Development of the western Limfjord, Denmark, after the last deglaciation: a review with new data

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This paper presents new marine evidence of Lateglacial and Holocene environmental changes in the western part of Limfjorden, and provides a review of the geological history/development of this part of northern Jylland, Denmark. Lateglacial clay without fossils is widespread in the region and is probably a glaciolacustrine deposit. Limfjorden began to form as a strait in the Early Holocene due to rising relative sea level and the oldest marine shells are dated to *c.* 9300 cal. years BP. We propose a new relative sea-level curve for the region based on new and published data, which appear to confirm that the relative sea-level change was not extremely rapid, which was suggested earlier. During the Mid-Holocene a wide connection existed from the western part of Limfjorden to the North Sea in the west and more narrow connections existed between Limfjorden and Skagerrak in the north. The marine fauna included several species that indicate warmer and more salty waters than at present. Gradually, the connections to the North Sea and Skagerrak closed due to long-shore sediment transport and deposition of aeolian sand combined with a fall in the relative sea level during the Middle- to Late Holocene. During the Viking Age, 800–1050 CE (Common Era), the western connection to the North Sea was still open, but around 1200 CE it was closed by a coastal sandy barrier and the western part of Limfjorden became brackish. The coastal barrier was flooded on several occasions but soon formed again. After 1825 CE the western connection from Limfjorden to the North Sea has been maintained artificially.

Keywords: Holocene, Lateglacial, relative sea-level changes, salinity changes, Limfjorden, Denmark.

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In coastal regions erosion and deposition of sand and mud by currents and waves can have a significant impact on habitats and human living conditions. This is in particular evident where areas may change from a fresh-water dominated to a marine-water or brackish-water dominated environment as a result of shifting isolation of inland water bodies from the sea. Such shifts in environmental conditions may occur very rapidly in response to a single storm surge, but may have long-term effects on environmental conditions. The area around Limfjorden in northern Jylland, Denmark, has undergone repeated and rapid changes in environmental conditions. Limfjorden is a long strait which today connects the North Sea in the west and the Kattegat in the east (Fig. 1). The opening to the Kattegat seems to have persisted during most of the Holocene, whereas the opening to Skagerrak in the north-west closed in the Middle to Late Holocene. The opening to the North Sea in the west has been closed during part of the Late Holocene (Jessen 1936).

Historical documents show that for a long time period prior to 1825 CE, the western Limfjord was separated from the North Sea by a coastal barrier known as Limfjordstangen, interrupted by a number of periods of open passage (Gram-Jensen 1991). Since then the opening to the North Sea has been permanent, in particular since 1863 CE, when it was decided to maintain the opening artificially. At that time the western Limfjord thus shifted from primarily brackish to consistently marine conditions.

This paper has three aims: (1) a review of the Lateglacial and Holocene history of the western part of

Limfjorden, (2) a discussion of the recent geological and environmental history of the western Limfjord, between Thyborøn Kanal in the west and Aggersund in the east (Fig. 1), and (3) an investigation of the effects of changing environmental conditions on the habitats for marine life. New data on sea-level changes are presented, which support a newly published sea-level curve (Jessen *et al.* 2019). Many of the previous

Fig. 1. Map of Denmark and neighbouring parts of Sweden and Germany. The box indicates the study area in Limfjorden.

