Late Glacial and Holocene shore-level changes in the Aarhus Bugt area, Denmark

Ole Bennike1, Katrine Juul Andresen2, Peter Moe Astrup3, Jesper Olsen4, Marit-Solveig Seidenkrantz2

1Geological Survey of Denmark and Greenland (GEUS), Aarhus, Denmark, 2Department of Geoscience and iClimate Centre, Aarhus University, Denmark, 3Moesgaard Museum, Aarhus, Denmark, 4Aarhus AMS Centre, Department of Physics and Astronomy, Aarhus University, Denmark

Abstract

We propose a new relative shore-level curve for the Aarhus Bugt area, an embayment in eastern Jylland, Denmark, based on a compilation of published and new radiocarbon ages of organic material. Lakes existed in the area during the Late Glacial and Early Holocene. Lake level rose gradually until the region was inundated by the sea at c. 9000 cal. years BP. The relative sea level reached a high stand at about 6000 cal. years BP, when the local relative sea level was c. 3 m above present-day mean sea level. The Aarhus Bugt area was inundated by the sea later than the Limfjord area in northern Jylland, but earlier than the Lillebælt region in southern Denmark. The shore-level curves for these areas differ partly because the glacio-isostatic uplift was more pronounced in the Limfjord area than farther south and partly because the northern regions were inundated by the sea earlier than the southern areas.

Introduction

During the Last Glacial Maximum, large parts of Denmark were covered by the Scandinavian ice sheet (Houmark-Nielsen et al. 2012). About 21 000 cal. years BP (before present, i.e. before 1950 CE), the ice sheet began to retreat partly because of melting and partly because of iceberg calving. As the colossal mass of glacier ice disappeared from the land areas, glacio-isostatic rebound began. Uplift of the land is still ongoing, with highest uplift rates in the northern part of Denmark and lowest in the southwestern part of the country (Vestel et al. 2019).

Concurrent with the glacio-isostatic rebound, global mean sea level also rose as large amounts of meltwater from the retreating ice sheets flowed into the world's oceans. In total, sea level has risen about 125 m after the Last Glacial Maximum (Chapell & Shackleton 1986; Lambeck et al. 2014). The combination of land uplift and sea-level rise results in local and regional relative sea-level changes. These relative sea-level changes can be reconstructed by dating samples that can be related to a former high-tide level, so-called sea-level index points. However, in the inner Danish waters, we do not have information on sea-level index points, instead we used dating of shells of marine
gastropods or bivalves that lived below sea level, peat that accumulated in bogs above sea level or tree stumps or roots of land plants. Archaeological finds from refuse layers can also provide knowledge of sea level at a given time. These limiting data can be used to reconstruct former sea level, but sea-level curves based on such data are less well constrained than sea-level curves based on index points.

The aim of this paper is to present a shore-level curve for the Aarhus Bugt area (Fig. 1), from where we have a fairly large number of radiocarbon ages from marine, lacustrine and terrestrial deposits (Table 1). We have compiled 32 ages and propose a new curve for the Late Glacial and Holocene relative shore-level changes in the area. We use the term shore-level change rather than sea-level change because we have constructed both lake-level and sea-level changes. The shore-level curve for Aarhus Bugt fills a knowledge gap on shore-level changes in Denmark and adds to a growing number of shore-level curves from the region (e.g. Bennike & Jensen 2011; Clemmensen et al. 2012, 2018; Bennike et al. 2012, 2019; Hede et al. 2015; Sander et al. 2016).

Material and methods
New ages used to reconstruct shore-level changes come partly from two vibrocores (502052 and 502017-1) collected in relation to mapping of sand and gravel resources and from a gravity core (AU18-MG-09G) collected during a student cruise with the Aarhus University research vessel Aurora in 2018. Core positions were selected based on shallow seismic data and sub-bottom profiles collected during the cruise. We also include new ages from sediment cores retrieved from Brabrand Sø, a lake that was formerly a fjord. In addition, ages from published literature concerning archaeological excavations on land (Andersen & Liversage 1994; Heinemeier & Rud 1999, 2001; Kveiborg 2014), marine archaeological investigations in Kalø Vig (Fischer & Hansen 2005; Astrup 2018), geological studies of Aarhus Bugt (Jensen & Bennike 2009; Rasmussen et al. 2020) and an age of a pine (Pinus sylvestris) stump that was found during deepening of the harbour at Aarhus are included (Heinemeier & Rud 2000). The location of the dated samples appears in Fig. 1. We estimate that the elevation uncertainty is up to ± 0.25 m.

