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# LUNDQUA Thesis 67

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## **The Weichselian in southern Sweden and southwestern Baltic Sea: glacial stratigraphy, palaeoenvironments and deglaciation chronology**

*Johanna Anjar*

### **Avhandling**

Att med tillstånd från Naturvetenskapliga Fakulteten vid Lunds Universitet för avläggande av filosofie doktorsexamen, offentligen försvaras i Geocentrum IIs föreläsningssal Pangea, Sölvegatan 12, fredagen den 18 januari 2013 kl. 13.15.

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Abstract <p>In this thesis the Weichselian glaciation history of southernmost Sweden and the southwestern Baltic Basin is discussed, with special emphasis on Middle and Late Weichselian ice advances and subsequent deglaciations. The main study area was Kriegers Flak in the southwestern Baltic Sea where pre-Late Weichselian sediments were identified. We suggest that the lowermost till on Kriegers Flak, dated to the Early or Middle Weichselian, was deposited during the Ristinge advance, which implies an age of c. 55-50 ka. Following the deglaciation after this advance, isostatic depression enabled a marine influence in the southern Baltic Basin. During this time Kriegers Flak unit A, with a low-diversity benthic foraminifera fauna indicative of cold water and low salinities, was deposited. This was followed by a forced regression on Kriegers Flak, probably caused by a combination of isostatic rebound and a falling global sea level. Between 42 and 36 cal. ka BP wetlands and shallow lakes existed on Kriegers Flak (unit B). Macrofossil and pollen from this unit suggest tundra-like, or forest tundra-like vegetation, possibly with birch and pine in sheltered locations. From 28.5 to 26 ka, a thick succession of glaciolacustrine clay, unit C, was deposited at Kriegers Flak indicating a damming the Baltic Basin by an ice advance into Kattegat.</p> <p>The upper part of the stratigraphy has been reconstructed from published and new terrestrial sections in Skåne. Here three tills are identified. The lowermost, the Allarp Till, was deposited after the damming of the Baltic Basin at c. 30 ka. It was followed, after a deglaciation, by deposition of the Dalby Till, representing the Last Glacial Maximum advances including an early advance from southeast, the main advance from northeast and the first Young Baltic advances from southeast. The uppermost till, the Lund Till was deposited by the Öresund advance after a deglaciation.</p> <p>The deglaciation of southern Sweden was dated using cosmogenic nuclide surface exposure dating. We suggest that central Skåne was deglaciated between 17 and 16 ka. The deglaciation in southern Småland was dated to 15.6±0.8 and 16.6±0.9 ka, while a site in northern Småland was dated to 14.6±1.0 ka. Our northernmost site, situated only 25 km south of the Younger Dryas Moraine, was dated to c. 13.8±0.8 ka while cosmogenic surface exposure ages from Gotland suggest a deglaciation before 13.0±0.8 ka.</p>		
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# **The Weichselian in southern Sweden and southwestern Baltic Sea: glacial stratigraphy, palaeoenvironments and deglaciation chronology**

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22362 Lund, Sweden

This thesis is based on four papers, listed below as Paper I-IV. Paper I is reprinted with the permission of John Wiley and Sons. Paper II is reprinted with the permission of Elsevier. Paper III and IV have been submitted to the journal indicated and are under consideration.

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

Paper II: Anjar, J., Adrielsson, L., Bennike, O., Björck, S., Filipsson, H. L., Groeneveld, J., Knudsen, K. L., Larsen, N. K. and Möller, P., 2012: Palaeoenvironments in the southern Baltic Sea Basin during Marine Isotope Stage 3: a multi-proxy reconstruction. *Quaternary Science Reviews* 34, 81-92.

Paper III: Anjar, J., Adrielsson, L., Larsen, N. K., Möller, P., Barth, K. Weichselian glaciation history of the Fennoscandian ice sheet in southern Sweden and the southwestern Baltic Basin. Manuscript submitted to *Boreas*.

Paper IV: Anjar, J., Larsen, N. K., Håkansson, L., Möller, P., Linge, H., Fabel, D. and Xu, S. A  $^{10}\text{Be}$  based reconstruction of the Fennoscandian ice sheet's deglaciation in southern Sweden. Manuscript submitted to *Boreas*.



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## 1. Introduction

The last glacial period (the Weichselian, 115-11.7 ka) is characterized by major glaciations on the northern hemisphere. By studying the traces of these past ice sheets we get a unique opportunity to study the dynamics of an ice sheet over large timescales, such as an ice age cycle, and during highly variable climate conditions. However, the poor preservation of pre-Late Weichselian sediments and the rarity of dateable material often make it challenging to reconstruct the glacial history and palaeoenvironment.

By combining detailed studies of key sites, where the palaeoenvironments can be reconstructed and well dated, and more regional studies showing the spatial variations, the glacial history of a region can be reconstructed. In this project the Middle Weichselian history of the Baltic Basin was reconstructed from sediment cores from Kriegers Flak in the southwestern Baltic Sea. Fieldwork at terrestrial outcrops between Vellinge and Trelleborg in southernmost Skåne and a review of published stratigraphies from the region gave a better understanding of the Late Weichselian succession and enabled a regional correlation. In addition, a new deglaciation chronology based on cosmogenic surface exposure dating is presented for southern Sweden (Fig. 1).

The studies included in this thesis thus provide a broad effort to reconstruct the Weichselian glaciation history of southernmost Sweden and the southwestern Baltic Basin, with special emphasis on Middle and Late Weichselian ice advances and subsequent deglaciations.

The project has had three focus areas:

1. The main study area was Kriegers Flak in the southwestern Baltic Sea where the discovery of Middle Weichselian sediments made it possible to interpret and date the palaeoenvironmental history in the southwestern Baltic Basin (Paper I and II).
2. In the second part of the project the stratigraphy on Kriegers Flak was tied to the land-based stratigraphy by comparing the stratigraphy from Kriegers Flak with localities in southernmost Sweden (Paper III).

3. Finally,  $^{10}\text{Be}$  cosmogenic surface exposure ages from Skåne and southeast Sweden were used to establish an independent deglaciation chronology, which was compared to other deglaciation chronologies from the region (Paper IV).

## 2. Study areas

During the Weichselian the Fennoscandian ice sheet (FIS) repeatedly advanced from the Scandinavian mountain range. Southern Sweden and the southwestern Baltic Basin are situated in the southern part of the area covered by the ice sheet and was thus only glaciated during the more extensive Weichselian glaciations and ice-free during long periods in-between. In this study the focus has been on Kriegers Flak in the southwestern Baltic Sea and Vellinge-Trelleborg in southernmost Skåne.

### 2.1 Kriegers Flak

Kriegers Flak is situated in the southwestern Baltic Sea, approximately 30 km south of Trelleborg and thus relatively close to the inlets of the Baltic Basin (the Danish Straits). This makes it a sensitive area for any marine influence through the Danish straits. It is also situated at roughly equal distance from Trelleborg in southern Skåne, the island of Møn in southeast Denmark and Rügen in north Germany which makes it geographically well suited for correlations between the Swedish, Danish and German glacial records (Fig. 1).

The shallow water depth, approximately 20 m, has made it an interesting area for sea based wind power plants and during the surveys for such a project 40 sediment cores, 15-40 m long, were retrieved and a dense grid of seismic lines were acquired. A subset of this material has been studied in this thesis.

