Late Pleistocene and early Holocene drainage events in the eastern Fehmarn Belt and Mecklenburg Bight, SW Baltic Sea

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The Fehmarn Belt (FB) is an 18-km-wide passage between the islands Lolland (Denmark) and Fehmarn (Germany) connecting the Kiel Bight/Langeland Belt with the eastern parts of the Baltic Sea (Fig. 1). The FB and the Darss Sill are known as bottlenecks for water-mass exchange in the past and the present and therefore they are key areas for the development of the whole Baltic Sea basin and its environmental conditions since the Late Pleistocene. The FB has an up to 32-m-deep meandering incision at its western opening and a sea floor gently rising to about 25-m depth with an opening of the channel towards the east. The flanks of the FB and the margins of the MB basin show strong morphological gradients.

The development of the Baltic Sea during the deglaciation encompasses a complex history of regressive and transgressive phases, triggered by a combination of glacio-isostatic movements, threshold settings and eustatic sea-level rise (e.g. Andrén et al. 2011). The main Baltic Sea stages are the Baltic Ice Lake (BIL), the Yoldia Sea, the Ancylus Lake and the Littorina Sea (Lampe 2005; Björck 2008; Andrén et al. 2011). Due to various regional effects, the timing, the duration, the connections between basins and the open ocean, the regional extent and the environmental settings of these phases are complex and still under discussion.

After the Last Glacial Maximum (LGM), the Weichselian ice sheet receded step-wise from the SW Baltic Sea. At about 17 000–16 000 cal. a BP the ice margin was still very close to the study area (Lemke & Kuijpers 1995; Stroeven et al. 2016) but subsequently receded rapidly from the southern Baltic Sea. In the beginning local lakes developed and due to freshwater discharge from melting and retreating ice, a large connected water body was formed – the initial Baltic Ice Lake (BILi) (Houmark-Nielsen & Kjær 2003). At approximately 13 000 cal. a BP the receding ice opened a water pathway at Mt Billingen causing a drop of the lake level of some 10 m (Björck 2008), marking the end of the BILi phase. At 12 800 cal. a BP, the re-advancing Scandinavian Ice Sheet blocked that outlet and the subsequent water-level rise initiated the final Baltic Ice Lake (BILf) stage (Andrén et al. 2011), which inundated the Darss Sill threshold. A lake level of −20 m in the FB area was reached (Jensen et al. 1997, 1999). The Arkona Basin, MB, Great Belt (Bennike et al. 2004) and even Kiel Bight (Jensen et al. 1997, 2002) were connected during the BILf highstand via the FB (Novak & Björck 2004). Fine laminated layers of clay and silt, lacking organic material, are found in the FB and adjacent basins. They were described as lateglacial, distal ice-lake deposits (e.g. Bennike & Jensen 1998; Novak & Björck 2004), related to the BILf period (e.g. Kostecki et al. 2015; Endler et al. 2016). During the lake highstand, sandy clinoforms developed along the eastern MB margin, generated by sediment discharge from the ancient Warnow River (Jensen et al. 1997).

As the Mt Billingen passage opened again at approximately 11 700 cal. a BP, the BILf drained in an event...
lasting only 1–2 years (Björck et al. 1996; Jakobsson et al. 2007; Johnson et al. 2013) resulting in a rapid regression along the southern Baltic Sea coast (e.g. Björck 1995; Moros et al. 2002). A sandy facies found in the FB is associated with a westward-draining braided river following the BIL regression (Novak & Björck 2002). Simultaneously climate ameliorated resulting in glacial retreat at the end of the Younger Dryas. The BILf regression was followed by the brackish water Yoldia stage, which lasted until 10 700 cal. a BP (Andrén/C19en et al. 2011). In the southern Baltic Sea this stage is characterized by lowstand freshwater lake deposits (e.g. Hansson et al. 2016). Marine influence has not been reported from MB, nor have sediments from this time interval ever been associated with the Yoldia stage. The Darss Sill acted as a threshold during lowstand conditions, resulting in water levels of −25 m in the MB and −40 m in the Arkona Basin (Bennike & Jensen 1998; Lemke 1998; Novak & Björck 2004). Lowstand indicators like peat or detritus gyttja (Bennike & Jensen 1998; Lemke 1998; Feldens & Schwarzer 2012), braided river deposits (Novak & Björck 2002), regressive beach deposits (Novak & Björck 2004) and sandy layers (Endler et al. 2016) were all dated to the Yoldia time; however, the term ‘Yoldia’ was never mentioned. These lowstand conditions are followed by the Ancylus Lake stage, which represents warmer climate conditions and is characterized by the development of carbonate-rich gyttja deposits and lake marls within the SW Baltic Sea region (Kolp 1986; Lemke 1998; Jensen et al. 1999; Bendixen et al. 2017). The Ancylus Lake drained in a severe event between 10 200 and 9800 cal. a BP (Feldens & Schwarzer 2012). It was followed by the brackish/marine Littorina Sea (Björck 2008; Andrén et al. 2011; Bendixen et al. 2017), which transgressed into the SW Baltic Sea between 8500–7500 cal. a BP (Rößler et al. 2011; Kostecki et al. 2015).

