Holocene sedimentary and environmental development of Aarhus Bay, Denmark – a multi-proxy study

PETER RASMUSSEN, GEORGE PANTOPOULOS, JORN B. JENSEN, JESPER OLSEN, HANS ROY AND OLE BENNIKE

Previous studies in the Kattegat region have dealt with the general Lateglacial and Holocene geological history based on a combination of seismic surveys and core studies (e.g. Bennike et al. 2000; Jensen et al. 2002; Bendixen et al. 2017; Wiberg-Larsen et al. 2019). Other studies focussing on Holocene oceanographic changes have revealed a complicated sedimentation history driven by relative sea-level changes and hydrographic variations due to fluctuating outflow of low-saline water from the Baltic Sea and inflow of high-saline water from the North Sea (Nordberg & Bergsten 1988; Nordberg 1991; Christiansen et al. 1994; Conradsen & Heier-Nielsen 1995; Gyllencreutz 2005; Christensen & Nielsen 2008; Erbs-Hansen et al. 2012).

Studies of the Holocene history of the Baltic Sea and the Danish straits have a long history, but many details are debated. Hence, the timing of the different Baltic Sea stages is poorly constrained. In particular, dating the transition from the limnic Ancylus Lake to the brackish Littorina Sea has proved difficult. According to some studies, the first inflow of marine water into the Baltic Sea occurred at c. 10 100 cal. a BP (Andrén et al. 2000) or at 9800 cal. a BP (Berglund et al. 2005; Andrén et al. 2011). However, the oldest dated marine shell from Aarhus Bay gave an age of c. 8700 cal. a BP (Jensen & Bennike 2009) and in the central part of the Great Belt the oldest dated shell of a marine mollusc gave an age of c. 8100 cal. a BP (Bennike et al. 2004). More dated samples from Aarhus Bay and other basins in Denmark may help to solve the enigma about the Ancylus Lake to Littorina Sea transition.

Aarhus Bay in eastern Jutland is an important site for biological, biogeochemical and sedimentological monitoring of the current Danish marine environment and the bay is used as a natural laboratory to study biological processes in the buried sediments (e.g. Kronvang et al. 1993; Jensen et al. 1995; Jorgensen & Jansen 1996; Dale et al. 2009; Leloup et al. 2009; Holmkvist et al. 2011; Langerhuus et al. 2012). Hence, this study also provides important background information of significance for assessing sediment-based studies of recent and sub-recent biotic and abiotic conditions in the area.

Aarhus Bay is a semi-enclosed embayment situated in the transitional area between the Kattegat and the Great Belt at the entrance to the Baltic Sea (Fig. 1). The late Quaternary history of the bay was described by Jensen & Bennike (2009), but no details on the Holocene evolution were provided. The aim of the present study was to improve our understanding of the temporal and spatial
Holocene sedimentary and environmental development, Aarhus Bay, Denmark

Study area

Aarhus Bay is a ~320 km² large hydrographically open embayment bordering the southwestern Kattegat with a mean water depth of ~15 m (Fig. 1). The bay is deepest in its eastern part and connected to the southern Kattegat and the Great Belt over narrow deep troughs and shallows, respectively. The tidal range is up to ~50 cm and the average water residence time in the order of 2 weeks. The water column in the bay is stratified about 70–80% of the year with a pycnocline depth of 8–10 m (Christiansen et al. 1994; Jørgensen 1996). The oldest outcropping deposits in the region are Tertiary clay partly modified by glacial deformations and covered by glacial tills (Houmark-Nielsen 1987; Pedersen & Petersen 2000). Geologically, the bay was formed during the last glaciation. The ice started to retreat from the area c. 18 000 cal. a BP (Lagerlund & Houmark-Nielsen 1993; Houmark-Nielsen 2003).

When the glacier retreated from Kattegat, the initial high relative sea level in the area was followed by a
regression caused by isostatic uplift as a response to the deglaciation (Mörner 1969; Lambeck 1999). The relative sea level then reached its minimum in the southwestern part of the Kattegat at a depth of ~30 m below present sea level c. 12,000–11,000 cal. a BP (Jensen et al. 2002). The influence of the isostatic uplift decreased with time and in combination with the Holocene global eustatic sea-level rise, the relative sea level increased in the region and at c. 9500 cal. a BP the sea flooded the southern Kattegat area commencing with a brackish estuarine phase (Jensen et al. 2005). The marine sediments in the Aarhus Bay area consist predominantly of organic-rich clay, silt and sand, which are the main sediment types being deposited until today. Present-day sedimentation in Aarhus Bay mainly derives from the open Kattegat possibly associated with inflows of high salinity water from the North Sea, while contributions from coastal erosion and fluvial activity only seem to constitute a minor proportion of the primary settling matter (Skyum & Lund-Hansen 1992; Christiansen et al. 1994; Jensen et al. 1995).

Material and methods

In the Aarhus Bay, a number of shallow seismic studies have been carried out and the acquired data were used to select the core sites. Detailed information on instruments, methane distribution and the general geology have been reported by Jensen & Laier (2003) and Jensen & Bennike (2009).

Two sediment cores were collected with a gravity corer in Aarhus Bay. One core (1101 cm in length) was collected at station M1 in the central part of the bay (latitude 56°07′N, longitude 10°21′E) at a water depth of ~16 m and the other core (645 cm in length), at station M5 in the eastern part of the bay (56°06′N, 10°27′E), at a water depth of ~28 m (Fig. 1). The cores were split and described in the laboratory and were subsequently X-ray fluorescence (XRF) scanned and subsampled for macrofossil analysis, determination of sedimentary properties and grain-size analysis.

A total of 187 fresh sediment samples were investigated for their macrofossil content in order to obtain material for 14C dating and for elucidating environmental changes. Sediment volume (15–40 cm3, mean 26 cm3) was recorded and the samples washed on a 0.01-mm sieve. Material retained on the sieve was analysed and macrofossils identified and counted using a dissecting microscope. Numbers of macrofossils were calculated per 50 cm3 of wet sediment, with the exception of opercula of Bithynia tentaculata, fragments of the bivalves Mytilus sp. and Nucula sp., remains of echinoids and tests of the foraminifer Quinqueloculina seminulum, which are shown as presence/absence. Concentrations of foraminifera were estimated for each sample in six abundance classes. Nomenclature for marine molluscs, freshwater molluscs and plants follow Petersen (2004), Mandahl-Barth & Bondsenn (1949) and Tutin et al. (1964–1980), respectively.

Subsamples of fixed volume were taken at approximately every 10 cm in each core for determination of sediment properties. The samples were dried at 105 °C to determine dry weight. Content of organic matter and CaCO3 was calculated as weight loss at 550 and 925 °C, respectively (Dean 1974; Heiri et al. 2001). The minerogenic matter consists of the non-organic, non-carbonate fraction of the sediment. For the calculation of sediment accumulation rates, the dry density results from the analyses of the sediment physical properties were used.

The grain-size composition of 50 sediment samples was measured using a Sympatec HELOS laser diffractometer at the Department of Geoscience, Aarhus University, Denmark. The instrument can measure particles in the 0.2–350 or 32–3350 μm ranges depending on the expected grain-size range of the sample. To avoid artefacts caused by very fine organic matter or shell material, organic and carbonate matter was removed using HCl and H2O2.

XRF core scanning was used to describe changes in elemental composition, using an ITRAX XRF Core Scanner with a Cr tube set at 60 kV with a 30 mA. The core scanner is located at the Leibniz Institute for Baltic Sea Research, Warnemünde, Germany. XRF scans were carried out on the surface of split sediment cores, which prior to scanning were covered with a 4 μm Ultralene film. Data are reported as counts per second.