### 2.2 Vellinge-Trelleborg

As the uppermost part of the glacial stratigraphy was poorly preserved in our Kriegers Flak material the glacial stratigraphy in terrestrial sections in the Vellinge-Trelleborg area was investigated. This area is situated only 35-45 km north of Kriegers Flak, which makes it one of the closest land areas to

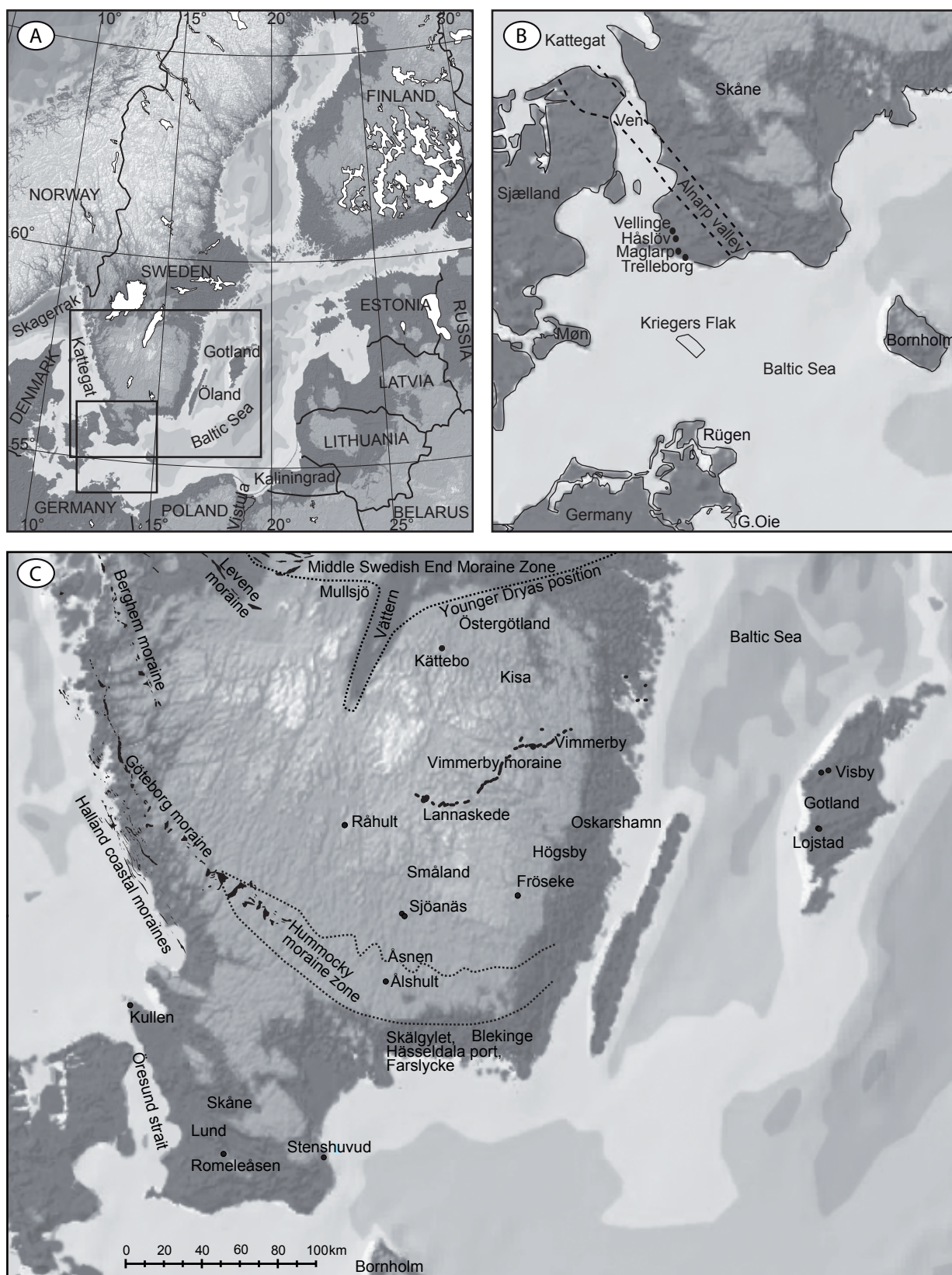


Figure 1. A: Overview map showing the Baltic Sea and surrounding regions. B: Skåne and the southwestern Baltic Sea with studied sites indicated. C: South Sweden. Background map modified from GRID-Warsaw ©European Environment Agency.

Kriegers Flak (Fig. 1). The bedrock consists of limestone, which is covered by 5-40 m of Quaternary deposits (Daniel 1977). Open sections are generally rare in this region but during the widening of the E6 highway several sections were temporarily opened. Three of those, Vellinge, Håslöv and Maglarp have been investigated.

Northeast of the studied area the 5-10 km wide, sediment-filled, Alnarp valley runs through southwest Skåne and continues across the Öresund strait and into northern Sjælland, there named the Esrum Valley (Houmark-Nielsen 1999). This valley is a key locality for the glacial stratigraphy in Skåne and up to 65 m thick successions of glacial deposits have been found on top of c. 30 m of valley infill sediments (Nilsson 1973).

### 3. Methods

#### 3.1 Sedimentology

The work presented in this thesis has largely been based on the study of sediment cores from Kriegers Flak (Fig. 2). Twelve cores, out of a total set of 40 cores, were chosen for detailed studies. These were photographed and described based on lithological properties and sampled for dating, fine gravel analysis and foraminiferal, macrofossil and pollen analyses. As the cores had previously been used for geotechnical investigations substantial parts were missing or poorly preserved, especially in the upper part but the geotechnical descriptions could be used to reconstruct these parts. Comparisons between the geotechnical descriptions and our own observations generally showed a good agreement for the lithological properties (grain sizes, colour, carbonate and limestone content).

In addition to the investigations of the Kriegers Flak cores fieldwork was carried out in sediment sections between Vellinge and Trelleborg in southernmost Skåne. The aim of these investigations was to complement the upper part of the glacial stratigraphy in the region, and to aid correlations between Kriegers Flak and Skåne. Three new sections, Vellinge (investigated by Kilian Barth as part of his master's thesis), Håslöv and Maglarp were investigated. These were described and unit boundaries and structures were mapped in scale

1:20. Samples were taken for OSL dating and fine-gravel analysis at all three sites. Clast fabric measurements were made in Vellinge and Maglarp, where 28-30 elongated clasts (a-axis/b-axis >1.5 and a-axis between 6 and 60 mm) were measured in each sample.

##### 3.1.1 Fine gravel analysis

Fine gravel analysis can, ideally, give information about ice directions and about interactions between the ice sheet and the local bedrock and enable correlations between different sites (Ehlers 1979; Kjær *et al.* 2003). In this study fine gravel samples were obtained from the diamicts on Kriegers Flak and in the Vellinge-Trelleborg sections. The samples were sieved and clasts in the fractions 2.8-4 mm and 4-5.6 mm were analysed and subdivided into ten categories: crystalline rocks, quartz, sandstones, fine sandstones, siltstones and shales, flint, Palaeozoic limestone, Cretaceous and Paleogene limestones, soft chalk, and unidentified clasts.

##### 3.1.2 Seismic profiles

By comparing sediment cores, which can give very detailed information (but which is essentially point data) with seismic surveys, which reveals the 2D structure of the sedimentary units, a better understanding of the sediment geometry is possible. On Kriegers Flak seismic profiles have been made both in connections with the survey of the area by Vattenfall and by the Swedish Geological Survey. These seismic profiles were compared with the sediment cores from the area and used to correlate the units. As no sound velocities had been measured on the cores we used assumed velocities of 1480 m/s for the water, 1700 m/s for the Quaternary sediments and 2486 m/s for the limestone taken from Perini *et al.* (1996) and Årebäck (2000).

#### 3.2 Palaeoenvironmental reconstructions

##### 3.2.1 Foraminiferal analyses

By studying foraminiferal assemblages important environmental factors, such as bottom-water temperature, salinity and water depth, can be