Due to the age of deposition, re-distribution processes and the stratigraphical position in the sedimentary record, sediments from the initial BIL have rarely been reported from the basins in the SW Baltic Sea. Therefore, only sparse information on the BIL stage, its termination and how the basins responded to the rapid ice retreat is available from this region. The objectives of this study are to (i) describe the pre-Holocene development in the SW Baltic Sea focussing on the FB and northern MB based on seismic investigations, and sedimentological and geochemical data; (ii) link the occurrence of event layers and major unconformities in the study area with drainage or melting situations during the BIL time; (iii) discuss the findings in relation to the receding ice margin and accompanying pre-Holocene isostatic movements and/or neo-tectonics,
and (iv) demonstrate that erosion was and is an important process in this area.

Material and methods

The presented material was collected during the cruises with RV ‘Alkor’ (GEOMAR Helmholtz Centre for Ocean Research) during the cruises AL-369 in 2011 (Schwarzer 2011), AL431 in 2014 and AL456 in 2015. The seismic data were obtained using a hull-mounted parametric sediment echo-sounder (SES, Innomar Technologies), which operated at frequencies between 6 and 8 kHz (secondary frequency). Navigational data were retrieved from a ship-board D-GPS. A water-level correction was applied using the tide-gauge data from the Station Marienleuchte (Fehmarn) against the normal height null (NHN = NormalHöhenNull). The raw data were post-processed using the Innomar ISE Post-Processing Software (TVG, stacking, and noise reduction).

Three gravity cores were retrieved for the seismic interpretation (Table S1). Each station was sampled at least twice, resulting in twin cores. X-rays of thin vertical core slices were produced and used to investigate the internal microscale sedimentological structures and the contacts between lithological boundaries within the core sections (e.g. Bouma 1964). Carbon analyses were performed on dried (at 60 °C) and homogenized samples to derive the TCN (total carbon and nitrogen) and Corg contents to resolve the environmental changes that are archived in the core material (e.g. Rößler et al. 2011). The results were calibrated and background corrected.

Samples for grain-size determination were treated with hydrochloric acid and hydrogen peroxide to remove carbonates and organic matter prior to the granulometric analyses, which were conducted with a laser diffraction particle size analyser (Beckman Coulter LS 13 320). The results were analysed with GRADISTAT version 8.0 (Blott & Pye 2001) and statistical grain-size parameters were determined using the methods of Folk & Ward (1957).

An Avaatech X-ray fluorescence (XRF) core scanner with an A Canberra X-PIPS® Detector was used to obtain logs of the elemental compositions of the core material, following the methodology of Tjallingii (2006). The measurements were carried out at 10 and 30 kV; the latter includes the usage of a Pd-thick filter. The measurements were performed at 10-mm increments in the coarse laminated part and at 2-mm increments for the fine laminated sections. The presented element counts were normalized to total counts per second (tcps).

