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

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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.

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Abbreviations:
AARAMS: Aarhus AMS Centre
AMS: accelerator-mass spectrometry
BP: Before present

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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 (Vestøl *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

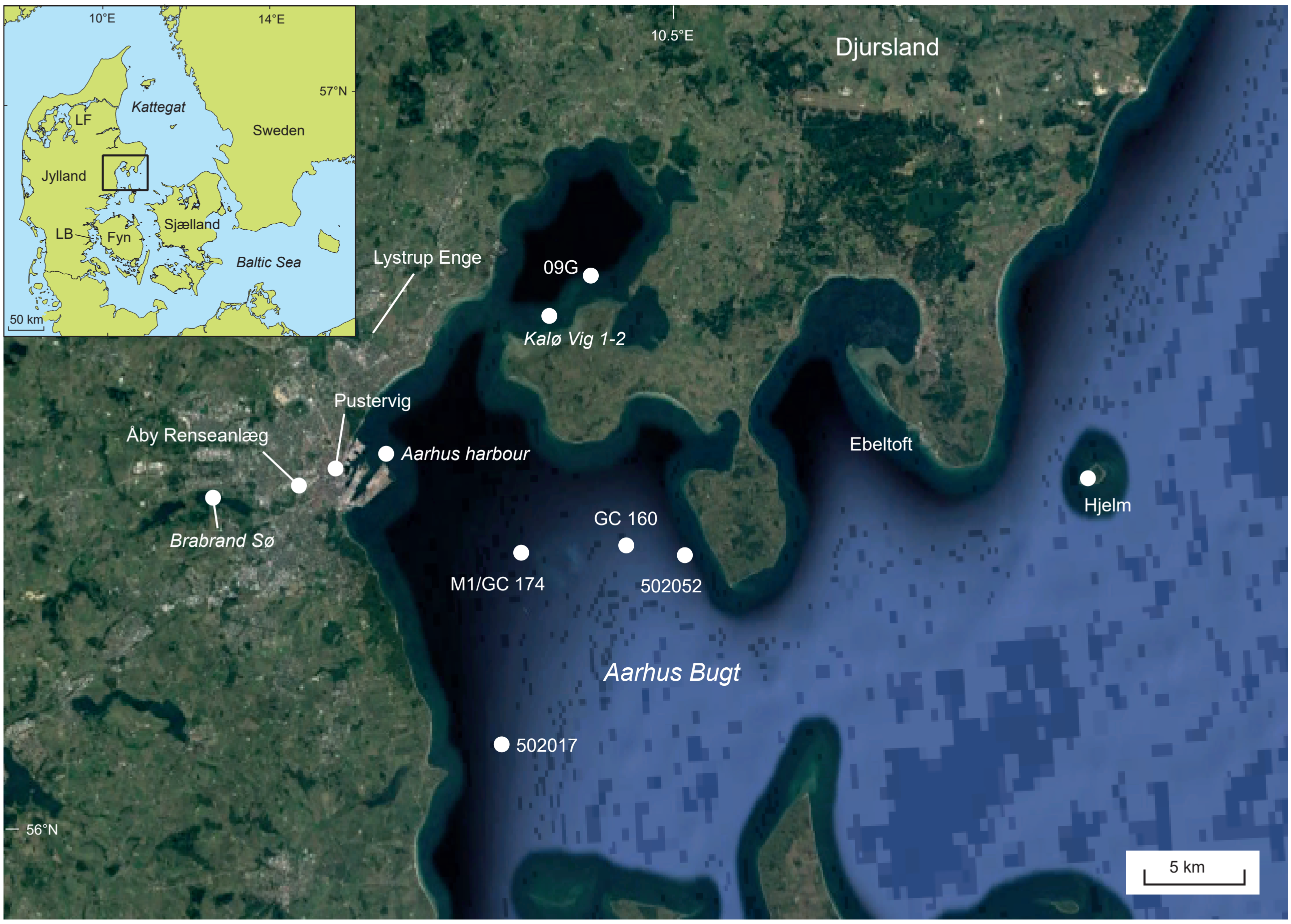

Fig. 1 Map of the Aarhus Bugt area, showing localities with radiocarbon-dated samples. **LF**: Limfjorden; **LB**: Lille Bælt (inset map).