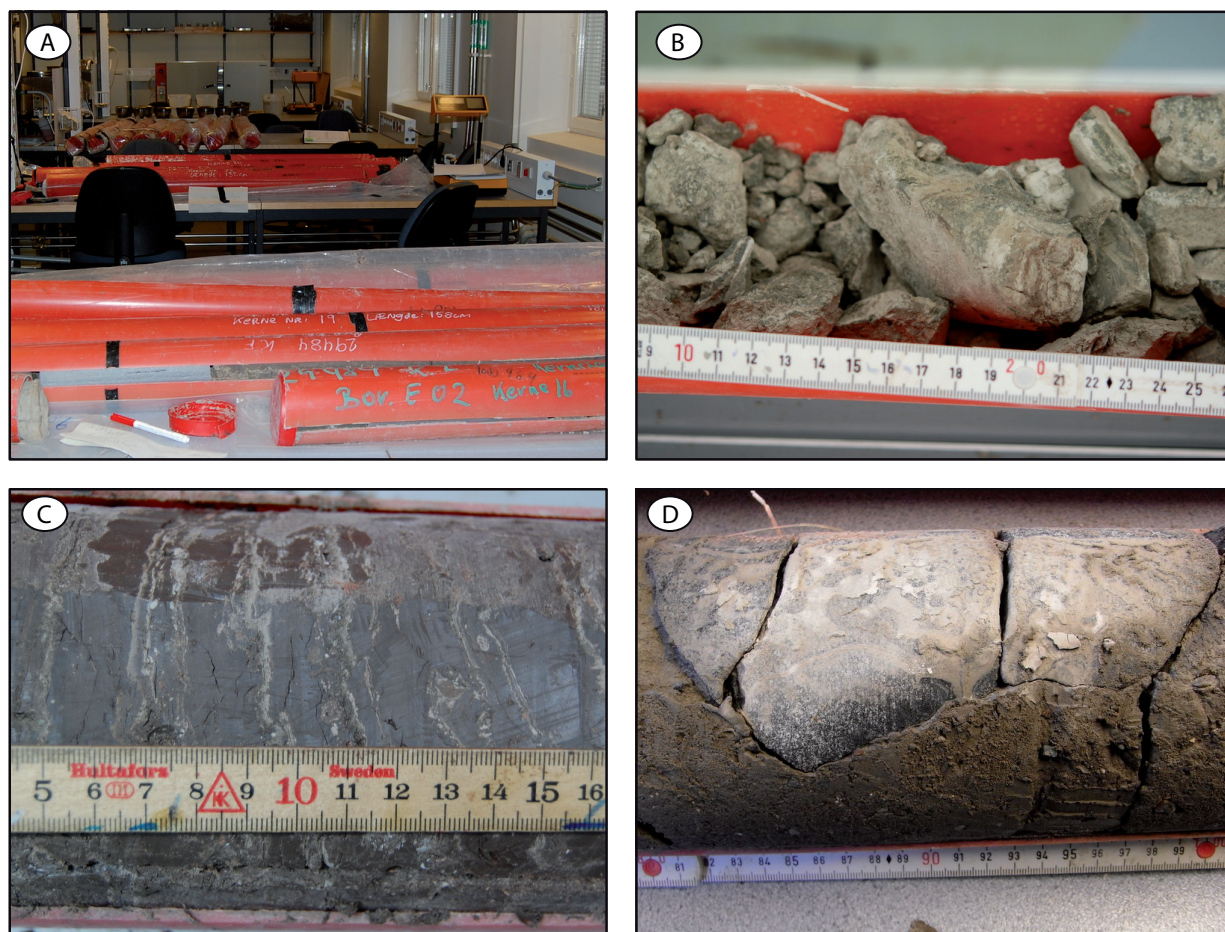


Figure 2. A: Core sections from one core at the time it was described and sampled at Lund University. The quality of the cores, where preserved, ranged from very poor (B) to excellent (C and D).

constrained. In the Kriegers Flak cores samples were collected for benthic foraminiferal analyses in Kriegers Flak unit A. A total of 19 samples covering the zones with abundant benthic foraminifera were chosen for faunal analyses. These samples were dry sieved on 0.1 and 1 mm sieves and the foraminifera in the 0.1-1mm fraction were subsequently concentrated by floatation in a high-density fluid (tetrachloroethylene;  $\rho = 1.62 \text{ g/cm}^3$ ). Where possible a minimum of 300 specimens per sample was identified to species level.

Foraminiferal tests (shells) were also picked for stable oxygen and carbon isotope analyses in core C06 and E02.  $\delta^{18}\text{O}_c$  varies as a function of the water temperature and of the isotopic composition of the water (and thereby of salinity).  $\delta^{13}\text{C}_c$  can be used as a proxy for water circulation and organic input and thereby also to primary productivity. In the lower foraminifera zone *Haynesina orbiculare* (Brady) and *Elphidium excavatum* f. *clavata* Cushman were used for the isotope analyses while

*E. excavatum* f. *selseyensis* (Heron-Allen & Earland) and *E. excavatum* f. *clavata* were analysed in the upper part. The samples were measured at Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, using a Finnigan Mat 251 mass spectrometer.

In addition the Mg/Ca ratio in foraminiferal tests, which is usually regarded as a proxy for temperature, was measured. These samples were analysed at the Department of Geosciences, University of Bremen using an ICP-OES [Perkin Elmer Optima 3300RL with autosampler and ultrasonic nebulizer U-5000 AT (Cetac Technologies Inc.)].

### 3.2.2 Macrofossil and pollen analysis

The macrofossil assemblage can be used to reconstruct the local flora and fauna and thus to interpret local climatic and other palaeo-environmental factors. A total of 25 samples from

unit B in Kriegers Flak core C06 and unit B and C in core D03 were sampled for macrofossils. These samples were wet sieved on a series of 0.4, 0.2 and 0.1 mm sieves and the macrofossils in the residue were studied in a dissecting microscope. As a complement two pollen samples, which add information about the regional vegetation, were taken in a bed of calcareous clay gyttja in unit B in core E02. More than 300 pollen grains were identified in both samples.

### 3.3 Chronological methods

#### 3.3.1 Radiocarbon dating

Radiocarbon dating was performed on organic material; macrofossils, bulk material and foraminiferal tests (200-610 tests/sample), and measured at Lund University Radiocarbon Dating Laboratory, Sweden. In addition two foraminifera samples, consisting of 1000 and 1200 tests respectively, were measured at the <sup>14</sup>CHRONO Centre, Queens University, UK. Ages younger than 45 <sup>14</sup>C ka BP were calibrated using OxCal v.4 and the IntCal09 dataset (Bronk Ramsey 2009; Reimer *et al.* 2009) except in Paper I where the calibration curve from Fairbanks *et al.* (2005) was used.

#### 3.3.2 Optically stimulated luminescence dating

Optically stimulated luminescence (OSL) dating has been extensively used on glacially associated sediments where suitable material for radiocarbon dating is rare. In this study eight samples for OSL dating were taken in the Kriegers Flak cores. Core sections for sampling were chosen primarily considering the potential for light exposure during deposition, representation of all interstadial units, and preservation of the core and, secondarily considering grain size (favouring core section with a higher sand content), and maximizing distance to unit boundaries. As the cores had been subject to light exposure only the centre of the core was used for dating.

OSL samples were also taken during the fieldwork along the E6-highway. Here samples were taken by hammering sample tubes into sandy units

in vertical or near vertical sediment sections. The samples were sent to Sheffield Centre for International Drylands Research for dating.

#### 3.3.3 Cosmogenic surface exposure dating

Cosmogenic surface exposure dating enables a direct dating of a landform or sediment surface and can thus, e.g., be used to directly date the deglaciation of an area, while radiocarbon and OSL ages from associated sediments normally only provide maximum or, more commonly, minimum ages for the deglaciation. 23 samples for cosmogenic surface exposure dating on boulders and bedrock were therefore taken in ten localities in southern and southeastern Sweden. By measuring the concentration of cosmogenic nuclides, produced by the exposure of a rock surface to high-energy cosmic ray particles, the duration of subaerial exposure can be estimated (Lal & Peters 1967; Gosse & Phillips 2001; Ivy-Ochs & Kober 2008).

## 4. Summary of papers

This thesis includes the work of several researchers who all made valuable contributions to the articles on which they are co-authors. Specific author contributions for each article are indicated in Table 1.

### 4.1 Appendix I

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.

The aim of this article was to introduce the stratigraphy of the interstadial sediments on Kriegers Flak for the first time and provide a framework for the early history of the Baltic Basin. Based on existing geotechnical descriptions of nine sediment cores and lithological observations and samples from four cores, an interstadial unit, subdivided into three subunits, was identified between two diamict successions. The lowermost subunit consists of clay. The benthic foraminiferal fauna indicate a brackish influence, at least periodically, while diamict beds in the lower part

Table 1. Author contributions.