The material for radiocarbon dating has been dried and submitted to a variety of laboratories; most
samples, however, have been dated at the Aarhus AMS Centre (AARAMS; marked AAR in Table 1). These are partly remains of land plants and shells from marine molluscs. Most of the age determinations were performed by accelerator-mass spectrometry (AMS) by measuring the ratio of $^{14}$C to $^{12}$C atoms (Olsen et al. 2009), but ages marked K in Table 1 are conventional $^{14}$C ages. The ages are stated in conventional radiocarbon years BP and corrected for isotope fractionation by normalising to a $^{6}$LiC value of $-25\%$ VPDB (Stuiver & Polach 1977). The radiocarbon ages are calibrated to calendar years before present using the CALIB version 8.2 program (Stuiver et al. 2021). For marine samples, we used the marine calibration curve MARINE20, and for terrestrial samples, we used the INTCAL20 curve. For marine samples, we used a reservoir age of 400 years (i.e. $\Delta R = -150$ years). Both the new ages and previously published ages have been recalibrated for this study.

**Sediments and macrofossils**

The sediments in the cores from Aarhus Bugt area encompass till deposits from the last glaciation (Weichselian), Late Glacial lacustrine clay, Holocene non-marine deposits and, finally, Holocene marine sediments. Late Glacial fossiliferous (terrestrial and lacustrine plants and invertebrates) deposits were found in vibrocore 502052, which was 11.6 m long and collected at a water depth of 29.1 m (Fig. 1 and Table 1). The Late Glacial flora comprised the woody plants *Betula nana*, *Dryas octopetala*, *Salix polaris* and *Emmetrus nigrum*. Macrolimnophytes were represented by *Menyanthes trifoliata*, *Potamogeton filiformis*, *P. perfoliatus*, *P. natans*, *Callitriche hermaphroditica* and *Chara* sp. Invertebrates comprised the leech *Erpobdella* sp., the ostracods *Cytherissa lacustris*, *Limno- cytthea* sp., *Condona* sp., the gastropods *Valvata cristata* and *V. piscinalis*, the bivalve *Psidium* sp. and the bryozoan *Cristatella mucro.*
A subsample of *Betula nana*, *Dryas octopetala* and *Salix polaris* remains was dated to the Younger Dryas, a cold period at the end of the Weichselian (Table 1). This is in accordance with the flora and fauna, which are typical of Younger Dryas deposits in the region (Bennike et al. 2004). The terrestrial plants indicate a tree-less, tundra-like landscape characterised by dwarf shrub heaths. The Early Holocene terrestrial flora from Aarhus Bugt included the trees *Betula* sect. *Albae* (tree birch), *Populus tremula* (aspen), *Pinus sylvestris* (pine) and *Alnus glutinosa* (alder), indicating a landscape with open forests.

Vibrocore 502017-1 shows an example of a succession with clayey till, peat, lacustrine gyttja, marine mud and, finally, marine sand and gravel (Fig. 2). The lower part of the peat is dominated by stems and leaves of the brown moss *Scorpidium*, whereas the upper part of the peat is dominated by twigs, indicating that the former bog was overgrown by trees or bushes. Woody plants are represented by *Alnus glutinosa*, *Betula* sect. *Albae* and *Cornus sanguinea*. A fruit stone of the latter, which came from the upper part of the peat, was dated to c. 8850 cal. years BP (Fig. 2). The lacustrine gyttja is dominated by vegetative remains of *Phragmites*; it also contains numerous shells of lacustrine cladocerans. The marine mud contains a mollusc fauna that indicate lowered salinity and the ostracod *Cyprideis torosa*, which is typical of environments with low and strongly fluctuating salinities (Frenzel et al. 2012; Pint et al. 2012). The submerged macromolluskyne *Ruppia* indicates shallow water. The marine mud is overlain by marine sand and gravel, presumably reflecting an increasing energy level as the sea level rose.

**Shore-level changes**

In Fig. 3, we have plotted ages against elevation for marine, lacustrine and terrestrial deposits. Based on these ages, we suggest a curve that shows the development of the shore level in the Aarhus Bugt region over the last 12 000 years. The dated material comes from different sources, and it is difficult to quantify the vertical error on the samples, but we suggest an error of ± 0.5 m. Peat can be compacted significantly when covered by sand and many metres of seawater, which will lower the deposit (Baeteman et al. 2012).