Table 1 Selected radiocarbon ages from the Aarhus Bugt area, Denmark.

Core/site	Latitude (°N)	Longitude (°E)	Laboratory number	Material	Elevation (cm)	Age (^{14}C a BP)[1]	Cal. age (a BP)[2]	Ref.
502017-1	56.033	10.326	Ua-57753	*Cornus sanguinea*	−1120	7972 ± 37	8648–8993	a
502052	56.112	10.478	AAR-29102	*Menyanthes trifoliata*	−3318	10 007 ± 36	11 280–11 697	a
502052	56.112	10.478	AAR-29103	*B.nana+Dryas+S.pol.*	−3420	10 158 ± 54	11 405–11 971	a
GC 160	56.117	10.433	POZ-7848	*Cerastoderma edule*	−2580	8290 ± 40	8628–9002	b
GC 174	56.117	10.35	POZ-10516	*Mytilus edulis*	−1640	7870 ± 50	8150–8477	b
GC 174	56.117	10.35	POZ-10517	*Cerastoderma lamarcki*	−1740	8240 ± 50	8567–8976	b
M1	56.117	10.35	AAR-16263	*Cerastoderma edule*	−2616	8349 ± 45	8690–9107	c
M1	56.117	10.35	UBA-19004	*Corylus avellana*	−2640	8565 ± 43	9473–9658	c
M1	56.117	10.35	AAR-18772	*Deciduous leaf fragment*	−2660	8432 ± 32	9328–9530	c
M1	56.117	10.35	AAR-18773	*Betula, Meny, Schoeno*	−2695	8910 ± 34	9906–10 183	c
Aarhus Havn	56.147	10.24	AAR-4859	*Pinus sylvestris stump*	−1350	8200 ± 70	9003–9406	d
Pustervig	56.158	10.208	AAR-4161	*Littorina*	−36	4885 ± 50	4943–5366	e
Åby Rense.	56.152	10.178	AAR-12828	*Cerastoderma sp.*	−100	5179 ± 39	5325–5648	f
Brabrand Sø	56.146	10.109	AAR-30708	*Ostrea edulis*	−710	6260 ± 31	6495–6836	a
Brabrand Sø	56.146	10.109	AAR-30707	*Ostrea edulis*	−865	5862 ± 34	6079–6395	a
Brabrand Sø	56.146	10.109	AAR-30706	*Mytilus edulis*	−877	8512 ± 40	8967–9310	a
Brabrand Sø	56.146	10.109	AAR-30705	*Twig*	−890	9249 ± 40	10 262–10 560	a
Brabrand Sø	56.146	10.109	AAR-30704	*Populus tremula*	−898	9377 ± 37	10 500–10 702	a
Brabrand Sø	56.143	10.09	AAR-30093	*Schonoplectus lacustris*	−58	2831 ± 32	2853–3058	a
Brabrand Sø	56.143	10.09	AAR-30092	*Cerastoderma*	−62	5428 ± 33	5602–5909	a
Brabrand Sø	56.143	10.09	AAR-30091	*Littorina littorea*	−216	7274 ± 36	7564–7848	a
Brabrand Sø	56.143	10.09	AAR-30090	*In situ root, woody plant*	−224	6895 ± 39	7624–7834	a
Kalø Vig 1	56.219	10.383	AAR-8413	*In situ Quercus root*	−670	7690 ± 45	8394–8586	g
Kalø Vig 2	56.219	10.383	AAR-27412	*Tree stump*	−750	7813 ± 75	8417–8977	h
09G	56.236	10.418	AAR-30088	*Twig*	−1363	8219 ± 46	9022–9399	a
09G	56.236	10.418	AAR-30089	*Twig*	−1359	8256 ± 41	9032–9412	a
Hjelm	56.135	10.8	AAR-5486	*Littorina littorea*	+380	5525 ± 55	5674–6083	i
Lystrup Enge	56.223	10.225	K-4053	*Corylus branches*	−85	6210 ± 105	6799–7411	j
Lystrup Enge	56.223	10.225	K-5730	*Populus dugout boat*	−35	6110 ± 100	6741–7252	j
Lystrup Enge	56.223	10.225	K-6012	*Tilia dugout boat*	−81	6550 ± 105	7259–7614	j
Lystrup Enge	56.223	10.225	K-6335	*Quercus tree trunk*	−25	5450 ± 100	5950–6440	j
Lystrup Enge	56.223	10.225	K-6397	*Quercus tree trunk*	−48	6570 ± 100	7273–7613	j