	Paper I	Paper II	Paper III	Paper IV
Writing*	Anjar	Anjar Bennike Knudsen Filipsson Groeneveld	Anjar Adrielsso Larsen	Anjar Linge
Fieldwork	-	-	Anjar Barth Adrielsso Larsen Möller	Larsen Håkansson Linge Möller
Sediment descriptions	Anjar	Anjar	Anjar	-
Subsampling	Anjar	Anjar	Anjar Barth	-
Macrofossil identification	Funder	Bennike	-	-
Pollen	-	Björck	-	-
Foraminifera fauna	Knudsen Filipsson	Knudsen	-	-
Mg/Ca	-	Groeneveld	-	-
Cosmogenic surface exposure dating	-	-	-	Linge Fabel Håkansson Xu
Fine gravel analysis	-	-	Adrielsso Anjar Barth	-
Data interpretation*	Anjar Larsen Björck	Anjar Larsen Knudsen Bennike Filipsson Björck	Anjar Adrielsso Larsen	Anjar Larsen Linge

\*All authors gave valuable contributions to the discussions and data interpretation and commented on the manuscripts but only the major contributions are indicated in the table.

indicate a nearby ice sheet. In the middle part of the succession a heterogeneous unit with alternating beds of minerogenic sediments, peat and gyttja, was identified, indicating deposition in wetlands and shallow lakes. Radiocarbon dates gave ages ranging from 31–35<sup>14</sup>C ka BP. (36–41 cal. ka BP) implying that the water depth in the southwestern Baltic Basin was at least 40 m lower during this time. In the uppermost unit renewed clay deposition indicate a transgression of the area, perhaps caused by a damming of the Baltic Basin by an ice advance into Kattegat from southern Norway.

## 4.2 Appendix II

Anjar, J., Adrielsson, L., Bennike, O., Björck, S., Filipsson, H. L., Groeneveld, J., Knudsen, K. L., Larsen, N. K., Möller, P., 2012: *Palaeoenvironments in the southern Baltic Sea Basin during Marine Isotope Stage 3: a multi-proxy reconstruction*. *Quaternary Science Reviews* 34, 81–92.

In the second article a multi-proxy study of the interstadial sediments in three sediment cores from Kriegers Flak was presented. The interstadial succession was subdivided into three units, A–C (Fig.3; corresponding to subunits A–C in Anjar *et al.* 2010). In the lowermost unit, A, a deglaciation sequence, gradually transforming into brackish-water clay was identified. A benthic foraminiferal fauna was identified in two zones, subdivided by a zone with few or no foraminifera. The low diversity foraminiferal fauna, dominated by species tolerant to low temperatures and salinities, together with measurements on stable oxygen isotopes and Mg/Ca ratios on the foraminiferal tests, all indicate low temperatures and salinities during the deposition of unit A. Two OSL samples gave ages of 71.8±4.4 and 86.4±5.7 ka respectively while radiocarbon samples gave non-finite ages of >55 ka supporting deposition after an Early or Middle Weichselian glacial advance. Unit A was followed, after a hiatus, by unit B, consisting of alternating beds of minerogenic (clay, silt and sand) and organic sediments (peat and gyttja). Macrofossil and pollen analyses indicated deposition in shallow lakes and wetlands in a region characterized by a tree-less open tundra environment, possibly with birch and

pine in sheltered positions. This unit was radiocarbon dated to 42–36 cal. ka BP, while two OSL samples gave ages of 38.5±2.6 and 39.0±2.5 ka. The uppermost interstadial unit, C, separated from unit B by a hiatus, consists of reworked clay. Two OSL samples gave ages of 28.5±1.8 and 26.0±1.7, while radiocarbon ages of 34.1 and 35.1 cal. ka BP probably represent reworked material. Unit C was deposited after a transgression over Kriegers Flak, most likely during the Kattegat advance when an ice advance from southern Norway dammed Kattegat and thereby the Baltic Basin. This study provides for the first time a well dated palaeoenvironmental reconstruction of *in situ* MIS 3 sediments from the Baltic Basin.

## 4.3 Appendix III

Anjar, J., Adrielsson, L., Larsen, N. K., Möller, P., Barth, K. *Weichselian glaciation history of the Fennoscandian ice sheet in southern Sweden and the southwestern Baltic Basin*. Manuscript submitted to *Boreas*.

In the third article the complete Quaternary stratigraphy on Kriegers Flak was described for the first time and correlated with the terrestrial stratigraphies in new sections in southern Skåne and with previously published stratigraphies from Skåne and eastern Denmark. Four Weichselian advances were identified. The oldest was only identified on Kriegers Flak where it was dated to the Early or Middle Weichselian. It was tentatively correlated to the Ristinge advance previously identified in Denmark, there dated to 55–50 ka and 50±4 ka. It is overlain by interstadial unit A, B and C, previously discussed in Paper I and II. The uppermost part of the Kriegers Flak cores is poorly preserved and the upper part of the stratigraphy was instead inferred from terrestrial records from south Skåne. Here the Allarp Till, deposited by an ice advance through the Baltic Basin, can be found in coastal areas. It overlies lacustrine sediments in the Alnarp valley and we therefore suggest that it was deposited after the damming of the Baltic Basin at c. 30 ka. It is followed, after a deglaciation, by two more till units, the Dalby Till and the Lund Till, deposited during the LGM advance and the Young

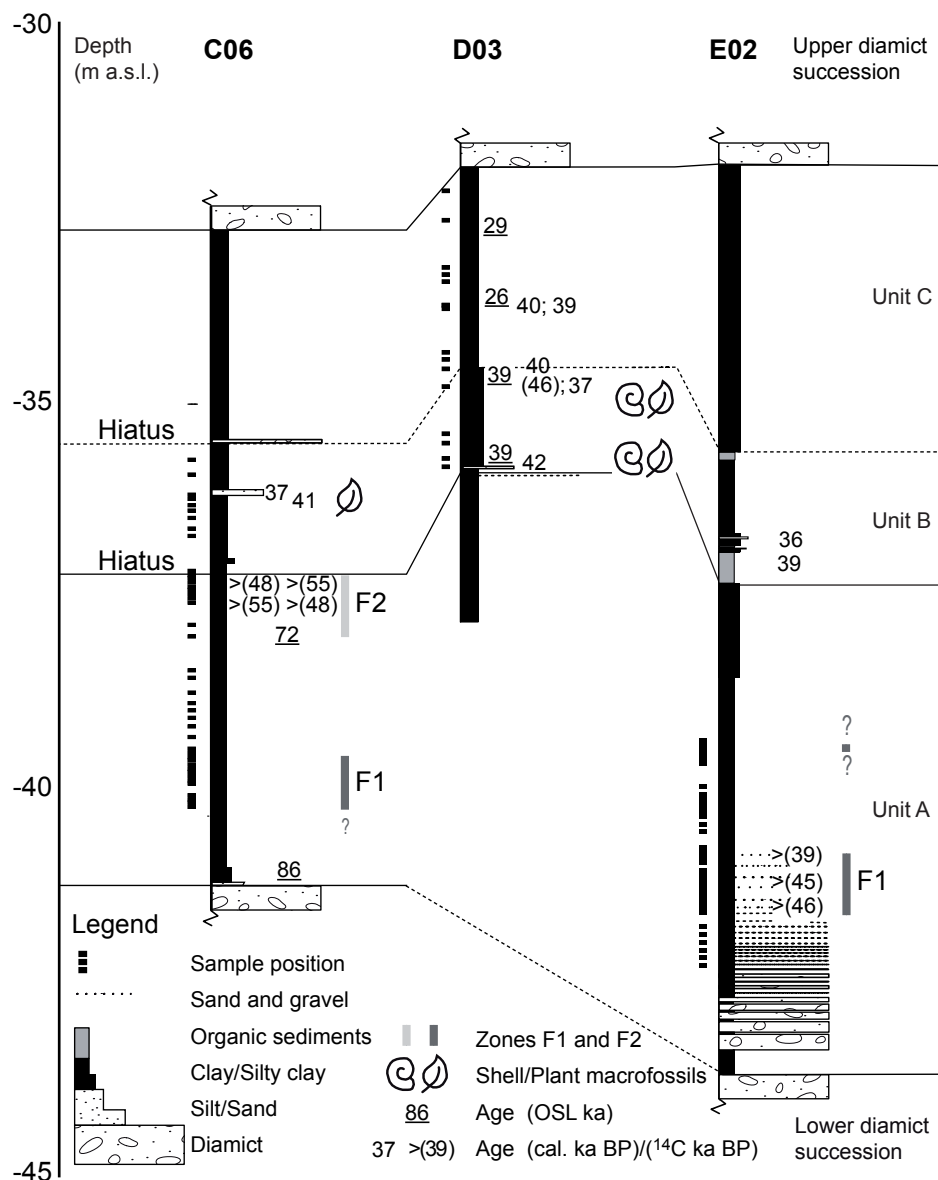


Figure 3. Detailed lithological logs for interstadial units A-C on Kriegers Flak. See paper II for further details.

