Early Holocene sea-level changes in Øresund, southern Scandinavia

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The Baltic Sea and Kattegat are connected via three straits: Storebælt, Lillebælt and Øresund (Fig. 1). Øresund is the shallowest with a threshold around 7 m deep and increasing water depths to the north (Fig. 2). In the early Holocene, global sea-level rise led to reflooding of Øresund. It started in northern Øresund which was transformed into a fjord. However, so far the timing of the transgression has not been well determined, but sediment cores collected north of the threshold, at water depths of 12 to 20 m, and a new series of radiocarbon ages help to constrain this. As the relative sea level continued to rise, the threshold in Øresund was also flooded, and Øresund became a strait. In mid-Holocene time, the relative sea level rose until it was 4–5 m higher than at present, and low-lying areas around Øresund became small fjords. During the late Holocene, the relative sea level fell again. Part of the data set discussed here was presented by Andreasen (2005).

Active glacier ice disappeared from the region around 17 cal. ka BP (calibrated kilo-years before present; Houmark-Nielsen & Kjær 2003). During deglaciation, the ice margin receded southwards and huge amounts of meltwater flowed northwards and formed deep holes and channels.

Shortly after the deglaciation of the region, marine waters inundated Øresund and remains of Arctic species such as polar cod (*Boreogadus saida*) and ringed seal (*Phoca hispida*) have been found and dated to around 16 and 17.6 cal. ka BP (Lagerlund & Houmark-Nielsen 1993). During this time, the relative sea level must have been high, reflecting the loading of the Fennoscandian Ice Sheet during the Last Glacial Maximum.

Somewhat later Øresund played an important role in draining the Baltic Ice Lake, and a major delta formed north of Øresund. Radiocarbon dating of marine mollusc shells from the delta has given ages between 16.3 and 11.8 cal. ka BP. Following isostatic rebound the relative sea level fell, and major parts of Øresund became dry land with forests, lakes and peat bogs. Submarine lake and peat deposits from the Younger Dryas and the early Holocene have been reported (Jessen 1923). Several now submarine former settlements have been reported from Øresund (Fischer 1993), which can be referred to the Mesolithic based on artefacts and radiocarbon dating.

Methods

Sediment coring was carried out with a 10 cm diameter vibrocorer from R/V *Alexander von Humboldt* and R/V

Fig. 1. Map of Denmark and the surrounding area showing the location of Øresund and other place names mentioned in the text.
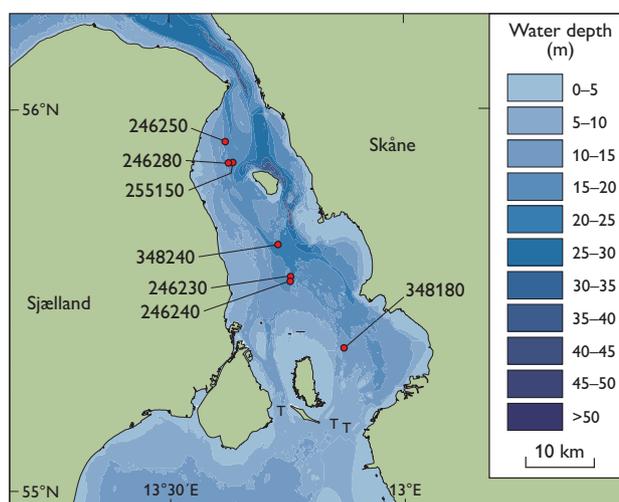
Fig. 2. Map of the Øresund region showing the bathymetry and the location of vibrocores. **T**: Threshold.