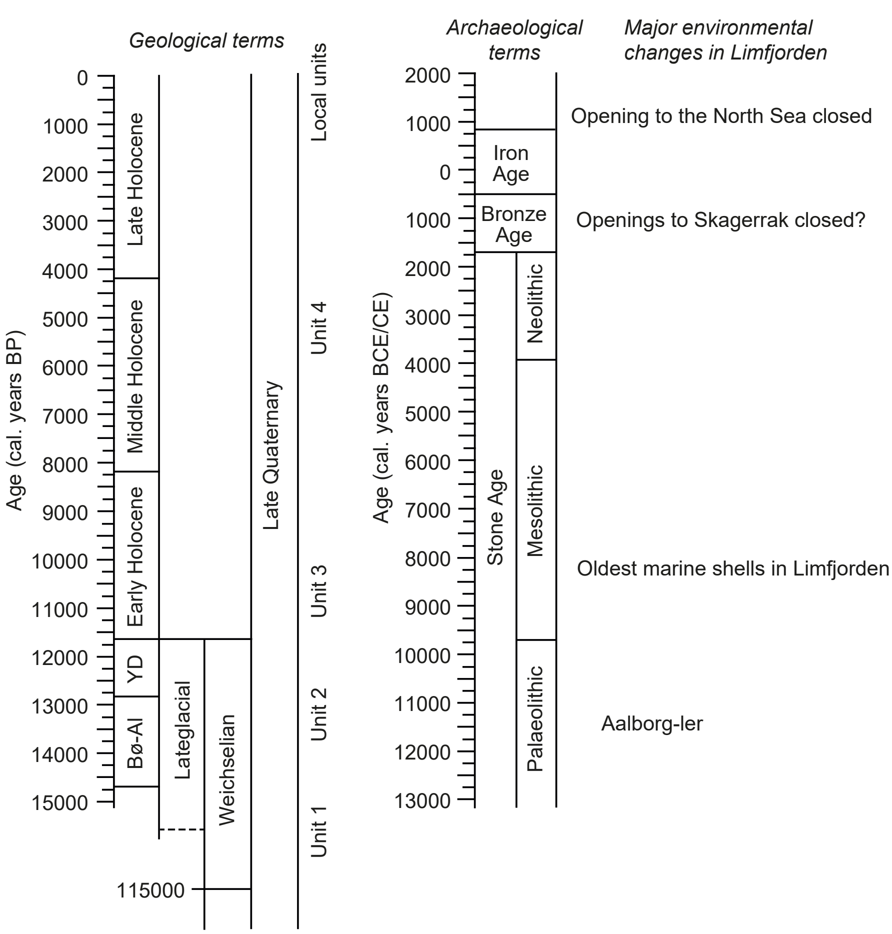

Fig. 2. Late Quaternary geological and archaeological terms used in this paper. YD: Younger Dryas stadial, Bø-Al: Bølling-Allerød interstadial. The term Lateglacial is used in this paper for the time period from the last deglaciation to the transition to the Holocene. The division of the Holocene is according to Walker *et al.* (2019) and the chronology of the archaeological time periods is according to Skousen (2008). BP (before present) refers to 1950 CE. The local units 1-4 are shown in Figs 4, 5. Peat accumulated during the Early Holocene prior to the marine transgression – at different elevations at different times. CE: Common Era, BCE: before Common Era.

studies of the Lateglacial and Holocene development in the western Limfjorden are published in Danish and in reports that are difficult to access. We review the Late Quaternary history of the strait and discuss the rates of relative sea-level changes, based on new data. The geological and archaeological chronological terms used in this paper are shown in Fig. 2.

Geological setting

The pre-Quaternary surface in the region mainly consists of Danian to Miocene strata, but Upper Cretaceous chalk is locally present (Håkansson & Pedersen 1992). Coastal cliffs expose the Fur Formation, an Eocene diatomite with dark layers of volcanic ash (Pedersen & Surlyk 1983; Pedersen *et al.* 2012). Salt diapirs and salt pillows are fairly common in the region and it has been suggested that the salt structures have lead to local uplift of the land or subsidence due to dissolution of salt by ground water (Hansen & Håkansson 1980; Madirazza 1980, 1981). The area is still subject to glacio-isostatic rebound after the Weichselian glaciation. The current uplift rate in the region is 0.9–1.4 mm per year, but large deviations from this figures are seen, for example near the salt structures (Vognsen *et al.* 2011). In some areas, the land is sinking by more than 1 mm per year (Vognsen *et al.* 2011).

Pleistocene till as well as glaciofluvial and glaciolacustrine deposits are widespread, and interglacial and interstadial marine and non-marine deposits occur locally (e.g. Jensen & Knudsen 1984; Knudsen 1994; Knudsen *et al.* 2014). Both pre-Quaternary and Pleistocene deposits are partly disturbed by glaciotectonic deformations such as folding, faulting and thrusting as seen in coastal cliff sections (e.g. Jensen 1985; Pedersen 1996). The region is characterised by buried valleys, some of which are more than 100 m deep (Jørgensen & Sandersen 2006). The last deglaciation of the region started *c.* 18000 cal. years BP (in the following years BP; Houmark-Nielsen *et al.* 2012), but the oldest dated plant remains post-dating the deglaciation gave an age of *c.* 14300 years BP (Korsager *et al.* 2003).