[1] Ages in conventional radiocarbon years BP (before present = 1950; Stuiver & Polach (1977)); [2] Calibration to calendar years BP (2 sigma) is according to the INTCAL20 or MARINE20 data (Reimer *et al*. 2020; Heaton *et al*. 2020).
Ref.: References. a: this study, b: Jensen & Bennike (2009), c: Rasmussen *et al*. (2020), d: Heinemeier & Rud (2000), e: Heinemeier & Rud (1999), f: Kveiborg (2014), g: Fischer & Hansen (2005), h: Astrup (2018), i: Heinemeier & Rud (2001), j: Andersen & Liversage (1994).

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 δ^{13}C value of −25‰ VPDB (Stuiver & Polach 1977). The radiocarbon ages are calibrated to calendar years before now 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. ΔR = −150 years). Both the new ages and previously published ages have been (re)calibrated 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 *Empetrum nigrum*. Macrolimnophytes were represented by *Menyanthes trifoliata*, *Potamogeton filiformis*, *P. perfoliatus*, *P. natans*, *Callitriche hermaphroditica* and *Chara* sp. Invertebrates comprised the leach *Erpobdella* sp., the ostracods *Cytherissa lacustris*, *Limnocythere* sp., *Candona* sp., the gastropods *Valvata cristata* and *V. piscinalis*, the bivalve *Pisidium* sp. and the bryozoan *Cristatella mucedo*.

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

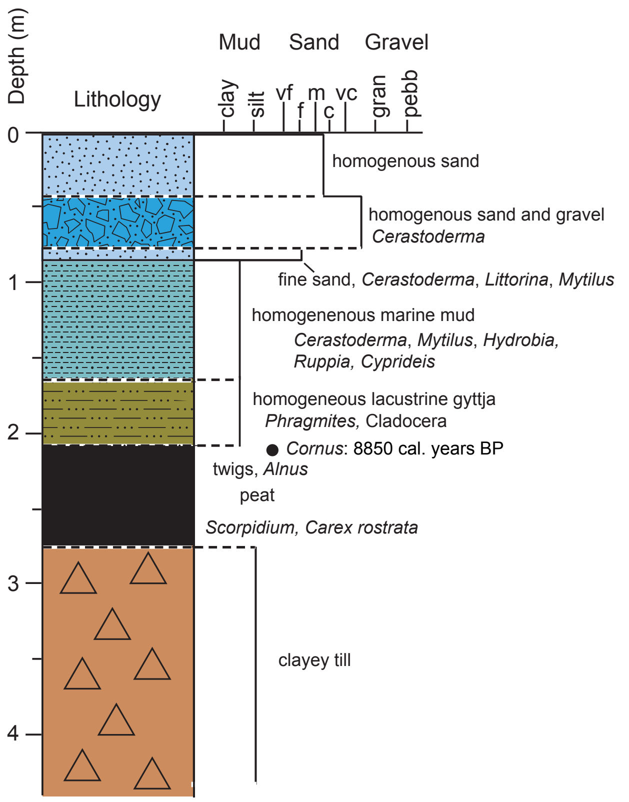

Fig. 2 Sedimentological log of vibrocore 502017-1, collected at 56.033°N, 10.326°E, at a water depth of 9.1 m. The presence of peat with remains of *Alnus* overlain by lacustrine gyttja and marine mud shows that the area has been transgressed by the sea. A fruit stone of *Cornus sanguinea* was dated to *c.* 8850 cal. years BP (Table 1).