Baltic advances. The two tills observed in our sections between Vellinge and Trelleborg likely correlate with these two tills but the small differences in clast provenance in southernmost Skåne and the problematic OSL ages on associated sediments, ranging from 79.0 to 15.4 ka, make secure correlations difficult.

#### 4.4 Appendix IV

Anjar, J., Larsen, N. K., Håkansson, L., Möller, P., Linge, H., Fabel, D. and Xu, S. A  $^{10}\text{Be}$  based reconstruction of the Fennoscandian ice sheet's deglaciation in southern Sweden. Manuscript submitted to *Boreas*.

In the fourth article the deglaciation of southern Sweden was dated using cosmogenic surface exposure dating. This method has the advantage, at least during ideal conditions, of dating the actual glacial sediment or landform rather than associated sediments, which generally only provide maximum or minimum ages. By using the same methods as had previously been used on the Swedish west coast the results were directly comparable. Based on a total of 23 cosmogenic surface exposure ages from ten localities as well as a review and recalibration of previously published deglaciation ages we could present an updated deglaciation chronology for south Sweden. For Skåne we suggest a deglaciation of the Kullen Peninsula in northwestern Skåne at

some point between  $17.9 \pm 0.4$  cal. ka BP and  $16.8 \pm 1.0$  ka while central Skåne was deglaciated c. 17-16 ka. Further north the ages become increasingly younger. In southern Småland two localities gave ages ranging from  $15.2 \pm 0.8$  to  $16.9 \pm 0.9$  ka ( $n=5$ ). Our third locality in the region gave ages ranging from  $10.2 \pm 0.5$  to  $18.4 \pm 1.6$  ( $n=3$ ), thus providing little information on the deglaciation age. Råhult in central Småland was dated to  $14.5 \pm 0.8$  ( $n=3$ ) and Kättebo in north Småland to  $13.8 \pm 0.8$  ( $n=2$ ). For central Gotland, situated beneath the highest shoreline, we suggest a minimum age of deglaciation of 13.0 ka.

## 5. Synthesis

### 5.1 Early and Middle Weichselian 115-25 ka

The Weichselian glaciation in Scandinavia began c. 115 ka, but sediments from the early part are rare in southern Scandinavia. At Mommark in south Denmark a transition from marine to lacustrine conditions was observed close to the boundary between the Eemian and the Weichselian (Kristensen & Knudsen 2006) and in Vendsyssel, north Denmark, a significant drop in relative sea level was identified at the same time (Knudsen *et al.* 2009). Marine conditions prevailed, however, in Vendsyssel until c. 65-60 ka when the Sundsøre advance advanced into northern Denmark (Knudsen *et al.* 2009; Larsen *et al.* 2009a).

During the Marine Isotope Stage 3 (MIS 3, 60-25 ka) three ice advances reached as far south as Denmark. The first of them, the Ristinge advance, which advanced through the Baltic Basin and into Denmark from the east, has been dated to  $50 \pm 4$  ka in southern Denmark (Houmark-Nielsen 2010) and to 55-50 ka in northern Denmark (Larsen *et al.* 2009a). It was followed at  $32 \pm 4$  ka by the Klintholm advance, which also advanced into Denmark through the Baltic Basin (Houmark-Nielsen 2010). A third advance, the Kattegat advance, advanced from Norway and dammed the Norwegian Channel and thereby the Baltic Basin at c. 30 ka and reached northern Denmark and northern Skåne between 29 and 27 ka (Fig. 4; Larsen *et al.* 2009a, b).

These more extensive glaciations were interrupted

by periods with a very restricted or possibly completely absent FIS. Ice-free intervals attributed to MIS 3 have been identified in Finland (Helmens *et al.* 2000; 2007b; Helmens & Engels 2010), northern Sweden (Hättestrand & Robertsson 2010), central Sweden (Alexanderson *et al.* 2010; Wohlfarth 2010; Möller *et al.* 2012) and coastal Norway (Mangerud *et al.* 2010). In northeast Finland temperature reconstructions indicate July mean temperatures close to present day temperatures in northeast Finland during the early MIS 3 (Helmens *et al.* 2007a; Engels *et al.* 2008; Bos *et al.* 2009).

In the southern Baltic Sea the Kriegers Flak cores provide a unique insight into the MIS 3 development of the Baltic Basin. Here the lowermost till was dated to the Early or Middle Weichselian and is inferred to have been deposited during the Ristinge advance. It was followed by a deglaciation sequence, which gradually turned into clay deposited in a brackish basin. The relatively low global sea level during MIS 3 (Chappell *et al.* 1996; Cutler *et al.* 2003; Peltier & Fairbanks 2006; Siddall *et al.* 2008) means that a substantial glacial isostatic subsidence of the southern Baltic after the Ristinge advance is necessary to enable a marine influence in the Baltic Basin. The low-diversity, benthic foraminiferal fauna which established here indicate deposition in a brackish environment (Klingberg 1998; Anjar *et al.* 2012). An upward decrease in salinity in unit A is inferred from the change in faunal composition and  $\delta^{18}\text{O}$ . This could be a result of either increased freshwater input or decreased marine inflow. A reduced marine influence is also expected because of the isostatic rebound following the Ristinge advance and the resulting shallowing of the sill area (Anjar *et al.* 2012).

Marine sediments have been identified at several locations around the German Baltic Sea coast, but the uncertain biostratigraphy and lack of reliable dates make it difficult to correlate with any of these. At Greifswalder Oie, glacially dislocated brackish-marine clay has been attributed to the Early or Middle Weichselian by Obst and Ansorge (2010) and at Kleiner Klüsser radiocarbon dating of marine sediments gave ages of 36 and 29  $^{14}\text{C}$  ka BP (Steinich 1992; Panzig 1997), but the stratigraphic position of these sediments is still uncertain (Ludwig 2006).