For age control seven samples were analysed by the Leibniz-Laboratory for Radiometric Dating and Isotope Research Kiel for AMS-Dating (Accelerator Mass Spectrometry). The conventional radiocarbon age was calculated according to Stuiver & Polach (1977), with a correction for the effects of method-based isotope fractionation. The conventional ages were calibrated using OxCal v4.2 (Ramsey 2009) and the calibration was set to IntCal13 (Reimer et al. 2013). The ages are presented in calendar dates BP with a 95% confidence interval. Some radiocarbon ages for core K2 originate from a twin core that was taken at the same position (Table S1); identical lithological boundaries and unit thicknesses permitted the projection of the data points.

Results

Seismic units

Unit 1 shows a low acoustic transparency with diffuse and chaotic internal reflections. The unit forms the base of the acoustic penetration and features a strong relief in the eastern MB (Fig. 2D) and in the FB area (Fig. 3). In the FB it forms a wide channel (down to more than −40 m) with steep slopes. Additionally, a trough-like incision between −20 and −25 m is seen in the southern part of profile 2 (Fig. 3B). The surface of unit 1 is slightly inclined towards the east along the northern MB (Fig. 2).

Unit 2 is characterized by faint, partly disturbed, wavy and widely spaced parallel to subparallel reflections, onlapping unit 1 (Figs 2, 3) and features a higher acoustic transparency than unit 1. The reflectors are inclined and are situated about 10 m higher in the eastern MB in comparison to the FB (Fig. 2B).

Unit 3 conformably overlies unit 2 and onlaps unit 1 along the flanks of the FB channel (Fig. 3C). Unit 3 is dominated by horizontally aligned and narrowly spaced parallel internal reflectors. Six subunits are recognized (Fig. 3B). Subunit 3.1 represents the lowest portion of unit 3. It has a high acoustic transparency with numerous narrowly spaced internal subparallel reflectors, becoming more oblique towards the FB channel flank (Fig. 3). A concordant transition to subunit 3.2 (Figs 2D, 3) is dominated by finely spaced parallel reflections. It is followed by subunit 3.3, a homogeneous, highly transparent section with nearly no internal reflections. This unit can only be found in the FB area (Fig. 2B, C). It is followed by subunit 3.4, which consists of narrowly spaced parallel reflections very similar to subunit 3.2 (Fig. 2C). Subunit 3.5 shows a thin and again homogeneous transparency signature, with some disturbances along its upper boundary. It can only be tracked in the FB area (Fig. 2B). In the eastern MB, the horizontally aligned but tilted reflectors of subunits 3.1 and 3.2 are unconformably cut by subunit 3.6, which is characterized by westward dipping foresets (Fig. 2D). Unit 3 shows deformation structures and fault-like misalignments that predominantly appear in the FB area (Figs 2C, 3B, C). These deformations are pronounced along the elevated, step-like and truncated structure between −25 and −27 m. Seismic unit 3 is also found in the southwestern trough at depths between −22 and −25 m (Fig. 3). The reflectors of the subunits 3.1–3.5 are inclined from the FB to the eastern MB with a relative difference in height of about 10 m (Fig. 2B).
Unit 4 is located between \(-27\) and \(-32\) m and has medium acoustic transparency. It is separated from the underlying unit 3 by a distinct unconformity showing a high-amplitude reflection (Fig. 2C), which becomes more uneven and undulating near the channel flanks (Fig. 3D). Here and on the opposite channel flank, this unit features step-like structures with truncated and hummocky reflectors, characterizing downlapping clinoforms (Fig. 3D, F). It further forms approximately 3-km-wide hummocky and pillow-like structures in the central parts at the transition to the MB. Further, ridges in the eastern part of the MB are observed (Fig. 2B). In the FB unit 4 crops out at the seabed.

Unit 5 unconformably overlies unit 3 and onlaps the truncated clinoforms of unit 4 (Fig. 3E). Its acoustic transparency, as well as some diffuse and unstructured internal reflectors, fades slightly towards the eastern part of the MB (Fig. 2B). The unit is situated between \(-26\) and \(-30\) m. In the FB unit 5 crops out at the seabed (Fig. 2C).

The subsequent units 6, 7 and 8 are erosionally cut. They crop out at the seabed in the FB area until the channel opens towards the MB (Figs 2, 3). These units are not further described as they are not the focus of this study.