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 macrolimnophyte *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 bivalves *Cerastoderma* sp. and *Mytilus edulis*, the gastropods *Littorina littorea* and *Hydrobia* sp. 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

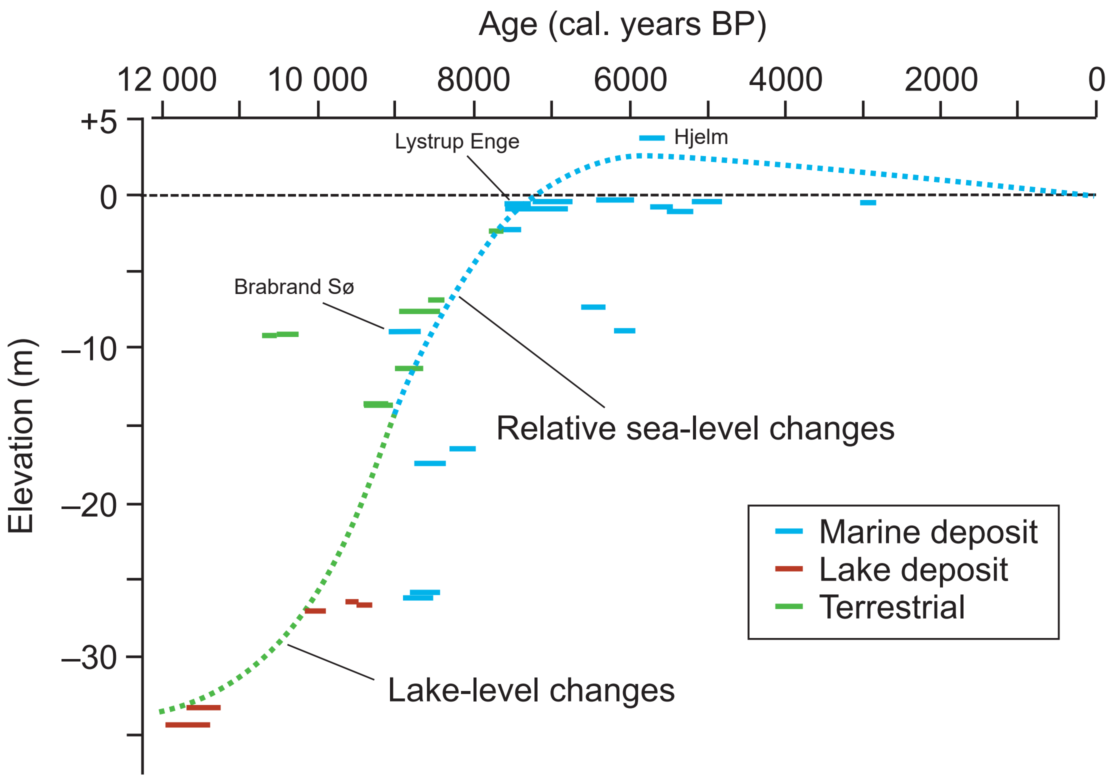

Fig. 3 Radiocarbon ages from the Aarhus Bugt area, plotted against elevation. The length of the bars represents the uncertainty range in the calibrated age (Table 1). The **dashed curve** shows our best estimate of the relative shore-level changes from *c.* 12 000 cal. years BP until today, with the shift from green to blue colour, indicating the time of the marine inundation of the Aarhus Bugt area.

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.

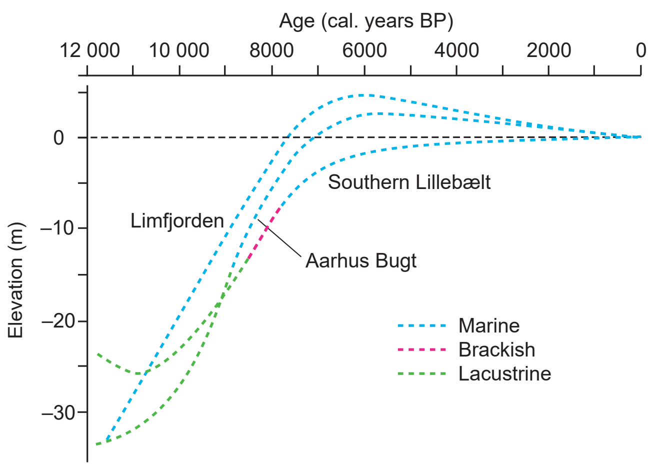

Fig. 4 Comparison of shore-level curves for the western Limfjord area (Bennike *et al.* 2019), the Aarhus Bugt (this study) area and southern Lillebælt region (Bennike & Jensen 2011).

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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