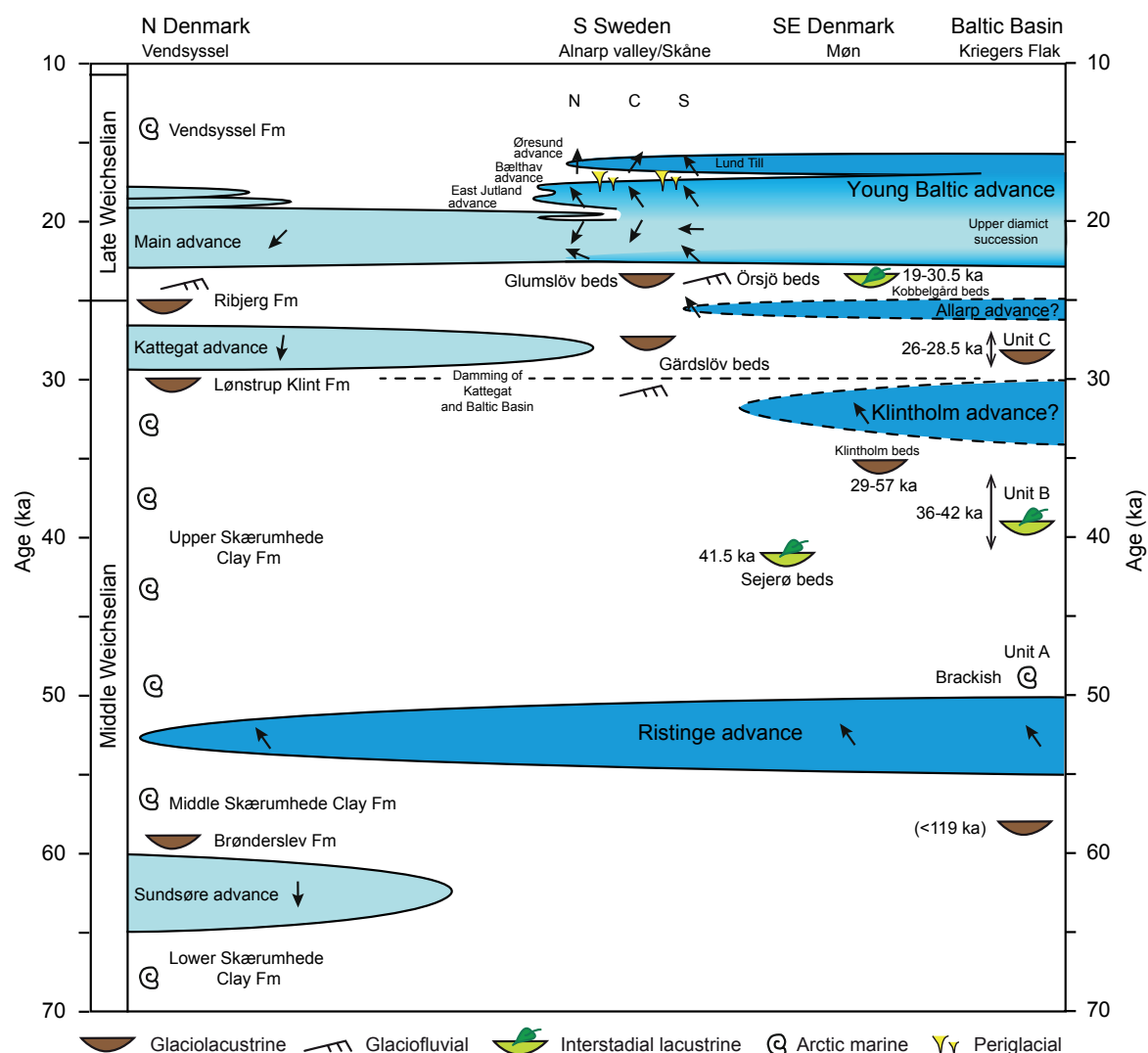


Figure 4. Suggested correlations of stratigraphic units within Skåne. The units are placed primarily based on stratigraphy but ages are indicated where they exist. Ice flow directions are indicated with arrows. The stratigraphies in north Denmark (Krohn *et al.* 2009; Larsen *et al.* 2009a, b) and south Denmark (Houmark-Nielsen 1994, 2003, 2010; Bennike *et al.* 2007) are included for comparisons. Note that some of the units are very poorly dated. These have been placed according to our best understanding of the stratigraphy. The suggested ages should thus not be taken at face value but nevertheless provides a framework for future comparisons. See Paper III for further discussion.

On Kriegers Flak the brackish phase was followed by a forced-regression of the area which turned Kriegers Flak into an island or a peninsula between 42 and 36 ka, Kriegers Flak unit B. Erosion and non-deposition connected to this regression could explain the hiatus found between units A and B. In unit B macrofossils indicate deposition in wetland and shallow lakes in a tree-less landscape dominated by tundra vegetation. The pollen record suggests vegetation resembling a forest tundra rich in wetlands. As these sediments are today found at c. 35 m below the present sea level it seems likely that large parts of the southern Baltic Sea floor were aerially exposed.

Ice-free periods of roughly the same age have been found in other areas around the present Baltic Sea. In Lithuania ice-free conditions were inferred at least between 55 and 33 ka (Satkunas *et al.* 2012) and Estonia seems to have been ice-free between 43.2 and 26.8 ka (Kalm 2006). This is further supported by lacustrine sediments from southwestern Estonia, which were deposited between 44.4  $^{14}\text{C}$  ka BP and 37 ka (OSL) (Rattas *et al.* 2010). In Latvia a large lacustrine lake existed between 52 and 26 ka (Saks *et al.* 2012). On Møn, southeast Denmark, six OSL samples gave ages ranging from  $57 \pm 4$  to  $29 \pm 2$ , four of them younger than 35 ka (Houmark-Nielsen & Kjær 2003;

Houmark-Nielsen 2010).

It seems probable that the Alnarp valley, the now sediment-filled valley which runs through southwest Skåne and into north Sjælland, was open during this time. This valley has a bedrock threshold at approximately 60 m below the present sea level, which makes it the lowest bedrock threshold of the Baltic Basin. In the base of the valley the Gärdslov beds, fluvial sand with high amount of Eocene amber and wood, is found. Holst (1911) and Nilsson (1973) have suggested that a river existed in the Alnarp valley draining large areas in the southern Baltic including what is today the river Vistula. Nilsson (1973) suggested a Weichselian interstadial age for this river. The low water level in the Baltic Basin, which such a river would imply, fits well with the exposed sea floor on Kriegers Flak. The existing radiocarbon ages of the Gärdslov Beds, ranging from  $21305 \pm 3000$   $^{14}\text{C}$  BP (c.  $28.3 \pm 5.6$  cal. ka BP) to non-finite ages (Miller 1977) are, however, highly uncertain.

A hiatus separated the lacustrine and wetland sediments in Kriegers Flak unit B from the overlying unit C, which was deposited in a glaciolacustrine environment between 28.5 and 26 ka. We relate the transgression between unit B and C to the damming of the Baltic Basin by the Kattegat advance. This ice advance dammed the Baltic Basin c. 30 ka and continued into north Denmark between 29 and 27 ka (Houmark-Nielsen & Kjær 2003; Larsen *et al.* 2009a). In Sweden this advance has been identified as far south as the island of Ven (Adrielssohn 1984). In the Alnarp valley the transition from deposition of fluvial sand to clay in the Gärdslov Beds probably reflect this damming. In the southern Alnarp valley this transition is followed by the deposition of the Allarp Till, which must thus be younger than 30 ka. A correlation with the lower part of the Upper diamict succession on Kriegers Flak seems reasonable and would suggest an age of less than  $26 \pm 1.7$  ka. A correlation with the hiatus between unit B and C is, however, also possible and would imply an age of c. 29 ka. The latter alternative would possibly allow a correlation between the Allarp Till and the Klintholm advance, which also advanced through the Baltic Basin. This advance has, however, been dated to  $32 \pm 4$  ka with a preferred age of c. 34–30 ka (Houmark-Nielsen 2010) which

means that it likely pre-dates the damming and corresponds to the hiatus between unit B and C on Kriegers Flak.

## 5.2 Late Weichselian, 25–11.7 ka

During the Late Weichselian the FIS reached its Weichselian maximum. The Baltic Basin was dammed by ice flowing through the Norwegian Channel and glaciolacustrine sediments were deposited in northern Denmark (the Ribjerg Formation; Houmark-Nielsen 1999; Larsen *et al.* 2009a) and in Skåne (Glumslöv and Örsjö beds; Adrielssohn 1984; Berglund & Lagerlund 1981).

At approximately 23 ka northern Denmark was overridden by ice from the north (Larsen *et al.* 2009a) while Skåne was glaciated after c. 22 ka and the Dalby Till was deposited (Kjær *et al.* 2006). This till has a stress direction from southeast and a Baltic provenance in its lowermost part. In northern and central Skåne a shift to a north-easterly ice direction and provenance, without a deglaciation in between, can be seen in the mid part of the till. In the uppermost part of the Dalby Till a south-easterly ice direction is again observed (Berglund & Lagerlund 1981).

After 21 ka the FIS began its retreat in Denmark and by 20 ka an ice dammed lake formed in northern Denmark followed by a small re-advance at 19 ka (Larsen *et al.* 2009a). In western Denmark the ice front retreated eastward from the Main Stationary Line in central Jylland before 19 ka. Two re-advances, the first at approximately 18 ka and a second between 18 and 17 ka, both advanced into Denmark from the east and reached the East Jylland and Bælthav ice margins, respectively (Houmark-Nielsen & Kjær 2003). In Skåne only one Young Baltic advance is observed. The uppermost part of the Dalby Till in Skåne was probably deposited by this advance (Berglund & Lagerlund 1981) while the Kullen peninsula in northwest Skåne could possibly already have been ice-free (Berglund 1971; Sandgren *et al.* 1999).

