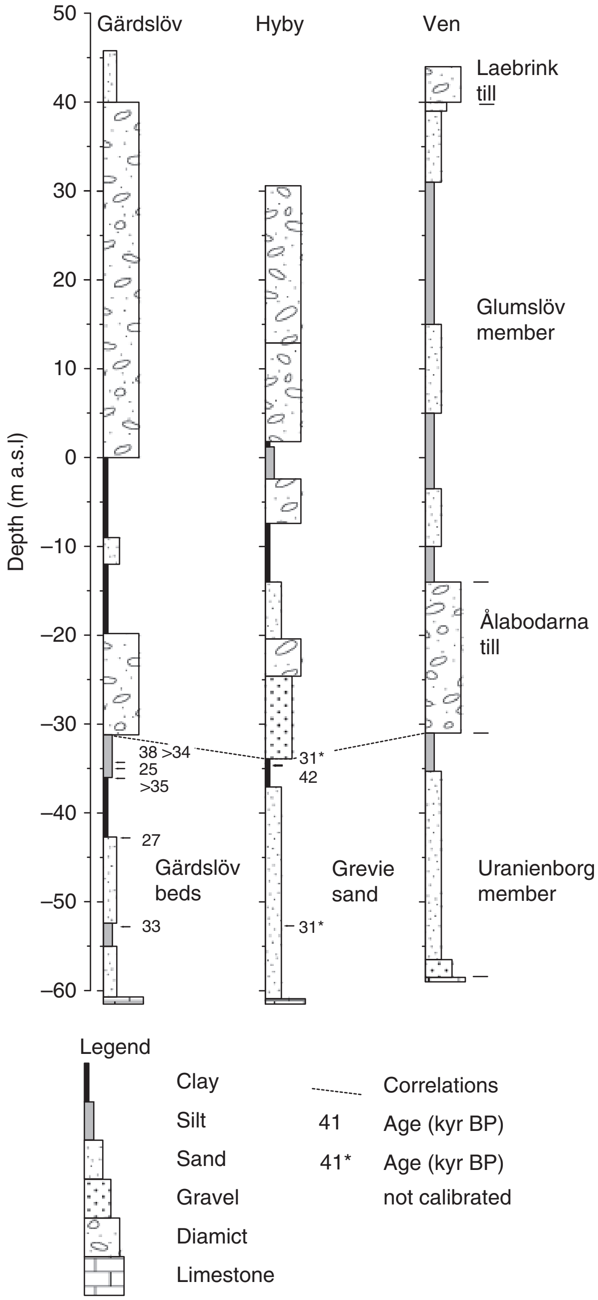

Fig. 4. Lithological logs of the Gärdslöv and Hyby cores (Nilsson 1973; Miller 1977) from the Alnarp Valley and of core site 17 on Ven (Adrielsson 1984).

alternations between organic and inorganic sediments and peat suggest deposition in smaller, local lake basins as opposed to in a larger, glacially influenced basin. This scenario would imply that terrestrial areas, possibly with wetlands and smaller lakes, were uncovered during a falling relative sea level in the Baltic Basin. The radiocarbon dates give an age of 41–36 kyr BP for this subunit.

The clay of subunit C indicates a shift from subaerial conditions with smaller ponds to sedimentation in a deeper basin. The large clasts found in the upper part of subunit C are interpreted as ice-rafted debris deposited by icebergs emanating from an advancing Scandinavian Ice Sheet.

Discussion

The presence of marine-brackish sediments (subunit A) in the Kriegers Flak area, the existence of a wetland with small isolated lake basins around 41–36 cal. kyr

Table 1. Compilation of radiocarbon dates from Kriegers Flak and the Esrum/Alnarp Valley: (1) This study; (2) Miller (1977); (3) Björck *et al.* (1990). Calibrated using Fairbanks *et al.*'s (2005) calibration (http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm).