Terrestrial samples used for 14C dating were treated with HCl, NaOH and by HCl. Shells used for 14C dating were cleaned and the outer 10 to 25% of the shells were leached with HCl. Small samples (below 5 mg) were treated with a H2O2 solution.

The chronologies of the sediment cores are based on accelerator mass spectrometry (AMS) 14C measurements (Table 1, Fig. 2). Dating results obtained from mollusc samples and terrestrial macrofossils were calibrated using Marine09 and IntCal09 (Reimer et al. 2009). We used a marine 14C reservoir age of 400 years. However, it is possible that the reservoir age has varied during the Holocene (e.g. Olsen et al. 2009, 2017). Age models were constructed using depositional models in OxCal v4.2 with a k value of 50 for core M1 (Amodel = 71.9%) and a k value of 150 for core M5 (Amodel = 105%) (Bronk Ramsey 2008).

Results and interpretation

The diagrams from cores M1 and M5 were divided into four and one zones, respectively. The zonation of the cores is mainly based on their macrofossil content, which further correlates rather precisely with the lithological units described in Table 2, the seismic reflector pattern shown in Fig. 3 and the general seismic mapping of the area as reported in Jensen & Bennike (2009).
Seismic data

Seismic line 502065 near the core M1 site shows a flat seabed in line with the known bathymetry of this part of the bay (Figs 1, 3). The marine deposits exhibit a pinching-out reflector in the upper part, which reflects the boundary between Zones 3 and 4 as indicated on the diagrams for the various proxy data from the M1 sediment succession (Figs 4, 5, 7A, 11).

The reflector is interpreted as an unconformity that marks a change in sedimentary environment and the pinching-out at the present seabed shows that erosion is taking place today. In contrast, seismic line AAB-WE-7000 near core M5 shows marine sediments deposited on a deeper, inclined seabed very near to the deep and narrow entrance of the bay. Inclined prograding reflectors inside the Holocene marine deposits show continuous sedimentation to recent time with minor variations in grain-size composition.

Sediment stratigraphy

Core M1 was collected at a water depth of ~16 m and is 1101 cm long. The sediment succession exhibits marked differences in lithology in its upper and lower parts and was visually subdivided into the units summarized in Table 2. Core M5 was collected at a water depth of ~28 m and is 645 cm long. The lithology is described in Table 2.

Macrofossils, core M1

The macroscopic plant and animal remains from the sediment cores were used to infer past environments. The macrofossil content of the M1 core is shown in two diagrams (Figs 4, 5). The diagram was divided into four zones.

Zone 1 (c. 10 000–9000 cal. yr BP). – Zone 1 is characterized by numerous remains of freshwater animals and plants. Limnic molluscs include the gastropods Bithynia tentaculata, Acroloxus lacustris, Valvata spp., Gyraulus laevius, Armiger crista and the bivalve Pisidium sp. (Fig. 4). Most of these species are currently widely distributed in Denmark in all kinds of fresh water except for G. laevius, which is rare and limited to standing water (Mandahl-Barth & Bondesen 1949). Other remains of freshwater animals include cocoons of the fish leach Piscicola geometra, ephippia of Daphnia, statoblasts of the bryozoan Cristatella mucedo and fish scales of the European perch (Perca fluviatilis). Most of the gastropods live on submerged aquatics and cocoons of P. geometra are also closely associated with macrophytes (Odgaard & Rasmussen 2001).

The freshwater submerged aquatic vegetation is dominated by Chara sp., Ceratophyllum sp., Stratiotes aloides, Najas minor and Zannichellia palustris (Fig. 5). The Early Holocene presence of Stratiotes aloides is noteworthy; the early immigration of this species to northwestern Europe was discussed by Bennike & Hock

---

Table 1. Chronological information for cores M1 and M5.

| Lab ID  | Material            | Depth (cm) | \(D_{\text{model}}\) (cm) | \(\delta^{13}\text{C}_{\text{AMS}}\) (\%o) | Age (\(^{14}\text{C}\) a BP) | Model age (cal. a BP) | Age agreement (%) |
|--------|---------------------|------------|---------------------------|---------------------------------|----------------------------|----------------------|-------------------|
| UBA-19897 | Nucula nucleus | 130–131 | 130.5 | 0 | 3750±28 | 3707±218 (3815–3610) | 90.0 |
| UBA-19898 | Nucula nucleus | 247–248 | 247.5 | 0 | 4432±33 | 4565±56 (4679–4444) | 102.1 |
| UBA-19899 | Nucula nucleus | 396–397 | 396.5 | 0 | 5077±30 | 5424±54 (5524–5318) | 103.8 |
| UBA-19000 | Corbula gibba | 573–574 | 573.5 | –1 | 5984±46 | 6402±54 (6505–6293) | 102.2 |
| UBA-19001 | Turritella communis | 752–753 | 752.5 | 1 | 6519±33 | 7031±48 (7130–6941) | 107.5 |
| UBA-19002 | Corbula gibba | 948–949 | 948.5 | 2 | 7185±36 | 7701±49 (7792–7604) | 61.7 |
| UBA-19327 | Cerastoderma edule | 978–979 | 978.5 | 2.3 | 7486±35 | 7917±42 (7995–7834) | 84.7 |
| UBA-19003 | Cerastoderma edule | 1011–1012 | 1011.5 | –1 | 8280±41 | 8805±75 (8950–8660) | 99.6 |
| AAR–16263 | Cerastoderma sp. | 1016–1017 | 1016.5 | –0.46 | 8349±45 | 8885±68 (9005–8755) | 92.4 |
| UBA-19004 | Corvules avellane | 1040–1041 | 1040.5 | –28 | 8565±43 | 9203±95 (9604–9475) | 98.8 |
| AAR–18772 | Deciduous leaf-fr. | 1060–1061 | 1060.5 | –28.67 | 8432±32 | 9469±27 (9525–9425) | 101.2 |
| AAR–18773 | Betula, Menyanthes, Schoenoplectus lac. | 1096–1097 | 1096.5 | –20.34 | 8910±34 | 10 045±80 (10 181–9915) | 100.0 |

\(^1\)Dual inlet \(\delta^{13}\text{C}\) (SD±0.02\%o).
In addition, there are scattered records of *Nitella* sp., *Potamogeton perfoliatus*, *Myriophyllum spicatum* and *Elatine hydropiper*. The species composition and not least the abundant occurrence of *Chara* sp. indicate clear water conditions. Most of the taxa grow in fairly eutrophic water except for *Elatine hydropiper*, which is an oligotrophic species (Schierup 1989). *Najas minor* is the only recorded taxon that does not grow in Denmark today; the present-day northern geographical range limit of this species is in Germany. The species was widespread in the Danish area during the Early Holocene; its former more northerly occurrence indicates warmer summers than at present during the time-span from 10,300 to at least 8000 cal. a BP (Bennike et al. 2000). The earliest occurrence of *Najas minor* in the M1 sediment core is dated to c. 9850 cal. a BP. In Zone 1 remains of freshwater floating-leaved taxa are also recorded (Fig. 5).