This phase was followed by an extensive deglaciation and formation of periglacial surfaces in Skåne (Lagerlund 1987). On Romeleåsen in central Skåne the deglaciation has been dated to between 17 and 16 ka (Fig. 5; Paper IV). In the low-lying

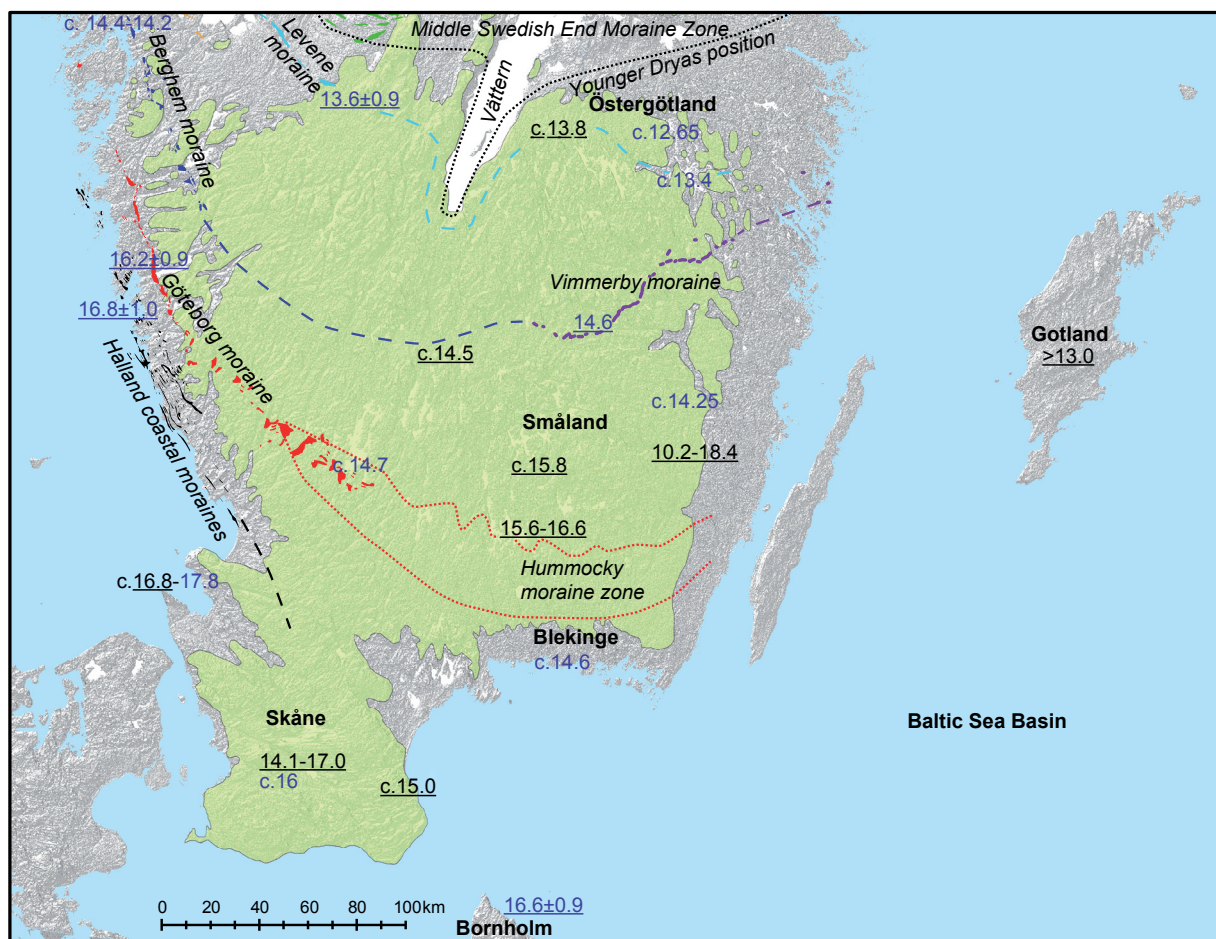


Figure 5. Overview map over southern Sweden showing estimated deglaciation ages suggested by Anjar *et al.* (submitted) in black, and by Sandgren *et al.* (1999) Lundqvist & Wohlfart (2001), Kjer *et al.* (2006), Johnsen *et al.* (2009, recalculated), Larsen *et al.* (2012, recalculated) and Houmark-Nielsen *et al.* 2012 (blue). Deglaciation ages based on cosmogenic surface exposure dating are underlined. Suggested correlations between the east and west coast of Sweden are marked with stippled lines but remain speculative. Digital elevation data from Jarvis *et al.* 2008. See Paper IV for details.

areas along the south and west coast of Skåne the deglaciation was, however, interrupted by the Öresund advance, which deposited the Lund Till (Ringberg 2003). In the southern Baltic Sea the island of Bornholm was deglaciated  $16.6 \pm 0.9$  ka (Houmark-Nielsen *et al.* 2012)

A combination of cosmogenic surface exposure ages and recalibrations of previously published radiocarbon ages was used to date the northward deglaciation. In southern Småland the deglaciation was dated to 15.6–16.6 ka while the Vimmerby moraine was dated to 14.5–14.6 ka (Johnsen *et al.* 2009; Paper IV). In northern Skåne the deglaciation of our northernmost locality, Kättebo, was dated to c. 13.8 ka (Paper IV).

In front of the retreating ice sheet the Baltic Ice Lake formed in the Baltic Basin. In the beginning it was probably at the same level as the North Sea but

as isostatic rebound progressed and the erosion of the sill areas reached into the flint-rich bedrock the Baltic Basin was dammed at c. 14 ka (Björck 1995; Andrén *et al.* 2011). Gradually the difference in water level increased as the isostatic rebound of the sill areas in Denmark was faster than the eustatic sea level rise until the ice front retreated north of Mt. Billingen enabling drainage through the Mid-Swedish lowlands (Björck 1995; Andrén *et al.* 2011). At c. 12.8 ka the Younger Dryas re-advance dammed the Baltic Basin once more (Björck 2008; Andrén *et al.* 2011). The final ice retreat at the end of the Younger Dryas stadal led to a catastrophic 25 m drainage of the Baltic Basin, which occurred a few decades before the onset of the Holocene (Björck *et al.* 1996; Björck 2008; Jakobsson *et al.* 2007; Andrén *et al.* 2011).

## 6. Conclusions

We suggest that the lowermost till on Kriegers Flak, dated to the Early or Middle Weichselian, was deposited during the Ristinge advance, which implies an age of c. 55-50 ka. Following the deglaciation after this advance, isostatic depression enabled a marine influence in the southern Baltic Basin. Kriegers Flak unit A, with a low-diversity benthic foraminifera fauna indicative of cold water and low salinities, was deposited. This was followed by a forced regression on Kriegers Flak, probably caused by a combination of isostatic rebound and a falling global sea level, which led to a period of non-deposition and erosion. Between 42 and 36 cal. ka BP, wetlands and shallow lakes existed on Kriegers Flak (unit B). Macrofossil and pollen analyses suggest tundra-like, or forest tundra-like vegetation, possibly with birch and pine in sheltered locations. From 28.5 to 26 ka, a thick succession of glaciolacustrine clay, unit C, was deposited at Kriegers Flak indicating a damming the Baltic Basin by an ice advance into Kattegat.

The upper part of the stratigraphy has been reconstructed from published and new terrestrial sections in Skåne. Here three tills are identified. The lowermost, the Allarp Till, was deposited after the damming of the Baltic Basin at c. 30 ka. It was followed, after a deglaciation, by deposition of the Dalby Till, representing the Last Glacial Maximum advances including an early advance from southeast, the Main advance from northeast and the first Young Baltic advances from southeast. The uppermost till, the Lund Till was deposited by the Öresund advance after a deglaciation.

The deglaciation of southern Sweden was dated using cosmogenic nuclide surface exposure dating. By using the same methods as had previously been used on the Swedish west coast the two regions could be correlated. We suggest that central Skåne was deglaciated between 17 and 16 ka, somewhat later than the Kullen Peninsula, while the south and southwest coast of Skåne could still have been influenced by the Öresund advance. In southern Småland the eastward continuation of the Göteborg Moraine has been dated to  $15.6 \pm 0.8$  and  $16.6 \pm 0.9$  ka, while a site close to the Vimmerby Moraine in northern Småland was dated to  $14.6 \pm 1.0$  ka, in

good agreement with a previous dating of the moraine. Our northernmost site, situated only 25 km south of the Younger Dryas Moraine, was dated to c.  $13.8 \pm 0.8$  ka while cosmogenic surface exposure ages from Gotland suggest a deglaciation before  $13.0 \pm 0.8$  ka.