Borehole	Depth (m b.s.l.)	Latitude	Longitude	Lab no.	Radiocarbon age (yr)	Calibrated age (kyr, ±1σ)	Unit	Reference
Kriegers Flak C06	36.2	55°3′2″	13°7′47″	LuS 8669	32 600±400	38±0.4	Subunit B	1
Kriegers Flak D03	34.5	55°2′39″	13°9′31″	LuS 8670	35 200±600	41±0.6	Subunit B	1
Kriegers Flak D01	37.7	55°2′11″	13°10′15″	LuS 7439	35 250±500	41±0.5	Subunit B	1
Kriegers Flak E02	36.8	55°2′44″	13°10′31″	LuS 8454	30 800±350	36±0.4	Subunit B	1
Kriegers Flak E02	37	55°2′44″	13°10′31″	LuS 7440	33 850±600	39±0.6	Subunit B	1
Hanö Bay H29	60.3	55°39′53″	14°43′63″	Lu 3075	>35 000		Unit ReW	1, 3
Hanö Bay H29	60.4–60.5	55°39′53″	14°43′63″	Lu 3076	>44 000		Unit ReW	1, 3
Hanö Bay H29	60.7	55°39′53″	14°43′63″	Lu 3077	>34 000		Unit ReW	1, 3
Hanö Bay H26+H32	65.9 73.4	55°38′7″ 55°35′38″	14°41′62″ 14°37′96″	Lu 3084	>38 000		Unit D gyttja clay	1, 3
Gärdslöv	34.1–34.5	55°28′	13°25′	St 4946	32 880±1770	38±2	Gärdslöv beds	2
Gärdslöv	34.5–35.0	55°28′	13°25′	St 4274	>34 000		Gärdslöv beds	2
Gärdslöv	34.5–35.0	55°28′	13°25′	St 3158	32 730±2800	38±3	Gärdslöv beds	2
Gärdslöv	34.9–35.2	55°28′	13°25′	St 4273	21 305±3000	25±4	Gärdslöv beds	2
Gärdslöv	36.0–36.2	55°28′	13°25′	St 4272	>35 000		Gärdslöv beds	2
Gärdslöv	42.6–42.9	55°28′	13°25′	St 4938	22 835±1680	27±2	Gärdslöv beds	2
Gärdslöv	52.6–53.0	55°28′	13°25′	St 4271	27 535±5000	33±5	Gärdslöv beds	2
Hyby	34.5–34.8	55°35′	13°16′	St 4961	31 425±5400		Gärdslöv beds	2
Hyby	34.5–35.0	55°35′	13°16′	St 3157	36 995±2865	42±3	Gärdslöv beds	2
Hyby	52.4–53.0	55°35′	13°16′	St 5093	31 380±5880		Gärdslöv beds	2

ago (subunit B), and the deposition of the overlying clay (subunit C) have important implications for the palaeoenvironmental history of the southwestern Baltic during MIS 3. During the Middle Weichselian the Baltic Basin was probably connected to Kattegat via the Esrum/Alnarp valley (Lagerlund 1987; Houmark-Nielsen & Kjær 2003) (Fig. 1B). This valley is currently sediment-filled but has a bedrock threshold at *c.* 60 m b.s.l., which makes it the lowest sill of the Baltic depression. The main sediments in the central and northern parts of the Esrum/Alnarp valley are composed of a fluvial fining-upward sequence referred to as the Grevie sand by Nilsson (1973); this sequence has been correlated with the Gärdslöv beds (Lagerlund 1980) at Gärdslöv (Nilsson 1973) and with the Uranienborg member (Adrielsson 1984) on Ven and Sjælland (Adrielsson 1984; Lagerlund 1987; Houmark-Nielsen 1999; Houmark-Nielsen & Kjær 2003) (Figs 1B, 4). Bulk radiocarbon dates give ages of 31 ^{14}C kyr BP (not calibrated owing to very large uncertainties) and 42 kyr BP for the Grevie sand, and 25 kyr BP to infinite ages for the Gärdslöv beds (Miller 1977) (Table 1), whereas the Uranienborg member in Vejby, north Sjælland, has been OSL-dated to between 32 and 44 kyr BP (Houmark-Nielsen & Kjær 2003). The mixture of arctic and temperate pollen, palynomorphs and plant fragments found in the Grevie sand and Gärdslöv beds (Holst 1911; Ekström 1953; Miller 1977) indicates reworking of previously deposited sediments, which may also explain the old and infinite radiocarbon ages. The youngest ages are, therefore, believed to be the most reliable (cf. Nilsson 1973). This would imply that the oldest sediments presently found in the Esrum/Alnarp valley were deposited during or after the deposition of the organic sediments in subunit B.

The following tentative depositional model for the sediment succession at Kriegers Flak is therefore proposed. The transition from the lower diamict unit to clay with beds of diamict (subunit A) suggests deposition in a basin close to a retreating ice front from where debris flows and icebergs were released. Higher up in the subunit, sand and gravel grains become scarce and eventually disappear, pointing to a further retreat of the ice front. The benthic foraminifera found at 40 m b.s.l. in core E02 indicate occasional brackish influences during the deposition of subunit A. At present, however, we are unable to determine whether brackish conditions prevailed throughout subunit A or whether the brackish interval represents a shorter period. Because no indications of an ice advance have been identified in the clay sequence, we suggest that this marine phase probably occurred after the Ristinge Advance (55–50 kyr BP) (Larsen *et al.* 2009a). The brackish phase identified in subunit A could correspond to sediments from the northeastern part of Kriegers Flak, which indicate boreo-arctic conditions and a brackish environment (Klingberg 1998). Unfortunately, these latter sediments only provided infinite ages (Klingberg 1998), and our correlations therefore remain speculative. A possible correlation may also exist between subunit A and a boreo-arctic, brackish-marine clay identified on Rügen that has tentatively been dated to the Middle Weichselian (Panzig 1997) (Fig. 5), and between subunit A and marine sand in coastal bluffs in western Latvia that has been OSL-dated to 45–43 kyr BP. Because global sea level for the latter half of MIS 3 has been reconstructed at *c.* 80–100 m b.s.l. (Lambeck & Chappell 2001; Siddall *et al.* 2008), our findings of