The flora of emergent aquatic macrophytes is species-rich and dominated by remains of *Typha* sp., *Schoenoplectus lacustris* and *Carex* sp. (Fig. 5) but including for example *Alisma plantago-aquatica*, *Eleocharis* sp., *Eupatorium cannabinum*, *Equisetum* sp., *Filipendula ulmaria*, *Juncus* sp., *Lycopus europaeus*, *Mentha aquatica*, *Menyanthes trifoliata*, *Phragmites communis*, *Solanum dulcamara* and *Urtica dioica*. These taxa grow in reed swamps of mesotrophic-eutrophic lakes or in alder carrs at the margin of lakes. Nitrophilous plants such as *Solanum dulcamara*, *Mentha aquatica* and *Urtica dioica* are typical of alder carrs (Hannon & Gaillard 1997).

Remains of the following tree taxa were recorded: *Betula* sect. *Albae* sp. (tree birch), *Alnus glutinosa* and *Corylus avellana*. Remains of *Alnus glutinosa* and *Corylus avellana* are scarce and occur for the first time c. 9800 cal. a BP (*A. glutinosa* nutlet) and c. 9400 cal. a BP.

**Table 2.** Lithological descriptions of cores M1 and M5.

| Depth (cm) | Lithostratigraphy |
|-----------|-------------------|
| Core M1   |                    |
| 0–30      | Dark grey-olive, slightly sandy, silty clay with some gyttja and few scattered mollusc shells. |
| 30–100    | Grey-olive, sandy, silty clay with some gyttja and very few scattered mollusc shells. |
| 100–700   | Grey-olive, slightly sandy, silty clay with some gyttja and few scattered mollusc shells. |
| 700–1000  | Grey-green, slightly sandy, silty clay with some gyttja and few scattered mollusc shells. |
| 1000–1017 | Grey-green, slightly sandy, silty clay with some gyttja and scattered mollusc shells. |
| 1017–1053 | Grey-greenish sand with relatively many mollusc shells, organic detritus and a few pebbles. |
| 1053–1062 | Grey-greenish, sandy, silty clay with some gyttja and organic detritus. |
| 1062–1095 | Grey-greenish silty clay with some gyttja, less organic detritus than in the layer above. |
| 1095–1101 | Grey-greenish silty clay with some gyttja, a little organic detritus plus a larger piece of wood. |
| Core M5   |                    |
| 0–20      | Very dark grey-greenish, sandy, silty clay with some gyttja and a few scattered mollusc shells. |
| 20–265    | Dark grey-greenish, sandy, silty clay with some gyttja and a few scattered mollusc shells. |
| 265–645   | Bright greyish olive, sandy, silty clay with some gyttja and a few scattered mollusc shells. |
a BP (C. avellana anther) (Fig. 5). The frequent occurrence of terrestrial and especially lake-shore macro-remains during Zone 1 indicates that the shoreline was situated close to the coring point.

The upper boundary of this zone is set at the occurrence of the first marine mollusc (the bivalve Cerastoderma edule; Fig. 4). However, the presence of a few foraminiferan tests 5 cm below the marine bivalve (i.e. in Zone 1) may indicate marine influence slightly earlier. The level containing the first few foraminifera tests is dated to c. 9020 cal. a BP.

Zone 2 (c. 9000–7700 cal. a BP). – This zone is characterized by marine molluscs; however, in the lower part of the zone between 9000 and c. 8900 cal. a BP a few freshwater gastropods were found (Bithynia tentaculata,
Fig. 4. Simplified macrofossil diagram for Aarhus Bay core M1 with limnic and marine animals. Number of fossils per 50 cm³ of wet sediment. Dots indicate presence of taxa. The numbers following selected marine animals indicate lower salinity tolerances. [Colour figure can be viewed at www.boreas.dk]
Fig. 5. Simplified macrofossil diagram for Aarhus Bay core M1 showing plant remains. Number of fossils per 50 cm$^3$ of wet sediment. Dots indicate presence of taxa.
Valvata spp. and Lymnaea peregrina; Fig. 4). The first marine mollusc – Cerastoderma edule – occurs from the start of the zone concurrent with the freshwater snails. A 100 years later, there are scattered occurrences of other marine species: the gastropods Hydrobia ventrosa and Hydrobia ulvae and later a few specimens of the bivalves Corbula gibba and Mytilis edulis. Towards the top of the zone, Scrobicularia plana and Hinia reticulata occur. The abundance and diversity of the marine mollusc fauna is low. Cerastoderma edule, Hydrobia spp. and M. edulis are typical brackish water species while C. gibba, S. plana and H. reticulata require higher salinities (Sorgenfrej 1958).

Some of the plants that have been grouped as limnic on the diagram (Fig. 5) such as Chara sp., Zannichellia palustris, Ceratophyllum demersum, Nuphar sp., Typha sp. can also grow in slightly brackish water; for example, C. demersum can tolerate a salt concentration of up to 5% (Moeslund et al. 1990). Other aquatic macrophytes, such as Najas minor, Nymphaea sp., Ranunculus sect. Batrachium and Schoenoplectus lacustris recorded, in Zone 2 are unambiguously freshwater plants. Remains of these taxa may be reworked from the underlying limnic sediments during the marine transgression or they were brought in via streams and rivers. The latter mode of transportation probably also explains the presence of a number of other freshwater taxa in Zone 2: Potamogeton sp., Alisma plantago-aquatica, Eupatorium cannabinum, Mentha aquatica, Menyanthes trifoliata, Phragmites communis and Urtica dioica. Terrestrial macrofossils in Zone 2 include fruits from Betula sect. Albae sp. and Alnus glutinosa. The fossil assemblage indicates brackish-water conditions. The upper boundary of Zone 2 is placed where limnic and terrestrial macrofossils almost disappear from the record.

Zone 3 (c. 7700–3700 cal. a BP). – Remains of echinoids occur for the first time near the beginning of this zone (c. 7500 cal. a BP) and are present almost continuously throughout the remainder of the sediment succession (Fig. 4). Quinqueloculina seminulum appears a few hundred years later, c. 7200 cal. a BP, and is present more or less continuously throughout the zone. Echinoids prefer habitats without wide variations in salinity and Q. seminulum has a rather high salinity requirement (>25%, Knudsen 1971). The mollusc fauna in Zone 3 is scanty but dominated by high salinity demanding species such as the gastropods Turritella communis and Onoba vitrea and the bivalves Nucula nucleus, Tellimya ferruginosa, Saxicavella jeffreysi, Thracia phaseolina and Clausinella fasciata (Fig. 4). Overall, the fauna in Zone 3 indicates full marine conditions. The scanty occurrence of freshwater and terrestrial plant remains in Zone 3 suggests a high sea level and a large distance from the coastline to the coring point.

Zone 4 (topmost non-dated part of the sediment core; 0–130 cm below seabed). – The mollusc fauna is very sparse consisting of two taxa, Nucula sp. and Mysella bidentata. Remains of echinoids and foraminifera occur sporadically (Fig. 4) and the same is the case for fish bones and fish scales. Terrestrial/limnic plants also show a very scarce and sporadic occurrence including Juncus sp., Eupatorium cannabinum, Carex sp. and Chenopodiaceae undiff. The fossils indicate marine conditions.

Macrofossils, core M5
The macrofossil content of this core is uniform (Fig. 6), and it is described as one local macrofossil assemblage zone. The presence of high salinity demanding mollusc taxa such as the bivalves Nucula nucleus, Tellimya ferruginosa, Thyasira flexuosa, Ostrea edulis and Nuculana pernula and gastropods such as Turritella communis and Lunatia pallida (Fig. 6) indicates full marine conditions during the last c. 4400 years. A full marine environment is further consistent with an almost continuous presence of echinoid remains and Quinqueloculina seminulum. The content of land plants is very sparse (Fig. 6), which emphasizes the nature of an open marine environment with a long distance between the core site and the coast.