Table 1. Selected radiocarbon ages from Øresund

Core/ locality	N. lat. no.	W. long.	Lab. no.	Material	Depth bct* (cm)	Depth b.s.l. (m)	Age (^{14}C years BP)	Calibrated age (years BP)[†]
246230	55°46.801′	12°44.461′	AAR-8284	*Mytilus edulis*	105–115	21.2	8310 ± 70	8765–8981
246230	55°46.801′	12°44.461′	AAR-8285	*Mytilus edulis*	542	25.5	9155 ± 70	9840–10 101
246230	55°46.801′	12°44.461′	AAR-8286	*Phragmites australis*	560–570	25.7	9445 ± 70	10 569–10 781
246240	55°46.440′	12°44.392′	AAR-8287	*Macoma balthica*	120–130	18.0	9200 ± 70	9907–10 129
246240	55°46.440′	12°44.392′	AAR-8288	*Macoma balthica*	380–390	20.6	9380 ± 80	10 147–10 333
246250	55°57.811′	12°36.327′	AAR-8626	*Littorina littorea*	58–60	16.4	8455 ± 35	9003–9109
246250	55°57.811′	12°36.327′	AAR-8627	*Littorina littorea*	64–70	16.5	8565 ± 40	9113–9301
246250	55°57.811′	12°36.327′	AAR-8603	*Macoma balthica*	270–280	18.7	9475 ± 35	10 253–10 372
246250	55°57.811′	12°36.327′	AAR-8601	Woody plant roots	300–310	18.9	8820 ± 40	9740–10 115
246280	55°56.104′	12°36.696′	AAR-8628	*Cerastoderma edulis*	203–207	18.4	9270 ± 45	10 039–10 189
246280	55°56.104′	12°36.696′	AAR-8630	Wood	215–223	18.6	8940 ± 40	9941–10 193
246280	55°56.104′	12°36.696′	AAR-8604	*Phragmites australis*	220–230	18.6	8975 ± 50	9951–10 228
246280	55°56.104′	12°36.696′	AAR-8631	*Corylus avellana*	352–356	19.9	8740 ± 35	9606–9772[‡]
255150	55°56.144′	12°37.247′	AAR-8632	*Scirpus* spp.	190–200	20.3	8765 ± 40	9686–9887
348180	55°40.883′	12°51.410′	Poz-42496	*Cladium mariscus*	365–370	15.7	8660 ± 50	9546–9662
348240	55°49.398′	12°42.976′	Poz-42497	*Phragmites australis*	400	26.0	9240 ± 50	10 298–10 498
Pilhaken			AAR-1225	*Corylus avellana*		7.8	8120 ± 90	8980–9259[$]
Pilhaken			T-10667	*Quercus* sp.		7.8	7945 ± 75	8649–8977[$]
Svalerumpen			K-6036	Tree root		5.9	7680 ± 115	8386–8586[$]
Svalerumpen			T-10665	*Pinus sylvestris*		6.5	8225 ± 95	9031–9300[$]

* Below core top. [†] Calibration is according to the INTCAL09 data (terrestrial samples) and the Marine09 data (marine samples). [‡] Too young compared with the other dates from the core. [$] Fisher (1993).

Professor Penck. Coring positions were selected from high-resolution shallow seismic profiles. The seismic equipment comprised a boomer, an X-star and a sediment echosounder. Differential GPS was used for navigation. The cores were split and described in the laboratory, and selected cores were subsampled for palaeoecological analyses. The samples were wet sieved on 0.4, 0.2 and 0.1 mm sieves, and the residue left on the sieves was analysed with a dissecting microscope. Macrofossils were identified using a reference collection. Remains of terrestrial plants and marine molluscs were used for accelerator mass spectrometry (AMS) radiocarbon age determination (Table 1).

Results

Most of the cores consisted of Holocene marine clayey and silty mud, sometimes with marine sand in the upper part. One core (348180) contained rootlet-peat overlain by sediment with numerous fruits of *Cladium mariscus* and shells of land gastropods. Core 348240 contained sediment with *in situ* rootlets tentatively identified as *Phragmites australis*.

Figure 3 shows an example of a macrofossil diagram. A total of 74 taxa were noted, but only 17 of them are shown in the simplified diagram. The sequence coarsens upwards; this is interpreted as an increased energy level as the sea level rose and the basin was transformed to a fjord. Common remains of tree birch (*Betula* sect. *Albae*) and pine (*Pinus sylvestris*, not

shown) as well as rare remains of aspen (*Populus tremula*) indicate that the shore was not far away.