**Sediment cores**

*Core K1.* – Within core K1 only 73 cm of material was recovered (S 1). From 6 to 73 cm, a white carbonate-rich gyttja with horizontally aligned plant remains and strong bioturbation marks is evident. It is overlain by a 6-cm-thick mud succession. The core catcher contained sandy material.

*Core K2.* – Unit A1 (308–578 cm) is characterized by highly laminated mineroclastic sediments, featuring rhythmic alternations in thickness, colour, grain sizes and elemental composition (Fig. 4). Brownish layers composed of clay to very coarse silt are found that show an internal coarsening-upward, sometimes terminating with increased sand content. These laminae are sharply followed by a clay-dominated layer of reddish colour. In some cases the regularly alternating layers are disturbed by cross-stratification (Fig. 5) and load casts. The XRF element record shows a saw-tooth pattern in the element

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Fig. 2. A. Seismic profile 1. B. Interpretation of major seismic units and erosional unconformities cutting seismic unit 3. C. Inset at coring sites K1, K2 and K3 close to the FB. D. Inset with the seismic unit boundaries in the eastern MB. [Colour figure can be viewed at www.boreas.dk]
counts of Fe, Ca and the element ratio K/Ca (Fig. 4). The fine-grained layers exhibit low Ca counts but high Fe and K counts, whereas the coarse-grained layers display the opposite. The overall distribution of layer thicknesses shows a slight increase from base to top, with a maximum thickness of around 9 cm (Fig. 6A, B). These rhythmic layers are interpreted as varves (see Discussion). Unit A1 is associated with seismic unit 3.2 (Fig. 4).

Unit A2 (290–308 cm) consists of homogeneous brownish mineroclastic sediments with grain sizes ranging from clay to fine sand (Fig. 4). A fining-upward trend from medium silt to fine silt can be observed in this unit. Single coarser grains are visible as opaque particles in the X-ray images. They occur more frequently close to the unit base (Fig. 5C). The transition to unit A1 appears concordant (Fig. 5C). The XRF data reveal a steady decrease in Ca, while Fe and K increase (Fig. 4). Unit A2 is interpreted as a drainage or event varve and is associated with the bottom part of seismic unit 3.3 (Fig. 4).

Unit A3 (274–290 cm) represents a silt-dominated and highly laminated mineroclastic sediment, which shows strong disturbances of the lamina (Figs 4, 5B). Contrary to Unit A2 the amount of clay and the element counts for Fe and K are slightly higher (Fig. 4). X-ray images reveal that the coarser material is situated in the bright layers. The base is sharp but uneven, with material from unit A2 turbulently incorporated (Fig. 5B). The sediments of Unit A3 are interpreted as disturbed varves and are associated with the top portion of seismic unit 3.3 (Fig. 4).

Unit A4 (192–274 cm) is characterized at its lower boundary by a sharp transition from unit A3 to again a horizontally aligned and highly laminated section (Fig. 4). Grey and red layers are dominated by clay and fine silt and alternate with brownish layers that are primarily composed of silt (up to coarse silt). A slightly coarsening-upward trend along with a decrease in sorting from bottom to top of this unit is observed. A sandy
Fig. 4. Photographs, X-rays, lithology, grain size distributions, XRF core logs, $C_{oxygen}$ content, seismic inset and radiocarbon ages for gravity core K2. $^{14}C$-Sample location number 6 was analysed two times (6a, 6b). [Colour figure can be viewed at www.boreas.dk]
admixture occurs occasionally in the upper portion of unit A4 and is mostly associated with the occurrence of the brownish layers. The layers of this unit are 0.1–4.5 cm thick and show steadily decreasing trends in varve thicknesses from bottom to top (Fig. 6A, B). The thicker layers are depleted, while the thinner layers are enriched in carbonate contents (between 5–20%). X-ray images revealed load casts (Fig. 5B), which appear more frequently in the upper portion of unit A4. The overall element records of this unit show a skewed saw-tooth pattern, with spikes in the Fe counts generally observed in the finer-grained layers. The bulk organic material of plant fibres that were extracted from the base of this unit was dated to 32 538–29 401 cal. a BP (Fig. 4, Table 1). A second bulk sediment sample was dated to 25 822–25 192 cal. a BP. The rhythmic sediments of unit A4 are interpreted as varves and are associated with seismic unit 3.4.