Sediment physical properties and accumulation rates, core M1
Zone 1 (c. 10 000–9000 cal. a BP). – The organic matter weight percentage (Wt%) is relatively high (~10–16%) until c. 9500 cal. a BP, whereafter it decreases to ~1.5% at the top of the zone (Fig. 7A). The carbonate wt% is very high at the beginning (~35%) and drops rapidly until the middle of the zone whereafter it remains at relatively low values. The minerogenic matter wt% exhibits the opposite tendency of the latter two sediment parameters with relatively low values at the start (~53%) and maximum values in the upper half of the zone (~97%). These changes in the weight percentages are also clearly reflected in the accumulation rates for the three sediment parameters.

Zone 2 (c. 9000–7700 cal. a BP). – Organic and carbonate matter wt% exhibit a slight increase at the start of the zone while minerogenic matter wt% shows a slight decrease. In the remaining part of the zone, all three sediment parameters exhibit rather constant values. The trends are again reflected in the accumulation rates, although with the difference that all three sediment parameters exhibit a marked increase in accumulation rates starting at the end of the zone around 7800 cal. a BP (Fig. 7A).
Fig. 6. Simplified macrofossil diagram for Aarhus Bay core M5 including marine animals and plant remains. Number of fossils per 50 cm³ of wet sediment. Dots indicate presence of taxa. The numbers following selected marine animals indicate lower salinity tolerances. [Colour figure can be viewed at www.boreas.dk]
Zone 3 (c. 7700–3700 cal. a BP). – The weight percentages for organic matter, carbonate and minerogenic matter are almost constant throughout the zone. The increase in accumulation rates for the three parameters, initiated at the end of the previous zone, peaks at the very beginning of Zone 3. The accumulation rates for all three parameters stay high (although with a slightly decreasing trend for carbonate and minerogenic matter) until c. 6300 cal. a BP. The accumulation rates are thereafter relatively constant during the remainder of the zone until 3700 cal. a BP.

Zone 4 (topmost non-dated part of the sediment core; 0–130 cm below seabed). – Through the topmost 130 cm of the sediment record weight percentages for organic and carbonate matter exhibit a steady decrease paralleled by a steady increase for minerogenic matter. Accumulation rates for this part of the record could not be calculated due to lack of chronology.

Sediment physical properties and accumulation rates, core M5

Weight percentages for organic, carbonate and minerogenic matter all exhibit rather constant values throughout the entire record (Fig. 7B). Organic matter wt% fluctuates between ~7 and 19, carbonate matter between ~4 and 11 and minerogenic matter between ~74 and 89. Accumulation rates for organic and carbonate matter are rather constant throughout the record, while the accumulation rates for minerogenic matter display a marked decrease around 1900 cal. a BP (Fig. 7B).

Grain-size distribution, core M1

Zone 1 (c. 10 000–9000 cal. a BP). – The lower half of the zone is characterized by rather fine-grained material with an average sand content of ~9% (Fig. 7A). This part is dominated by silt (75–80%). The upper half of the zone is dominated by sand (~68–94%).

Zone 2 (c. 9000–7700 cal. a BP). – The transition from Zone 1 to Zone 2 is marked by a sharp drop in sand content from 91 to around 8% (Fig. 7A).

Zone 3 (c. 7700–3700 cal. a BP). – This part of the sediment succession has a low and uniform sand content of 1–4% and a median grain size of fine silt.

Zone 4 (topmost non-dated part of the sediment core; 0–130 cm below seabed). – This part of the record exhibits a continuously increasing content of sand towards the seabed (from ~9% at 98.5 cm depth to 42.5% at 7.5 cm depth; Fig. 7A). The particle size distribution of this unit is mainly expressed by two modes (bi-modal; Fig. 8), thus indicating a distinct difference between the topmost ~100 cm of the sediment succession and the main part of the marine sediment record below (Zone 3), which is mainly characterized by one mode (Fig. 8).

Grain-size distribution, core M5

The median grain size of the M5 core sediments ranges from medium to very coarse silt. The samples exhibit a bi-modal particle size distribution similar to the most recent part of M1 (Fig. 8). The sand content of the record fluctuates between ~11 and 45% with a general upward coarsening trend interrupted by a lowered content centred about 2400 and 1300–700 cal. a BP (Fig. 7B).

XRF scanning

The XRF data of cores M1 and M5 are merged together to a single record for principal component analysis (PCA). The PCA loadings and biplots (Table 3, Fig. 9) show that terrigenous (land derived) elements (Ti, K, Al, Fe, Ca, Si, Sr) group together, suggesting an association with clay minerals and detrital input (Olsen et al. 2010; Kylander et al. 2011). Mn and S form another group with negative loadings on PCA, which together with Ti, K, Al and Fe explains the PCA variability (explaining 42.9% of the total variance). Both S and Mn are redox sensitive elements whose abundance may be influenced by both sedimentary and water column pH and redox potential. Ti, Fe and S have positive loadings on PCA2 (explaining 22.9% of the total variance) with Ca, Si and Sr having negative loadings (Table 3, Fig. 9). Elements such as Si and Ca may originate from allochthonous (detrital) as well as autochthonous (biogenic) sources. In order to differentiate the possible biogenic origins of Ca and Si and their abundances have been normalized to the chemically conservative element, Ti (Fig. 10). Similarly, Si is abundant in many aluminosilicate minerals but it may also be associated with biogenic sources, for example diatom productivity (Peinerud 2000). Hence, high Si/Ti values may indicate the presence of quartz and/or increased opal concentration. The strong correlation between Ca and Sr suggests that biogenic carbonate is particularly important in controlling the Ca abundance, which is confirmed by the close correspondence of the Ca/Ti ratio and the calcite content (Figs 9, 10). PCA3 (explaining 17.2% of the total variance) is dominated by Mn, S, Zr (Table 3, Fig. 9). Zr may be associated with coarse-grained deposits, whereas K is primarily associated with detrital clay minerals (Cuven et al. 2010) implying that the Zr/K ratio can be used as a grain-size indicator as supported by the grain-size analysis (Fig. 10).

Zone 1 (c. 10 000–9000 cal. a BP). – During the lower half of the zone, there is a switch from high Ca values and Ca/Ti ratios to elevated Ti values (Fig. 10), suggesting a change from predominantly carbonate content to a higher organic content. This is in good accord with both
Fig. 7. Stratigraphical plots of sediment data for cores M1 (A) and M5 (B) showing weight percentages for organic matter, CaCO\textsubscript{3} and minerogenic matter plus accumulation rates for the latter three sediment components. The curve for % sand is based on grain-size analysis.
the sediment and macrofossil analyses. Thus, the latter analysis shows a high content of molluscs, Chara and ostracods in the first part of the zone between c. 10 000 and 9600 cal. a BP. The upper half of the zone is characterized by steadily increasing Si/Ti ratios and elevated Zr/K ratios reflecting the presence of coarser-grained sediments, which is in accordance with the identified lithostratigraphical unit between 1017 and 1053 cm below the seabed (Table 2) predominantly consisting of sand with minerogenic matter weight percentages above 90% and a sand content between ~69 and 94% (Fig. 7A). The sand layer covers the period c. 9400–8900 cal. a BP.