The lower part of the sequence is dominated by lacustrine taxa, such as the leach *Erpobdella* sp. and the bryozoan *Cristatella mucedo*. Shells and head shields of freshwater fleas (Cladocera) are also abundant. Macrolimnophytes are represented by, for example, *Najas minor* and *Zannichellia palustris*. Both can tolerate some brackish water influence, and the sediments contain rare remains of Hydroidea and the ostracode *Cythoromorpha fuscata*, implying a weak influence of brackish water. The presence of *Najas minor* seeds indicates that summer temperatures were slightly higher than at present (Bennike *et al.* 2001). This may be confirmed by the common presence of *Cladium mariscus* fruits in core 348180, but this plant is calciphilous and its abundance in early Holocene deposits may reflect that leaching of the soils was not as far advanced as today.

In the middle part of the sequence a marked peak in *Scirpus* spp. (mainly *Scirpus tabernaemontani*) fruits is seen, and at about the same level *Phragmites australis* seeds also show a maximum. This may imply erosion of reed beds as the sea level rose.

At around 220 cm depth *Hydrobia ulvae* and at around 180 cm depth *Ruppia* sp., *Potamogeton pectinatus* and *Littorina littorea* appear, indicating increased salinity, followed by *Nucula nucleus*, *Corbula gibba* and other marine species that indicate a salinity similar to present values.
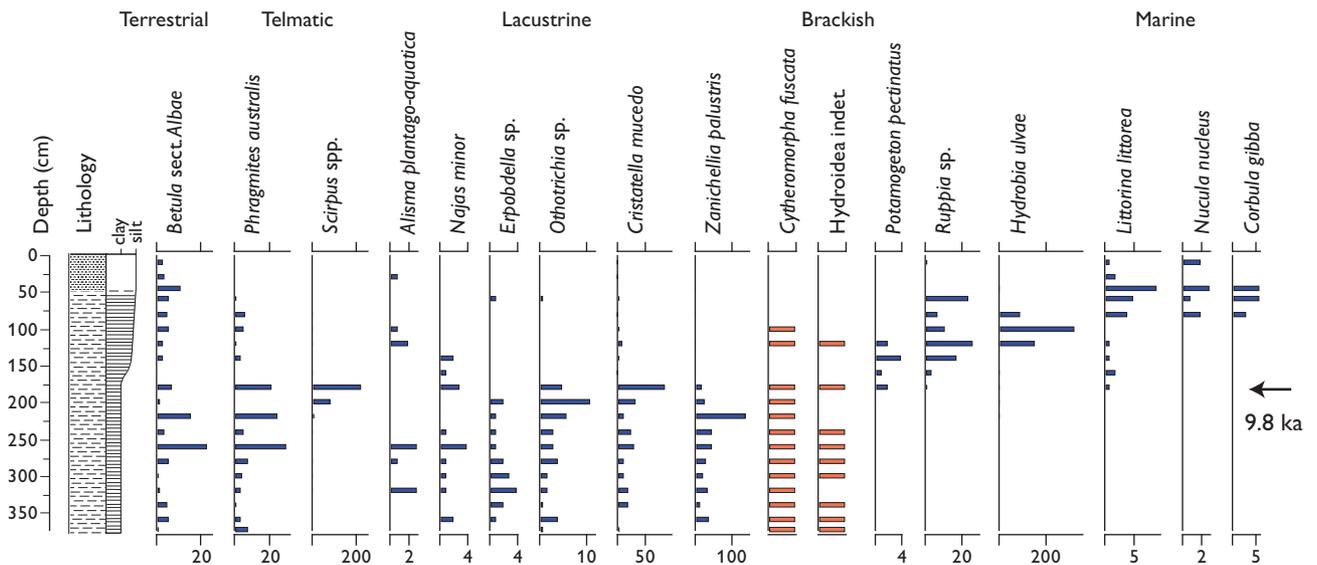
Fig. 3. Strongly simplified macrofossil concentration diagram of core 255150 from Øresund. The core consists of a lower unit of horizontally layered clay and silt and an upper unit of homogenous silty mud. A single sample has been dated to 9686–9887 cal. years BP (Table 1). The red bars show remains that were not counted.

Sea-level changes

Figure 4 shows a plot of the ages of radiocarbon dated samples against depth. We have included a few samples from archaeological sites (Table 1; Fisher 1993). The full black line shows relative sea-level changes during the mid-Holocene according to Christensen (2001), when a number of small transgressions and regressions occurred. A similar picture may have characterised the late Holocene, but due to lack of data we have drawn a straight, stippled line for this time period.