Unit A5 (177–192 cm) consists of homogenous grey and poorly sorted fine silt with an admixture of coarse grains (Figs 4, 5A). A fining-upward trend is observed, with an increase in the clay fraction from 15 to 30%. A minor carbonate content of 15–20% and occasional plant remains are also present. Bioturbation marks emanate from the upper contact (Fig. 5A), while its base appears slightly wavy and disturbed, probably erosional. Along unit A5 the Fe counts remain relatively constant, while Ca counts steadily decrease and K counts increase. Unit A5 was dated to 11 602–10 737 cal. a BP based on plant remains (Fig. 4, Table 1). The unit is interpreted as a drainage or event varve and associated with seismic unit 3.4.

Unit B (96–176 cm) features a carbonate (up to 80%) and organic-rich gyttja with an occasional admixture of silt and sand (Fig. 4). The colour is light beige to white and the layering is irregular due to bioturbation, especially in the lower part (Fig. 5A). Snail housings, shell fragments and plant remains are found. The contact with unit A5 is erosional, as marked by the admixture of sand, shell fragments and the wavy and irregular geometry (Fig. 5A). The base was dated to 11 710–11 291 cal. a BP based on the material from a snail shell, while the top was dated to 11 598–11 227 cal. a BP based on the material from a gastropod operculum (Fig. 4, Table 1). Unit B is interpreted as lake marl and is associated with seismic unit 5 (Fig. 4).

Unit C (70–96 cm) consists of light-olive grey silty gyttja (Fig. 4). It is mostly homogenous, but fine irregular laminations and horizontally aligned plant fragments occur. A carbonate content of approximately 20–25% and a C$_{org}$ content of 2–3% were measured. The transition to unit B is marked by an uneven contact enriched with shell fragments, organic particles and an admixture of sand. The base of unit C was dated to 9662–9498 cal. a BP based on material of a gastropod operculum (Fig. 4, Table 1). Unit C is interpreted as gyttja and is associated with seismic unit 7.

Unit D (0–70 cm) is an olive-grey, muddy and bioturbated sediment (Fig. 4). This unit is depleted in carbonate (5–10%), but features a steady increase in C$_{org}$, up to 5%. The transition to the lower unit C is gradual. Unit D is interpreted as marine mud and is associated with seismic unit 8.

Core K3. – The base of this core (291.5–302 cm) contains fine sandy material, followed by a bright and bioturbated carbonate-rich gyttja (271–291.5 cm). These lake marls turn into a 2-cm-thick dark organic-rich carbonate gyttja (269–271 cm) and grade into a peaty gyttja from 228.5–
269 cm, dated to 11 084–10 686 cal. a BP (Table 1). A sandy layer with 2.5 cm thickness appears on top of this peaty succession and is again followed by an organic-rich gyttja (68–226 cm), comparable to the gyttja of unit C in core K2 (Fig. 4). The core terminates with muddy deposits (0–68 cm).

Discussion

Pre-Baltic Ice Lake

Seismic unit 1 marks the basement, which is interpreted as glacial till (Fig. 8). Its strong undulating relief in the
eastern part of the MB area is associated with the ‘Velgaster Staffel’, which is located in the Darss Sill area (Lemke et al. 1994; Lemke & Kuijpers 1995). Depressions in the till deposits are filled up with sediments showing irregular internal reflectors (seismic unit 2). According to the observations by Novak & Björck (2004) in the FB and by Lemke (1998) in the Darss Sill area, this unit is interpreted as sandy glaciﬂuvial deposits (Fig. 8) formed in a river system draining northeastward (Lemke & Kuijpers 1995). This unit must have developed in an ice-marginal position between 17 000 and 16 000 cal. a BP (Houmark-Nielsen & Kjær 2003; Stroeven et al. 2016), shortly after the ice had left the FB and MB area.