Zone 2 (c. 9000–7700 cal. a BP). – Both Ca and Ti exhibit high values throughout Zone 2; however, interestingly the Ca/Ti ratio remains at similar values to the second part of Zone 1 (Fig. 10). Hence, the constant Ca/Ti ratio suggests a similar origin of both Ca and Ti pointing towards increased input from carbonate-rich till deposits. The most important factors controlling the magnitude of terrigenous input include freshwater discharge, sea-level change and depositional environment (bathymetry, current pattern and intensity). The ratios for Si/Ti and Zr/K are relatively stable throughout the zone. In addition, a constant Si/Ti ratio indicates that Ti, Si and Ca have a similar origin throughout Zone 2.

| Element | PCA1 | PCA2 | PCA3 |
|---------|------|------|------|
| Al      | 0.46 | 0.06 | 0.04 |
| K       | 0.45 | 0.21 | 0.00 |
| Ti      | 0.37 | 0.40 | 0.03 |
| Ca      | 0.35 | -0.32| -0.26|
| Si      | 0.33 | -0.26| 0.30 |
| Sr      | 0.32 | -0.40| -0.16|
| Fe      | 0.24 | 0.56 | -0.02|
| Zr      | 0.01 | -0.14| 0.61 |
| S       | -0.13| 0.30 | 0.47 |
| Mn      | -0.19| 0.21 | -0.47|

Table 3. PCA loadings on combined record of cores M1 and M5. PCA1–3 explain 82.9% of the total variance.

Zone 3 (c. 7700–3700 cal. a BP). – The Ti values slowly increase and then decrease whereas the Ca values decrease (Fig. 10). The Ca/Ti ratios slowly decrease, suggesting a decreased content of biogenic autochthonous Ca. A slight increase in the Zr/K ratio indicates a trend towards coarser grain size in concord with a minor increase in detrital content (Fig. 10).

Zone 4 (c. 3700–0 cal. a BP). – Most characteristic is the decreasing Ti trend throughout Zone 4 (Fig. 10). The Ca values show a minor decrease at the onset of Zone 4 and stabilize to constant values (Fig. 10). As a result, the Ca/Ti ratio is slightly elevated relative to Zone 3 probably indicating a higher relative content of biogenic Ca dominating the sediments. Interestingly the decreasing detrital or erosional derived Ti content occurs in concord with increasing Zr/K ratios suggesting a trend towards coarser grain sizes (Fig. 10). Fluctuating ratios for both Zr/K and Ca/Ti seem to indicate a varying depositional environment with changing grain sizes and input of terrigenous material. The latter interpretation is supported by the grain-size analysis, which shows a rather variable content of sand (Fig. 8). The slightly elevated Si/Ti ratios between c. 1100 and 800 cal. a BP may indicate an increased presence of quartz or an increased opal concentration.

Discussion

Based on the proxy data obtained for the sediment cores, the last c. 10 000 years of sedimentary and environmental development in the area can be inferred. The data indicate an overall development in three major phases: a limnic, a brackish-marine and a full marine phase.

Depositional and environmental reconstruction for core site M1

Limnic phase (c. 10 000–9000 cal. a BP). – The macrofossils in the lower part of the core indicate a near-shore lake environment with a shallow-water mollusc fauna and aquatic macrophyte vegetation (Figs 4, 5, 11). Remains of terrestrial species were either blown out into the freshwater deposits or transported into the basin by streams or rivers. The latter mode of transport may also apply to some of the aquatic macrophyte remains. According to the age model, the oldest remain of Alnus glutinosa (a nutlet) has an age of 9850±110 cal. a BP making it the oldest find of this species in Denmark. The hitherto oldest A. glutinosa remains from the Danish area were 14C dated to c. 9500 cal. a BP (Bennike et al. 2004).

The sediments in the limnic phase exhibit a marked change from deposits rich in carbonate and organic matter to almost pure sand (Figs 7A, 10). The nearly pure sand unit at the end of the phase probably represents lake shore deposits. The high carbonate values at the
Beginning of the phase are probably due to a high content of shell material and in particular of ostracods plus maybe outwash of carbonate from glacial tills. The phase is characterized by a low sedimentation rate with an average of \( \approx 0.68 \) mm a\(^{-1}\) (Fig. 11).

*Brackish-marine phase (c. 9000–7700 cal. a BP).* — The presence of marine molluscs and foraminifera from the beginning of this phase (Figs 4, 11) testifies that the area from now on was inundated by marine water, at least temporarily. According to the age model, the deepest-lying marine shell (*Cerastoderma edule*) has an age of 8950±90 cal. a BP; this age is interpolated and is therefore subject to some uncertainty. However, a specimen of *C. edule* situated 5 cm above the former shell was \(^{14}\)C dated to c. 8900 cal. a BP (Table 1), implying that it is reasonable to assume that the first marine inundation of the area took place around 9000 cal. a BP. This age is somewhat older than the hitherto oldest dating of a marine shell from the central part of Aarhus Bay.

![Fig. 9. Principal component analysis (PCA) on the combined XRF data from cores M1 and M5. The first three components explain 82.9% of the total variance.](www.boreas.dk)

![Fig. 10. PCA, XRF, CaCO\(_3\) and sand content for cores M1 and M5 as a function of age.](www.boreas.dk)
The evidence from Aarhus Bay is in good accord with results from two fjords south of Aarhus Bay, Horsens Fjord and Norsminde Fjord, where the first marine inundation has been dated to c. 8800 and c. 8900 cal. a BP, respectively (Olsen et al. 2009; Rasmussen in press). Although scarce the mollusc fauna in this part of the M1 record indicate relatively shallow brackish-marine conditions with predominance, especially in the early part of the phase, of typical low-salinity tolerant species such as *Cerastoderma edule*, *Mytilus edulis* and *Hydrobia ventrosa* (Fig. 4); at the end of the phase the former species are to some extent replaced by two more salt-demanding species (*Corbula gibba* and *Hinia reticulata*). At the beginning of the phase, freshwater molluscs and a substantial number of freshwater aquatic macrophyte remains occur together with the marine species. This mixture of brackish and freshwater taxa may be due to reworking of the limnic deposits in connection with the seawater flooding of the area. Disturbance of the previously deposited limnic sediments by the marine transgression probably also explains the occurrence of a few foraminifera a few centimetres deeper than the above-mentioned deepest-laying marine shell (i.e. at the end of the limnic phase; Fig. 4). The deposits with mixed occurrence of brackish and freshwater taxa have a high sand content while the subsequent sediments are fine-grained marine mud with high and stable Ti and Ca values (Fig. 10). The latter fine-grained sediments indicate an increasing sea level although still characterized by a relatively near-coastal environment with a certain input of terrestrial and freshwater macrofossils (Figs 4, 5) probably reflecting an estuarine environment. The average sedimentation rate in this phase is c. 0.95 mm a\(^{-1}\) (Fig. 11).