## 7. Future work

The Kriegers Flak cores show that pre-Late Weichselian sediments can be found in situ in the Baltic Basin highlighting the potential for using Baltic Sea sediment cores to reconstruct the Weichselian history of the Baltic Basin. The IODP drilling campaign in the Baltic Basin which is planned for 2013 will likely add much to our knowledge of the Weichselian history, but as this study shows also cores taken for geotechnical surveys can be successfully used.

Apart from investigating the stratigraphy in sediment cores from a wider area in the Baltic Sea, our understanding of the glacial chronology in the region would be greatly improved if the sediments in the Alnarp valley were re-dated using modern AMS radiocarbon dating. This buried valley contains a key stratigraphy for southernmost Sweden but the poor age constraint limits its usefulness. Re-dating the sediments in the Alnarp valley could potentially also aid in determining the timing of the Allarp Till in southern Skåne and its correlation with the Danish stratigraphy, which still remains problematic.

I also suggest that better correlations to the glacial stratigraphy in northeast Germany should be a priority as this would enable a better understanding of the development of glacial advances and palaeoenvironments on a regional scale. I would be especially interested in potential correlations between brackish sediments in northern Germany with the unit A sediments on Kriegers Flak.

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## **Svensk sammanfattning**

Genom att studera forna inlandsisar kan vi få en inblick i hur en inlandsis påverkar och påverkas av till exempel klimatförändringar och havsnivåvariationer i tidsperspektiv från hundratals till hundratusentals år. I Skandinavien är det framförallt spåren efter nedisningar under den senaste istiden, Weichsel-istiden, som bevarats.

I den här studien fokuserar vi på Östersjöns och sydligaste Sveriges historia under den senaste istiden. Östersjöns tidiga istidshistoria, innan den Skandinaviska inlandsisen lämnade området, har varit i det närmaste okänd eftersom den Skandinaviska inlandsisen eroderade och omformade tidigare avsatta sediment. Dessutom finns det få riktigt djupa borrhärlor i Östersjön och de sediment som trots allt identifierats i och kring Östersjön är ofta svåra att åldersbestämma och kan inte alltid jämföras mellan olika regioner och länder.

Vi har här använt borrhärlor ifrån Kriegers Flak, ett grundområde beläget ca 30 km söder om Trelleborg i sydvästra Östersjön. Det här området befinner sig i den södra delen av den Skandinaviska inlandsisens maximala utbredning under den senaste istiden vilket innebär att det endast var istäckt under de mer omfattande nedisningarna och

isfritt i långa perioder däremellan. I den understa, och därmed äldsta, delen av borrhämnarna hittar vi berggrunden som i området består av kritkalksten. Direkt ovanpå hittar vi en morän som markerar den äldsta bevarade isframstöten över Kriegers Flak. Vi kopplar den till den första kända isframstöten i östra Danmark under den senaste istiden vilket skulle innebära att den är ca 55–50 tusen år gammal eller möjligen något äldre.

När isen smälte bort fylldes västra Östersjön av en blandning av smältvatten från den tillbakasmältande isen och havsvatten från Atlanten. Genom att studera bottenlevande skalamöbor, foraminiferer, vars skal bevarats i sedimenten, kan vi se att de levde i en miljö där låga vattentemperaturer och salthalter innebar att bara de mest tåliga arterna kunde etablera sig.

Nästa bevarade enhet avsattes för mellan 42 och 36 tusen år sedan. Skalfragment, växtdelar och insektsfragment som bevarats i sedimenten visar att material som idag ligger 35–40 m under vattenytan, avsattes på land i våtmarker och grunda sjöar och att stora delar av Östersjön måste ha varit torrlagd. Istället fanns där för ca 40 tusen år sedan en trädlös tundra, möjligen med björk och tall i skyddade lägen.

För ungefär 30 tusen år sedan började så inlandsisen att växa igen och is ifrån södra Norge rörde sig söderut och dämde Kattegatt och därmed hela Östersjön så att en sjö bildades och vattennivån höjdes. Tjocka lerlager på Kriegers Flak, avsatta för mellan 28,5 och 26 tusen år sedan, visar att området översvämmades på nytt. Även i Östersjön växte isen och rörde sig över sydligaste Skåne och östligaste Danmark vid ett eller två tillfällen vid ungefär den här tiden. Det är dock oklart om det skedde före eller efter att leran avsattes på Kriegers Flak.

För ca 22 tusen år sedan var den Skandinaviska inlandsisen som störst i sin västra del och nådde då ända till centrala Jylland i Danmark och söder om Berlin i östra Tyskland. När den sedan började smälta tillbaka skedde det inte i en jämn takt utan is fortsatte att röra sig genom Östersjön och ryckte flera gånger fram på nytt över områden i östra Danmark och sydligaste Skåne som den tidigare lämnat.

Vi har daterat de sista skedena av den senaste istiden i Sydsverige, perioden då isen gradvis smälte

tillbaka, med hjälp av exponeringsdateringar. Det är en metod som bygger på att ett stenblock eller en klippa som ligger vid markytan ständigt utsätts för kosmisk strålning. Denna strålning bildar bland annat  $^{10}\text{Be}$  i stenen som sedan kan mätas. Ju mer  $^{10}\text{Be}$ , desto längre har blocket eller bergytan exponerats. En inlandsis kan nollställa räkneverket, antingen genom att erodera berget så att en ny yta exponeras eller genom att placera block vid ytan som inte tidigare exponerats. En stor fördel med metoden är därför att den kan mäta själva bildandet av landformen medan många andra dateringar av glaciala landformer bygger på att hitta daterbart material som är äldre och eller yngre än landformen som man egentligen är intresserad av.

Våra dateringar tyder på att Kullahalvön i nordvästra Skåne blev isfri för mellan 17 och 18 tusen år sedan, följt av centrala Skåne mellan 16 och 17 tusen år sedan. De sydligaste delarna kan dock fortfarande ha varit istäckta i och med att is fortsatte att röra sig genom Östersjön. Isen drog sig sedan tillbaka mot nordost och södra Småland verkar ha blivit isfritt för ungefär 15,6–16,6 tusen år sedan, Vimmerbytrakten för ungefär 14,5 tusen år sedan och nordligaste Småland för omkring 13,8 tusen år sedan.

Tillsammans ger studierna presenterade i den här avhandlingen en inblick i Östersjön och södra Sveriges istidshistoria med början för ca 55 tusen år sedan och fram till dess att den Skandinaviska inlandsisen slutligen lämnade Sydsverige för knappt 14 tusen år sedan.

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## Appendix A

Other publications which are not included in this thesis.

Paper published in peer-reviewed journal:

Möller, P., Anjar, J., Murray, A. S. in press: An OSL-dated sediment sequence at Idre, west-central Sweden, indicates ice-free conditions in MIS 3. *Boreas*, 10.1111/j.1502-3885.2012.00284.x.

Book chapter:

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.

Conference abstracts:

Anjar, J., Larsen, N. K., Björck, S. & Adrielsson, L. 2009: Lacustrine sediments at Kriegers Flak, southwestern Baltic Sea, and its implications for the MIS 3 glaciation history in southwest Scandinavia. EGU General Assembly, abstract #EGU2009-8609, April 2009. Poster presentation.

Anjar, J., Larsen, N.K., Filipsson, H.L., Björck, S., Adrielsson, L. & Möller, P. 2010: Reconstruction of the relative sea level and palaeoenvironmental history of the southwestern Baltic Sea during MIS 3. Nordic Geological Winter Meeting, January 2010. Poster presentation.

Anjar, J., Larsen, N.K., Adrielsson, L., Bennike, O., Björck, S., Filipsson, H.L., Knudsen, K. L. & Möller, P. 2010: Reconstructing the pre-late Weichselian history of the southwestern Baltic basin based on sediment cores from Kriegers Flak. Annual Conference of the INQUA PeriBaltic WG, September 2010. Oral presentation.

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Anjar, J., Larsen, N.K., Adrielsson, L. 2012: Weichselian stratigraphy and glacial history of Kriegers Flak in the southwestern Baltic Sea. Nordic Geological Winter Meeting, January 2012. Oral presentation.