_initial Baltic Ice Lake (BILI)_

At this stage the glaciﬂuvial environment turned into a proglacial basin as indicated by deposits that show regularly spaced parallel reﬂections (Fig. 2, seismic unit 3.1). During the development of the initial ice lake the deposition changed, which is marked by the occurrence of higher acoustic transparency and ﬁner-spaced internal reﬂectors (Fig. 2, seismic unit 3.2). This unit correlates with highly laminated mineral clay-silty sediments exhibiting rhythmic oscillations in colour, thickness, element counts and grain sizes (Fig. 4, Unit A1). The well-preserved layering, absent bioturbation, very low organic carbon content and load casts point to a glacially inﬂuenced environment (de Geer 1912; Zolitschka et al. 2015). The ﬁner-grained reddish and grey layers represent cold seasons, while the coarser-grained brown layers belong to the warm seasons (Peach & Perrie 1975; Saar 1990). During those warm seasons Ca is enriched due to the input of detrital carbonate resulting from weathering of exposed till deposits or through meltwater discharge from glaciers (rock flour). High Fe and K contents found in the winter layers correspond to Fe-rich clays occurring in the source region (Johnson et al. 2013). Aeolian transport during the cold and windy seasons also increases Fe and K input into the basins (Raiswell et al. 2006), originating from large uncovered sandplains on land south of the Velgaster Staffel (Schulz 1961; Ludwig 1964). An initial ice-lake environment with indications of reeding ice is preserved with an ice margin still close to the Darss Sill area. An ice margin at this location existed around 16 000 cal. a BP (Lemke & Kuijpers 1995; Houmark-Nielsen & Kjær 2003; Stroeven et al. 2016). The slight coarsening of the sediment and an increase in the thicknesses of layers towards the top of unit A1 (Fig. 6B) is interpreted as slow ice re-advance. An exceptionally thick varve layer interrupts the steady varve pattern and appears as a granulometric and geochemical mixture of summer and winter layers with a ﬁning-upward trend (Fig. 4). This layer represents a drainage or severe melting event probably accompanied by remobilization and settling of suspended ice-lake deposits, comparable to drainage varves of later Baltic Sea stages described by Wohlfarth et al. (1998) and Andrén et al. (1999). This drainage varve developed concordantly (Fig. 5C), pointing to an ice margin somewhere, either close to the ice margin or in coastal areas due to a partial lake-level drop. After this event, sedimentation of varves with reduced thicknesses continued (Fig. 4), indicating a re-established lake environment. However, convolute bedding structures in the vicinity of the drainage varve indicate another disturbance shortly after the event. These deformation structures look very similar to post-sedimentary disturbances previously reported in varved sediments attributed to palaeo-seismicity (Mörner 1996). After this event, gradually decreasing layer thicknesses in the upper part of the varve sediments in the FB (Fig. 6B) indicate a more distal ice-lake sedimentation, with less material reaching the area of deposition (Scheidegger 1965). The dates of 32 538–29 401 and 27 330–27 142 cal. a BP for the upper varve section represent interstadial times. These ages are unlikely to be the ages of the varve deposition and are considered as allochthonous. An admixture of allochthonous interglacial material in BILI sediments was previously reported by Bennike & Jensen (1998). Additionally, it is doubtful that the well-preserved varved units would have withstood the carving of glaciers. The observed changes in the elemental composition in the sediments throughout the initial ice-lake phase (Figs 4, 6) reﬂect changes in the source area. Ice retreat leads to the exposure of the previously glaciated areas and supports the input of K into the lake via surface runoff (Blume et al. 2010) or by aeolian input from exposed sandplains.