**Full marine phase (c. 7700–3700 cal. a BP).** – The appearance of a high salinity demanding fauna in this phase (several mollusc species, echinoids and *Quinqueloculina seminulum*) indicates a change to full marine conditions (Figs 4, 11). This marked environmental change coincides with a rapid and significant sea-level rise documented in both the Danish and the Baltic area dated to around 7600 cal. a BP (Fig. 11; Mørner 1969; Christensen 1995, 1997; Yu et al. 2007; Lampe et al. 2011; Sander et al. 2015) and probably of global

![Fig. 11. Diagram showing selected plant and animal taxa, % sand and sedimentation rate for core M1 along with regional sea-level curves from Vedbæk (VE), eastern Zealand, Denmark (Christensen 2001) and Blekinge (BL), southeast Sweden (Berglund et al. 2005). Dots indicate presence of taxa. The numbers following selected marine animals indicate lower salinity tolerances.](image-url)
extent related to the so-called ‘global meltwater pulse 3’ documented in Caribbean-Atlantic coral sea-level records. c. 7600 cal. a BP (Blanchon & Shaw 1995; Blanchon et al. 2002; Bird et al. 2010; Blanchon 2011a, b). Based on data from a recent study on the island of Samsø in the central Kattegat, Sander et al. (2015) estimated a relative sea-level rise of ~4.5 m between 7600 and 7200 cal. a BP. A high sea level in Aarhus Bay at this stage is supported by an almost complete absence of terrestrial plant macrofossils (Fig. 5) testifying to an increased distance between the core site and the shore. The start of the changing environmental conditions (high sea level, high salinity) in Aarhus Bay must be seen in conjunction with hydrographic changes demonstrated in the Skagerrak, Kattegat and Baltic Sea. Thus, in a study of the Holocene environmental development in Skagerrak the most distinct shift in the foraminiferal fauna was dated to c. 8000 cal. a BP and related to the opening of the English Channel and the Danish straits (Erbs-Hansen et al. 2012) – two events that are considered to be a prerequisite for the establishment of the modern circulation pattern in the North Sea, Skagerrak and Kattegat (e.g. Conradsen & Heier-Nielsen 1995; Knudsen et al. 1996; see also Nordberg 1991). It should be emphasized, however, that there is no consensus amongst different authors regarding the dates of these two important events (Gyllencreutz et al. 2006).

The English Channel obtained its present width c. 7950 cal. a BP (Behre 2007) and the oldest dates of marine shells in the central Great Belt area are c. 8100 cal. a BP (Bennike et al. 2004). Based on numerical models, Lambeck (1999) estimated that a free and unobstructed flow of water through the Danish straits was established by 7800–7500 cal. a BP, which is in good agreement with evidence from the southwestern Baltic Sea (Mecklenburg Bay, Germany) where mollusc and diatom data reveal that marine conditions with salinities higher than today were established c. 7600 cal. a BP (Witkowski et al. 2005; see also Moros et al. 2002; Schmölcke et al. 2006; Virtasalo et al. 2007; Rößler et al. 2011). In the Fårö Deep near Gotland in the central Baltic Sea, dinoflagellate data indicate a gradual salinity increase from 7800 cal. a BP and with a period of maximum sea-surface salinity from 7200 to 5200 cal. a BP (Willumsen et al. 2012). In a recent study of sediment cores from the Arkona Basin of the Baltic Sea, both alkenone distributions and hydrogen isotopic composition suggest a shift in haptophyte species composition from lacustrine to brackish type haptophytes around 7700–7200 cal. a BP reflecting a salinity change when the connection between the basin and the North Sea was established (Warden et al. 2016).

The opening of the English Channel created a direct route for inflow of the warmer Atlantic waters off northern France into the North Sea and the opening of the Danish straits ended the Ancylus freshwater stage of the Baltic area (Björck 1995, 2008; see also Weckström et al. 2017). It is our belief that the modern water exchange system between the Baltic and the North Sea was not permanently established until about 7700/7600 cal. a BP coinciding with the aforementioned significant sea-level rise and following a preceding period with brackish conditions (Björck et al. 2008; Weckström et al. 2017).

The above hydrographic changes, and in particular the sea-level rise, are probably the reason for the observed drastic increase in sedimentation rates in Aarhus Bay initiated around 7700 cal. a BP (Figs 7A, 11). A marked increase in sea level would have resulted in flooding of large land areas implying erosion and increased transport of terrestrial material (organic and inorganic) to the seabed. Due to intensified water exchange during a sea-level highstand (cf. Gustafsson & Westman 2002), there was probably also enhanced supply from primary production (organic matter, CaCO3) and from sediment-loaded inflows of high salinity water from the North Sea. In the period of greatly increased sedimentation (c. 7700–6300 cal. a BP), the average rate is ~2.8 mm a−1 (Fig. 11). The extensive coastal erosion during this sea-level highstand period is manifested in today’s landscape in the form of numerous fossil coastal cliffs situated above present-day sea level that formed during the Mid-Holocene when the relative sea level was ~3 m higher than present along the coasts of the Aarhus Bay area (Mertz 1924).

Taking dating uncertainties into account, the rapid and marked decrease in sediment accumulation rates around 6350 cal. a BP may be related to a drop in sea level evident in both the Danish and Swedish areas at about this time (Fig. 11; Christensen 1982; Berglund et al. 2005). A sea-level fall would have reduced the accommodation space resulting in less deposition of sediment. The slight but steady decrease in sedimentation rate subsequent to the marked drop in sea level c. 6400/6300 cal. a BP may probably be ascribed to a continuous reduction in accommodation space caused by long-term sediment infilling and isostatic uplift. Changes in lithology (coarser sediments) and foraminiferal data initiated around 6350 cal. a BP and lasting until c. 3800 cal. a BP have been ascribed to a strengthening of the Jutland current resulting in higher energy conditions and increased inflow of North Sea water into the Kattegat (Conradsen & Heier-Nielsen 1995; Knudsen et al. 1996; Jiang et al. 1997). This hydrographic shift (intensification of the Jutland current c. 6400/6300 cal. a BP) has been ascribed to the final flooding of the Jutland Bank area in the North Sea, dated to c. 6400–6200 cal. a BP (Leth 1996; Jensen et al. 2011; Erbs-Hansen et al. 2012).

The topmost 14C sample in the M1 core dated to c. 3700 cal. a BP is situated 130 cm below the seabed (Table 1). As this date fits well into the age model for the entire sediment core (Fig. 2), it appears to give a reliable age of this part of the succession implying that only 130 cm of sediment has been deposited over the past
3700 years. This is highly unlikely and as revealed by several proxies from the topmost ~100 cm of the record this unit differs markedly from the marine mud below in terms of a strong increase in sand, decreasing organic matter wt% and CaCO3 wt% and increasing minerogenic matter wt%, plus a strong increase in the Zr/K ratio (Figs 7A, 11). These sedimentary features – a marked upward coarsening grain size and decreasing organic content – clearly indicate that this part of the record is physically reworked and vertically mixed leading to a residual accumulation of coarser particles produced by winnowing of finer material. The reworked sediments may theoretically have been formed at any time between c. 3700 cal. a BP and the present day. However, in Norsminde Fjord, ~20 km south of Aarhus Bay, the base of similar reworked sediments has the same age (c. 3700 cal. a BP; Rasmussen in press) and this simultaneity strongly suggests a situation of widespread seabed erosion around 3700 cal. a BP. This assumption is further sustained by the recent investigations of Sander et al. (2015) on the island of Samsø where ages from three coastal lagoon sites for beds of marine sand overlaying marine mud deposits are consistently dated to 4300–3800 cal. a BP. The reason for widespread erosion around this particular time can be related to a pronounced sea-level drop precisely at this time as shown by several authors (e.g. Mörner 1979; Clemmensen et al. 2001; Hansen et al. 2016; Lomholt et al. 2017). In a study of the island of Anholt in the central part of the Kattegat, the drop in absolute sea level was estimated to 2.6 m over a 700-year period between 4300 and 3600 cal. a BP (with most of the sea-level fall taking place between 4250 and 3740 cal. a BP; Clemmensen et al. 2012). A sea-level lowering of that magnitude would undoubtedly have led to reduction in accommodation space and at places zero accommodation space leading to erosion and sediment by-pass. Based on changes in sedimentology and in foraminiferal assemblages in several cores from the Kattegat, Nordberg & Bergsten (1988) and Nordberg (1991) have previously demonstrated sediment cessation around 4000 14C-years BP (= c. 4800–4150 cal. a BP) at water depths less than 20–25 m. The chronologies for the latter cores are rather uncertain but the evidence from Kattegat presumably correlates with the findings in Aarhus Bay, Norsminde Fjord and Samsø and might therefore indicate that this cessation of sedimentation (erosion or non-deposition) is a widespread phenomenon. Nordberg & Bergsten (1988) and Nordberg (1991) interpreted their data as reflecting a hydrographic shift due to changes in the inflow-outflow between the North Sea and the Skagerrak–Kattegat–Baltic related to an increased flow of the Jutland Current (see also Gyllencreutz 2005; Gyllencreutz et al. 2006). The combination of the above inferred hydrographical changes around 4000 cal. a BP – a significant sea-level drop and strengthening of the current system – may together have led to erosion and non-deposition in many places in the Danish waters. The marked sea-level drop may ultimately be related to a climatic change of presumed northern hemispheric extent around 4200 cal. a BP (named the 4.2 ka BP climatic event), which in northern Europe is characterized by a shift to cooler and wetter conditions (Olsen et al. 2010; Walker et al. 2019).