We have also drawn a straight line for the early Holocene. We consider this unlikely, but the data do not allow us to draw a more elaborate line. The marine and terrestrial samples should fall respectively below and above the line. However, it is not possible to draw the line so that this is fulfilled. This means that some of the ages are not correct. Several explanations for this can be offered. One factor to consider is differential isostatic rebound. The samples come from a fairly large region, but most of the isostatic rebound occurred prior to the Holocene, and the marine limit only falls from *c.* 5.5 to *c.* 4 m from north to south (Christensen 2001). Hence we suggest that the depth of the dated samples should be moved by only 1–2 m, which does not change the picture.

We consider two other factors more important. One is the marine reservoir effect, for which a value of 400 years was used, which is common for the region. However, large variations are seen from place to place, and in closed fjords it can be several hundred years greater than the regional value. Variations of several hundred years may also take place over

time (Olsen *et al.* 2009). The other factor is that some mollusc species, such as *Macoma balthica* used in this study, can take up old carbon from the sediment, and dating of such species may therefore also produce ages that are several hundred years older than contemporaneous terrestrial samples (Mangerud *et al.* 2006).

Dating of terrestrial samples can also be problematic, and here we have excluded an age determination of a hazel (*Corylus avellana*) nut fragment that appears to be too young. An explanation for this could be contamination by modern carbon in the laboratory. We consider the other ages
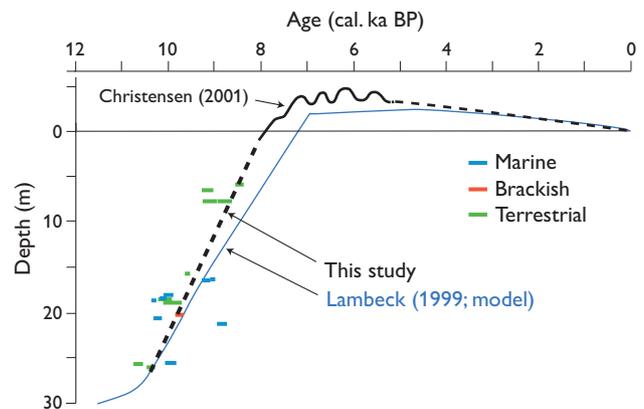
Fig. 4. Tentative curve showing relative sea-level changes in Øresund during the Holocene, based on radiocarbon dated samples. The curve is compared with a curve based on numerical, geophysical modelling by Lambeck (1999). **ka**: kilo-annum (one thousand years).

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of terrestrial material to be reliable and have drawn the curve so that the terrestrial samples fall above it. According to the curve, the relative sea level rose *c.* 25 m to the present level from 10 to 8 ka BP. We have compared the curve with a curve constructed by Lambeck (1999), using numerical modelling, which shows a good fit (Fig. 4).

Discussion and conclusions

During the earliest Holocene, large parts of Øresund were dry land, but local lakes and bogs existed in depressions. The shore level of the southern Baltic Sea and Kattegat reached a lowstand (Björck 1995). As the water level in Kattegat began to rise, a fjord with brackish water and limited water exchange formed in northern Øresund.

Later, the ongoing eustatic sea-level rise led to increased salinity, and the fjord became larger. At the same time, the water level in the Baltic Basin also increased (Jensen *et al.* 1999). The threshold in Øresund was flooded between 9 and 8 ka, and Øresund developed into a strait.

The oldest dated marine shell from Øresund gave an age of 10.3–10.4 cal. ka BP, but we suggest that this is somewhat too old, and marine water probably did not reach a level of around 25 m b.s.l. until *c.* 10 ka. However, at the entrance to Øresund where the water depth is 35–40 m, marine waters may have begun to enter several millennia earlier according to Lambeck's model (Fig. 4). In Storebælt, the oldest dated marine shell gave an age of *c.* 8100 cal. years BP (Bennike *et al.* 2004), in the Lillebælt the oldest shell date is *c.* 7700 cal. years BP (Bennike & Jensen 2010) and in Mecklenburger Bucht, the oldest reported shell date is *c.* 7600 cal. years BP (Bennike & Jensen 1998). These differences partly reflect different threshold levels. However, freshwater drainage from the Baltic Basin through Storebælt may also have inhibited marine bivalves from entering this strait for centuries or millennia.

Acknowledgements

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