| No. | Core  | Laboratory reference | Material                      | Water depth (m) | Conventional age (a BP)  | δ¹³C (‰) | Calibrated age (cal. a BP) (95% confidence) |
|-----|-------|----------------------|-------------------------------|-----------------|--------------------------|----------|--------------------------------------------|
| 1   | K2_B  | KIA50958             | Gastropod operculum           | 27.8            | 8595±40                  | –3.41±0.12 | 11 598–11 227                              |
| 2   | K2_B  | KIA50959             | Gastropod operculum           | 27.8            | 9915±40                  | 0.13     | 11 598–11 227                              |
| 3   | K2_A* | KIA50960             | Gastropod shell               | 28.6            | 10 010±40                | –4.24±0.14 | 11 710–11 291                              |
| 4   | K2_A* | KIA50961             | Plant remains                 | 28.6            | 9760±115                 | –16.01±0.13 | 11 602–10 737                              |
| 5   | K2_B  | KIA51341             | Insufﬁcient amount of carbon  | 28.7            | No data                  | No data  | No data                                    |
| 6a  | K2_B  | KIA51342             | Bulk organic                  | 29.5            | 26 748±700               | –26.07±0.22 | 32 538–29 401                              |
| 6b  | K2_B  | KIA51342             | Bulk organic                  | 29.5            | 23 200±200               | –24.51±0.37 | 25 822–25 192                              |
| 7   | K3_A  | KIA51343             | Organic detritus              | 28.5            | 9525±41                  | –29.43±0.16 | 11 084–10 686                              |
No clear indication for the drainage of the BILi exists in the presented cores, but the seismic data revealed that BILi sediments are erosionally truncated in the eastern MB by deltaic foresets (Fig. 8). These foresets have their origin in ancient Warnow River sediments deposited during the BILf phase (Jensen et al. 1997). No erosional
contact was mentioned by Jensen et al. (1997), but this is clearly visible within the presented seismic records of this study (Fig. 2D). Therefore, the youngest parts of the BILi deposits were completely eroded during the first BIL drainage or during the development of the subsequent BILf (Fig. 8). At the end of the BILi at 12 850 cal. a BP (Muschiello et al. 2016) the ice withdrawal from the Darss Sill area enabled a connection between the MB and the AB, while the ice margin moved further east in the neighbouring AB (Feldens et al. 2013; Obst et al. 2017).

Final Baltic Ice Lake (BILf)

Sediments of the BILf, representing deltaic foresets, are only found in the eastern MB (Figs 7, 8). This observation is consistent with the erosional unconformity, which cuts through BILi sediments (Figs 2, 3) and which was found in the FB and the eastern MB. The geochemical characteristics of Unit A5 indicate remobilization and mixing of varve material (Fig. 6C). This suspended material was re-deposited as shown by the upward-fining grain sizes. This succession is interpreted as the result of a sudden lake-level drop. The age of 11 602–10 737 cal. a BP for this event layer is in agreement with the final drainage of the BILf in the MB (Fig. 7). However, these data bear uncertainties as hard water effects (Walker 2005) and the $^{14}C$-plateau during that time (Björck 2008) need to be taken into consideration. These lowstand conditions are underpinned by bioturbation features that penetrate this unit, the occurrence of a thin sandy layer and the irregular contact with the subsequent unit B. The upper unconformity that marks the termination of the BILf joins the lower unconformity, which cuts the BILi sediments in the FB (Fig. 8). This indicates that BILf sediments were completely eroded during the final drainage within the FB main channel. They are only preserved at the channel margin at higher altitudes in local depressions (Figs 3, 8) and as foresets in the eastern MB at a level between approximately −20 and −30 m.

Yoldia-time lowstand

The thin sandy succession found at the transition from the varved BILi sediments to the lake marl deposits (Fig. 4) is correlated with the occurrence of the truncated clinoforms at the FB flanks and in the FB channel, where it opens towards the MB (Fig. 8). A low water-level situation with sandy riverbed and riverbank deposits (seismic unit 4) must have existed at the transition from the FB to the MB as already suggested by Novak & Björck (2002, 2004). The age of the drainage varve of 11 602–10 737 cal. a BP pre-dates the sandy riverine environment. Therefore, the BILf drainage occurred prior to the development of the braided river system. Sandy deposits of comparable ages overlaying BIL sediments in the MB were previously attributed to the BILf drainage (Lemke 1998; Jensen et al. 1999; Kostecki 2014). Moros et al. (2002) identified a sandy layer at approximately 10 600 cal. a BP as an indicator for a Yoldia-age lowstand in the Arkona Basin. The development of lake marls and peaty gyttja (Fig. 7) indicate a decreasing flow velocity as a result of a rising groundwater table probably due to a damming west of the FB. Ages of 11 598–11 227 and 11 710–11 291 cal. a BP for the lake marls indicate a deposition during Yoldia times and pre-date the age of the AL transgression at about 10 500 cal. a BP in the MB (Kostecki et al. 2015). The lake marl succession is followed by an organic-rich peaty gyttja that turns into a more solid peaty layer towards the east (Figs 7, 8). The peaty layer was dated to 11 084–10 686 cal. a BP, underpinning a Yoldia timed lowstand environment in the MB, matching the ages of the peaty successions in the eastern
MB (Fig. 7). Yoldia timed lowstand peat deposits were also found by Feldens & Schwarzer (2012) at the western entrance of the FB (Fig. 7) and at other locations in the southern Baltic Sea (e.g. Hansson et al. 2016).