Depositional and environmental reconstruction for core site M5

The retrieved M5 sediment succession covers the last c. 4400 years. Although sparse, the marine fauna with high salinity demanding molluscs, echinoids and Quinqueloculina seminulum (Fig. 6) indicate full marine conditions throughout the entire time-span. Furthermore, the sparse presence of terrestrial macrofossils and probably also the steady decrease in Ti values (Figs 6, 10) testify to a considerable distance between the core site and the coast. The variable sand content in the sediments and fluctuating Zr/K ratios indicate a relatively changeable depositional environment (Fig. 10). This pattern may possibly be related to the hydrographic regime initiated c. 6400/6300 cal. a BP characterized by a strengthening of the Jutland current, higher energy conditions and increased inflow of North Sea water into the Kattegat. Contemporary data indicate that inflow of high-salinity water into Aarhus Bay is associated with inflow of the Jutland current into the Kattegat, but the evidence does not allow a definitive conclusion (Lund-Hansen & Skyum 1992). The present-day current system in the bay is dominated by barotropic induced inflows (Skyum & Lund-Hansen 1992) and given such inflows also in the past, it is possible that the tendency for a bimodal grain-size distribution and generally high sand content (Figs 7B, 8) might be related to turbulence associated with inflow events of high-salinity near-bottom water, plus generally high-energy conditions in the outer eastern part of the bay, directly into the Kattegat. Opposite to the central part of Aarhus Bay (M1) sedimentation in the eastern part (M5) continued after c. 3700 cal. a BP and until today (see below). Thus, the marked sea-level drop between c. 4200 and 3700 cal. a BP (see above) has not led to non-deposition, which is probably due to the greater water depth with more available accommodation space at this site.

A marked decrease in minerogenic matter accumulation starting around 1900/1800 cal. a BP (Fig. 7B) may possibly be related to a roughly contemporary decrease in sedimentation in southern Kattegat observed by Nordberg & Bergsten (1988) and dated to c. 2000 cal. a BP. The latter authors ascribe this event to a minor hydrographic shift.

The very high sand content at the top of the M5 core (Fig. 7B; 45% at 20.5 cm depth below the seabed) may indicate some erosion, possibly as a result of near-bottom currents. The topmost 14C sample situated at 30.5 cm depth below the seabed gave the result c. 260 cal. a BP. As
this age fits well into the age model for the entire sediment succession (Fig. 2), it implies that apparently only sediments post-dating c. 260 cal. a BP may have been affected by erosion.

**Potential pitfalls revealed by the geological record**

As demonstrated in this study, there is some indication that the topmost sediments in the M1 sediment succession in the central part of the bay are strongly influenced by physical reworking. According to the seismic data, this sediment unit is present over large areas in the bay (Fig. 3) implying large-scale erosion, which in turn might explain the present-day flat seabed topography (Figs 1, 3) as a result of erosion-induced levelling of the seabed over extensive areas. The presence of reworked and vertically mixed sediments may also explain why there, despite several published studies from the bay, has not yet been (as far as we know) a well-developed radioisotope-based ($^{210}$Pb and $^{137}$Cs) age model from the bay providing a reliable chronology for the last 100–150 years. Studies of present-day sedimentation in the bay show an intense resuspension underlining the dynamic nature of the seabed; on an annual basis, the deposition of resuspended sediment is thus calculated to be about four times higher than the bottom sediment accumulation rate (Pejrup et al. 1996). Besides causing dating problems, sediment reworking may affect organic matter mineralization (Kristensen et al. 1992; Sun et al. 1999; Ingalls et al. 2000; Green et al. 2004), the structure and porosity of the sediment matrix (Meysman et al. 2005), the release of nutrients from the sediment to the water column (Biles et al. 2002; Mermillod-Blondin et al. 2005), and the sequestration of pollutants and contaminants (Lee & Swartz 1980; Thompson & Riddle 2005; Bradshaw et al. 2006). Hence, when dealing with a sediment unit in Aarhus Bay characterized by vertical mixing, by poor or lacking age control and by environmental data that may be biased, there is reason to caution against using the topmost ~1 m of the sediment record from the flat central part of the bay when trying to answer sedimentary, environmental and biogeochemical questions.

The present study illustrates the value of insights into the geological and palaeoenvironmental background for a certain marine area before commencement of major monitoring programmes and other studies based on recent and sub-recent sediments. A geological perspective on the depositional and environmental development may uncover potential pitfalls inherent in the sedimentary record with consequences for a correct comprehension of the recent and sub-recent conditions. A similar lesson was also drawn by Woods & Kennedy (2011) from work in estuarine environments in New Zealand, a lesson that they phrase in the following direct way: ‘Most short-term sedimentation methods are meaningless without knowledge of the estuarine development and infill over the Holocene’.

**Conclusions**

This study of two sediment cores from Aarhus Bay elucidates the sedimentary and environmental development of the area over the last 10 000 years. A sediment core from the central and shallower part of the bay covers the time-span from c. 10 000–3700 cal. a BP while a core from the eastern and deeper part of the bay covers the time-span from c. 4400 cal. a BP to the present.

Based on the proxy analysis and $^{14}$C dating, the development can be divided into three phases. (i) A limnic phase (c. 10 000–9000 cal. a BP). The macrofossils indicate a near-shore lake environment with mesotrophic–eutrophic water. The sediments in the lower half of the phase are dominated by carbonate and organic matter. In the upper half, the sediments are dominated by sand, which are interpreted as lake-shore deposits. (ii) A brackish-marine phase (c. 9000–7700 cal. a BP). The start of the phase is defined by the first occurrence of marine molluscs, reflecting the time of the first intrusion of seawater into the area. The fauna indicates a relatively shallow brackish-marine environment. A mixture of brackish and freshwater taxa found in sandy deposits at the beginning of the phase indicates reworking of the underlying limnic sediments associated with the marine transgression. Hereafter, the sediments consist of fine-grained marine mud reflecting an increased sea level, although still relatively shallow and near-shore as evidenced by a significant input of terrestrial and freshwater plant remains probably reflecting an estuarine environment. (iii) A full marine phase from c. 7700 cal. a BP until the present day with high salinity demanding species.