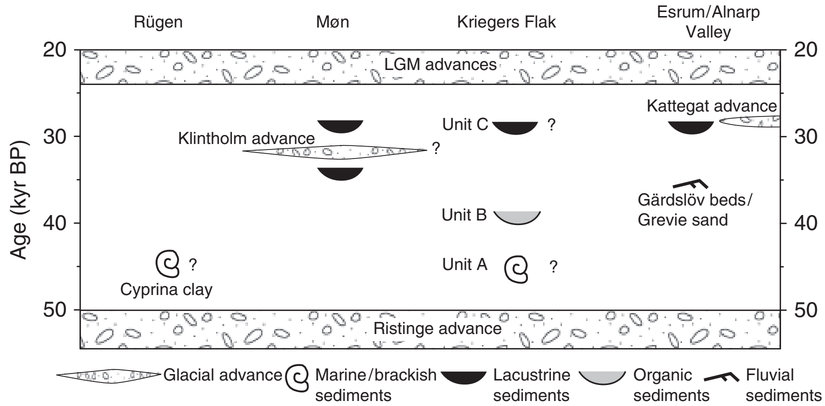

Fig. 5. Suggested correlation between Middle Weichselian stratigraphic events in the southwestern Baltic Basin and the Esrum/Alnarp Valley. Data from Adrielsson (1984), Houmark-Nielsen (1994), Houmark-Nielsen (2008), Houmark-Nielsen & Kjær (2003), Nilsson (1973), Steinich (1992) and Panzig (1997).

brackish clay at 40 m b.s.l. imply a substantial isostatic depression of the southern Baltic Basin. Ongoing and further studies will allow this hypothesis to be tested. At *c*. 41–36 kyr BP a lower relative Baltic Sea level turned parts of Kriegers Flak into a wetland with peat bogs and shallow lakes. Water-level fluctuations either in the Baltic or in these local lakes could explain the repeated periods of organic deposition indicated in subunit B in several of the cores. It is possible that this period with low water levels and large dry-land areas in the southern Baltic Basin is the same as that indicated by old organic sediments in Hanö Bay (Björck *et al.* 1990). It could be speculated that the Baltic Basin was drained by a fluvial system through the Esrum/Alnarp valley, where the Grevie sand, the Gärdslöv beds and the Uranienborg member were deposited (Holst 1911; Nilsson 1973; Adrielsson 1984; Houmark-Nielsen & Kjær 2003) (Fig. 5). However, the poor chronological precision of the dates from the Esrum/Alnarp valley makes detailed correlations difficult at this point.

A transgression is indicated by the renewed deposition of clay on top of subunit B. A likely cause for the transgression is the Kattegat ice advance that flowed from the north into Skagerrak and dammed Kattegat and the Baltic Basin *c*. 29 kyr BP (Lagerlund 1987; Houmark-Nielsen & Kjær 2003; Larsen *et al.* 2009a), which led to the deposition of a fining-upward sequence in the northwestern Esrum/Alnarp valley (Nilsson 1973; Miller 1977; Lagerlund 1987). The Ålabodarna till, which overlies the Uranienborg member on Ven, has been correlated with the Kattegat advance (Adrielsson 1984). This interpretation would indicate the existence of a hiatus between the deposition of the organic sediments at Kriegers Flak *c*. 41–36 kyr BP and the damming of the Kattegat *c*. 29 kyr BP (Fig. 5), although it is difficult to estimate the temporal extent of this assumed hiatus until more dates from subunit B are obtained.

Conclusions

A succession of inorganic and organic sediments and peat was identified between thick till beds in drill cores from Kriegers Flak, southwestern Baltic Sea. The lower clay (subunit A) was deposited in a partly brackish environment following a deglaciation of the southern Baltic Basin. This interval was followed by falling water levels, which led to the formation of wetlands with small isolated lakes where gyttja and peat were deposited *c*. 40 kyr BP (subunit B). Fluctuations of the water level are recorded as shifts between clay, peat and gyttja deposition. The upper clay (subunit C) at Kriegers Flak implies a transgression, probably related to the Kattegat advance *c*. 29 kyr BP. The new data from Kriegers Flak, showing significant changes from brackish to lacustrine and terrestrial environments, have regional implications, as they provide a basic framework for reconstructions of the history of the Baltic Basin during MIS 3. However, further investigations, including better chronological constraints, are needed to confirm the scenario presented here, and to provide a better understanding of the sedimentary environment at Kriegers Flak between *c*. 40 and *c*. 29 kyr BP.

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