The curve is, thus, not well constrained, and we only indicate a likely development with a dashed line. The oldest age based on remains of dwarf shrubs from vibrocore 502052 yielded an age of 11 405–11 971 cal. years BP (Table 1). The lithology and fossil content of the core shows that at this time, there were lakes in the deep parts of Aarhus Bugt. The water level in the lakes rose in the following period, and the lakes became larger. In the Early Holocene, peat bogs were probably widespread in wet areas of the Aarhus Bugt area, whereas more dry areas were forested.

Based on the radiocarbon ages, it appears that the sea began to inundate the Aarhus Bugt area about 9000 years ago (Fig. 3), as also concluded by Rasmussen et al. (2020). The marine inundation occurred because the rising global sea level surpassed the local glacio-isostatic land uplift of the area. At c. 9000 cal. years BP, global mean sea level was approximately 15 m lower than today (Lambeck et al. 2014). Initially, mixing of freshwater and seawater in the littoral zone created brackish conditions, as evidenced by the occurrence of low salinity species associated with shallow-water conditions, such as the bivalve *Cerastoderma* sp. and *Mytilus edulis*, the gastropods *Littorina littorea* and *Hydrobia*, and the ostracod *Cyprideis torosa*. The relative sea-level rose until about 6000 cal. years ago, when it reached its maximum (Fig. 3). The timing of the sea-level maximum is constrained by dating of a shell of *Littorina* from a raised beach ridge on the island of Hjelm. The marine limit on the island is c. 3 m above mean sea level, but raised beaches occur up to 5.3 m (Mertz 1924). The shell was found at an elevation of 3.8 m, and the beach was probably deposited during a storm. The shell yielded an age of c. 5900 cal. years BP (Table 1; Heinemeier & Rud 2001). At Aarhus, the marine
limit is c. 2.5 m, at Ebeltoft, it is c. 3.5 m and in the north-eastern part of Djursland, it is c. 5 m above present levels (Mertz 1924). Over the last 6000 years, global sea levels have been largely stable (e.g. Lambeck et al. 2014), whilst in the Aarhus Bugt area, this period is marked by land uplift out-pacing the rate of sea-level rise resulting in a fall in the relative sea level. We have indicated a steady decline until today, but this part of the curve is poorly constrained with data and very uncertain (Fig. 3).

Dating of a *Mytilus edulis* (blue mussel) shell from marine deposits in lake Brabrand Sø gave a surprisingly old age (Fig. 3). This indicates that the reservoir age was more than 400 years in the early stages of the fjord. It is also seen that two ages from Lystrup Enge appear to be too old. These ages come from samples deposited in shallow water close to the former seashore.

Comparisons with other shore-level curves from Denmark (Bennike & Jensen 2011; Bennike et al. 2019) show similar trends to the curve from the Aarhus Bugt area (Fig. 4). However, marine waters inundated the western Limfjord earlier than Aarhus Bugt, which, in turn, was inundated earlier than southern Lillebælt. Raised marine deposits are found up to 5 m above present sea level in the western Limfjord area, whereas raised marine deposits are not found in southern Lillebælt, where the rate of sea-level rise surpassed the glacio-isostatic uplift.

Conclusions

During the Younger Dryas, most of Aarhus Bugt was dry land with dwarf shrub heaths, but small lakes existed locally. In the earliest Holocene, most of Aarhus Bugt was dry land, but lakes soon filled the deeper parts of the area. The lakes expanded in size and shore-level rose. During this period, the trees *Betula* sect. *Albae*, *Populus tremula*, *Pinus sylvestris* and *Alnus glutinosa* immigrated to
the region forming open forests. Rising global sea levels resulted in a marine inundation of the deepest parts of Aarhus Bugt at about 9000 cal. years BP, and the relative sea level rose gradually during the following millennia and reached a high stand at c. 6000 cal. years BP, as documented by raised beach ridges on Hjelm island. We propose that the relative sea level fell gradually during the Late Holocene due to gradual glacio-isostatic rebound, but the timing is not yet fully constrained.

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Author contributions

OB: macrofossil analyses and manuscript writing. JO: radiocarbon dating, kJA, PMA and MSS: field work and editing of the manuscript.

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