The marked change in the environment at c. 7700 cal. a BP is probably related to a contemporary rapid and significant sea-level rise documented in the Danish and Baltic areas around 7600 cal. a BP. This sea-level rise is probably on a global scale and may have resulted in the final opening of the Danish straits and establishment of the modern water exchange system between the Baltic and the North Sea. The sea-level rise is also the likely background for a greatly increased sedimentation rate in Aarhus Bay between c. 7700 and 6400/6300 cal. a BP, as a high sea level would lead to flooding of large areas of land and increased input of eroded material. The subsequent drop in sedimentation rate around 6400/6300 cal. a BP may be related to a sea-level decrease dated to about this time.

Continuous sedimentation ceased at the shallow site around 3700 cal. a BP most probably due to a dramatic sea-level drop in the Kattegat region between 4250 and 3740 cal. a BP. The sediments between ~100 cm depth and the seabed show clear signs of physical reworking and vertical mixing (marked upward-coarsening sediments, bi-modal grain-size distribution and decreasing organic content) implying that great caution should be exercised when using this part of the sediment record for
elucidating recent and sub-recent biotic and abiotic conditions in Aarhus Bay.

In contrast to the shallow core site, sedimentation in the eastern and deeper part of Aarhus Bay continued until the present day. A distinct decrease in minerogenic matter sedimentation rates around 1900/1800 cal. a BP may reflect a small hydrographic change, which has previously been described for the southern Kattegat around this time.

**Acknowledgements.** – Funding for the fieldwork for this study was received from the Danish National Research Foundation and the German Max Planck Society to Bo Barker Jørgensen (Aarhus University). Kaarina Weckstrøm assisted with the figures, Bente Rasmussen (Aarhus University) assisted with the grain-size analysis, Rudolf Endler (IOW) helped with the XRF scanning and Jonathan P. Lewis (Loughborough University) made linguistic corrections to the manuscript. Heartfelt thanks to everyone for their help. Constructive comments by journal referees Thomas Andren and an anonymous referee as well as the editor Jan A. Piotrowski helped to improve the paper.

**Author contributions.** – PR and JBJ designed the study; JBJ acquired the seismic data, chose coring sites and logged cores; PR conducted macrofossil analyses; GP conducted sedimentological analyses; JO carried out age-depth modelling and interpreted XRF data; OB contributed to the interpretation of the results and final text editing; and PR wrote the manuscript with input from all authors.

**Data availability.** – The data that support the findings of this study are available from the corresponding author upon reasonable request.

**References**

Andrén, E., Andrén, T. & Søhlenius, G. 2000: The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from Bornholm Basin. *Boreas* 29, 233–250.

Andrén, T., Björck, S., Andrén, E., Conley, D., Zillén, L. & Anjær, 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. Central and Eastern European Development Studies (CEEDES)*, 75–97. Springer, Berlin.

Behre, K.-E. 2007: A new Holocene sea-level curve for the southern North Sea. *Boreas* 36, 82–102.

Bendixen, C., Jensen, J. B., Boldrell, O. L., Clausen, O. R., Bennike, O., Seidenkrantz, M.-S., Nyberg, J. & Häuscher, C. 2017: The Holocene Great Belt connection to the southern Kattegat, Scandinavia: Ancylus Lake drainage and early Littorina Sea transgression. *Boreas* 46, 53–68.

Bennike, O. & Høeg, W. 1999: Late Glacial and early Holocene records of *Stratratia aloides* L. from northwestern Europe. Review of Paleoecology and Palynology 107, 259–263.

Bennike, O., Jensen, J. B., Konradi, P. B., Lemke, W. & Heinemeier, J. 2000: Early Holocene drowned lagoon deposits from the Kattegat, southern Scandinavia. *Boreas* 29, 272–286.

Bennike, O., Jensen, J. B., Lemke, W., Kuijpers, A. & Lomholt, S. 2004: Late- and postglacial history of the Great Belt, Denmark. *Boreas* 33, 18–33.

Berglund, B. E., Sundgren, P., Barnekow, L., Hannon, G., Jiang, H., Skog, G. & Yu, S. Y. 2005: Early Holocene history of the Baltic Sea, as reflected in coastal sediments in Blekinge, southeastern Sweden. *Quaternary International* 130, 111–139.

Biles, C. L., Paterson, D. M., Ford, R. B., Solan, M. & Raffaelli, D. G. 2002: Bioturbation, ecosystem functioning and community structure. *Hydrology and Earth System Sciences* 6, 999–1005.

Bird, M. I., Austin, W. E. N., Wurster, C. M., Fitfield, L. K., Mojahid, M. & Sargeant, C. 2010: Punctuated eustatic sea-level rise in the early mid-Holocene. *Geology* 38, 803–806.
Nordberg, K. & Bergsten, H. 1988: Biostratigraphic and sedimentological evidence of hydrographic changes in the Kattegat during the later part of the Holocene. Marine Geology 83, 135–158.

Odgaard, B. V. & Rasmussen, P. 2001: The occurrence of egg-cocoons of the leech Piscicola geometra (L.) in recent lake sediments and their relationship with remains of submersed macrophytes. Archiv für Hydrobiologie 152, 671–686.

Olsen, J., Ascough, P., Lougheed, B. C. & Rasmussen, P. 2017: Radiocarbon dating in estuarine environments. In Weckström, K., Saunders, K. M., Gell, P. A. & Skilbeck, C. C. (eds.): Applications of Paleoenvironmental Techniques in Estuarine Studies, 141–170. Developments in Paleoenvironmental Research 20. Springer Science, Dordrecht.

Olsen, J., Noe-Nygaard, N. & Wolfe, B. B. 2005: Mid to Late Holocene biogeochemistry: a multi-proxy dataset of lake Søby, Denmark. Journal of Paleolimnology 34, 323–343.

Olsen, J., Rasmussen, P. & Heinemeier, J. 2009: Holocene temporal and spatial variation in the radiocarbon reservoir age of three Danish fjords. Boreas 38, 458–470.

Pedersen, S. A. S. & Petersen, K. S. 2000: Djsralsk Geologi, 96 pp. Geological Survey of Denmark and Greenland, Copenhagen.

Peinerud, E. K. 2000: Interpretation of Si concentrations in lake sediments: three case studies. Environmental Geology 40, 64–73.

Pejrup, M., Valeur, J. & Jensen, A. 1996: Vertical fluxes of particulate organic matter in Aarhus Bight, Denmark. Continental Shelf Research 16, 1047–1064.

Pedersen, K. S. 2004: Late Quaternary environmental changes recorded in the Danish marine molluscan faunas. Geological Survey of Denmark and Greenland Bulletin 3, 372 pp.

Rasmussen, P. in press: The terrestrial and marine palaeoenvironment in the Danish marine molluscan faunas. Geological Survey of Denmark and Greenland Bulletin 3, 372 pp.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Burr, G. S., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haji cb, I., Heaton, T. J. H., Hughen, K. A., Kaiser, K. F., Kromer, B., McCormac, F. G., Manning, S. W., Reimer, R. W., Richards, D. A., Southon, J. R., Talamo, S., Turney, C. S. M., van der Plicht, J. & Weyhenmeyer, C. E. 2009: IntCal09 and Marine09 radiocarbon age calibration curves. Radiocarbon 51, 387–498.

Schörling, B.-H. 1989: Aquatic macrophytes. In Vestergaard, P. & Hansen, K. (eds.): Distribution of vascular plants in Denmark, 25–30. Opera Botanica 96. Council for Nordic Publications in Botany, Copenhagen, Denmark.