Neo-tectonics

The BILi sediments at the transition from the FB to the MB show the occurrence of convolute bedding structures (Fig. 5), an exceptionally thick drainage varve (Figs 4, 5), fault-like disturbances and misalignments (Figs 2, 3), and post-sedimentary basin inclination from west to east (height difference about 10 m) (Figs 2, 8).

These features can be the result of neo-tectonic movements. Indications for neo-tectonic activities in the FB area have already been reported by Novak & Björck (2002, 2004) and Reicherter et al. (2005). Possible causes for such vertical movements are palaeoseismic activities, salt tectonics and/or ice retreat. Given these potential causes, interactions between these processes are highly probable. Palaeoseismic activities can form convolute bedding structures in varved sediments, as described in Mörner (2004) and Hoffmann & Lampe (2010). Winn et al. (1986) analysed numerous cores from the Kiel Bight, Fehmarn Sund and MB and argued that inhomogeneities in the northern German isostatic movements are most likely related to salt tectonics, as was also concluded for the FB area by Novak & Björck (2002, 2004). Richter et al. (2006) confirmed this spatial heterogeneity in the magnitude of the movements through an analysis of coastal nivellement data. He determined the maximum upward movements along Fehmarn Island. However, the strongest tilting is observed only in the BIL sediments. As the erosional contact between the BILi sediments and the Yoldia timed lowstand deposits is nearly horizontal (Fig. 8), the tilting must have occurred before the development of the braided river phase and the lake marls. Further, the joining of the unconformities in the eastern MB (Fig. 8) indicates that the vertical movement took place after the deposition of the BILi sediments and prior to the BILf drainage. This strengthens the hypothesis of an uplift probably supporting the establishment of a threshold at the Darss Sill area and a change in drainage direction towards the west. Finally, the environmental changes that were recognized in the varved successions linked to the dynamics at the ice margin suggest that compensatory movements were likely during ice retreat from the SW Baltic Sea.

Conclusions

Varve sediments of the initial BIL stage were found in the FB and northern MB. Event-like changes in the varve thicknesses and geochemical and sedimentological signatures in the BILi sediments show strong indications of ice-margin dynamics relatively close to the northern MB area. Tilting of units and fault-like misalignments demonstrate that disturbances and vertical movements in the area between the FB and Darss Sill took place and are related to the recession of the ice margin. This glacio-isostatic movement occurred before the Yoldia timed lowstand and supported a threshold development in the Darss Sill area. Two prominent erosional unconformities were documented and associated with the two main drainages of the BIL. A hiatus in the FB demonstrates that parts of the BILi and large amounts of BILf sediments were eroded during the BIL drainage events or by a braided river system during lowstand conditions. The fluvial system was followed by lake marl and peaty deposits of Yoldia age, which can be tracked from the FB to the eastern MB margin. Finally, this study demonstrates that the morphologically narrow FB and northern MB were governed by strong erosional processes. This area was affected by erosion during all major drainage phases since the initiation of the BIL. Erosion is still active as demonstrated by the regressive wedge of deposits.

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**Supporting Information**

Additional Supporting Information may be found in the online version of this article at http://www.boreas.dk.

*Table S1.* Coring stations. Analysed cores are highlighted. Twin cores are marked with asterisks.