Palaeogeographical maps of northern Denmark, including the Limfjord area, have been published by Larsen *et al.* (2009). These maps indicate that the area occupied by the modern western Limfjord had a Late Quaternary development different from that of Vendsyssel.

After the Last Glacial Maximum, solar insolation-controlled warming caused a marked decrease of ice sheets and a global eustatic sea-level rise of *c.* 130 m (Lambeck *et al.* 2014). During the same time period northern Jylland experienced isostatic land uplift because the ice load disappeared. The combined effects led to significant relative sea-level changes.

Physical geography

The Limfjord strait is *c.* 160 km long and its eastern part is mainly a relatively narrow strait, whereas the western part consists of a mosaic of narrow straits, more open shallow waters and small fjords. The western area includes the islands Mors and Fur and several small islands. The coastal barrier between Limfjorden and the North Sea comprises Agger Tange to the north and Harboøre Tange to the south, separated by Thyborøn Kanal (Fig. 3). The sea floor in Limfjorden is usually fairly flat, but local large depressions are interpreted as pockmarks (Dahlin *et al.* 2018). The water depth is less than 5 m over large areas (Fig. 3) where widespread submerged macrophytes support a rich marine fauna. For centuries, the area housed large populations of fish, which have been eagerly exploited, but this has changed in recent decades and the population of demersal fish is now at a low level (Poulsen *et al.* 2007; Riisgård *et al.* 2012). The present-day salinity decreases from west to east from about 30 to 20 psu (Burman & Schmitz 2005). The tidal amplitude in the region is up to 11 cm (DMI 2019), but sea level variations up to 2–4 m caused by stormy weather have been registered at different sites in the region (Ingvardsen *et al.* 2011).

The surface sediments are characterised by Holocene mud and muddy sand in the deeper parts of the western Limfjord. In shallow water areas sandy sediments are widespread, whereas glacial till is found at the seafloor in relatively small areas, often near the coast or in shallow areas (GEUS 2014), where wave activity prevents settling of sediments.

Material and methods

Several marine projects were carried out in the region in the 1970s and 1980s in order to map sand and gravel deposits below the sea floor. During this work shallow seismic data acquisition was combined with coring and grab-sampling (e.g. Fredningsstyrelsen 1981). In 2016, a survey was carried out in Løgstør Bredning and Livø Bredning using the GEUS survey vessel *Maritina* (Al-Hamdani *et al.* 2016). The aim was to locate sites that could be suitable for artificial stone reefs and in 2017 such a stone reef was established.

The main seismic equipment was an Innomar sediment echo sounder; differential GPS was used for navigation. We used an acoustic velocity of 1500 m s^{-1} for the conversion of two-way travel time to metres. Based on the high resolution shallow seismic profiles from 2016, we selected a number of core sites and in 2017 the marine sediments were sampled from the Aarhus University research vessel *Aurora*. Sediment cores were collected at six sites in Livø Bredning and Bjørnsholm Bugt (Fig. 3) using a 10-cm diameter gravity corer with a top weight of *c.* 700 kg. The upper loose sediments close to the sea floor are usually disturbed using this corer and we used a Rumohr Lot to sample these sediments.

The sediment cores were split, described and photographed 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 using a dissecting microscope. Remains of terrestrial plants and shells of marine molluscs collected in 2017 were used for accelerator mass spectrometry (AMS) radiocarbon age determination. These samples were dated at the laboratory Beta Analytic in Florida, USA (marked Beta; Table 1). We have also compiled older relevant ages from the region in Table 1. The ^{14}C ages marked Beta, AAR and KIA have been corrected for isotopic fractionation by normalising to a δ^{13}C value of –25 ‰. Marine samples from the former Copenhagen laboratory (marked K) were normalised to a δ^{13}C value of 0 ‰ and 400 years were added to K-ages prior to calibration to calendar years. For marine samples, we used a reservoir age of 400 years, which corresponds to a ΔR value of 0 in the calibration program. It is possible that the reservoir age in Limfjorden has varied both in space and time. In closed fjords the reservoir age can be several hundred years greater than the regional value (Olsen *et al.* 2009) and some studies indicate that this problem is particularly large in the Limfjord area due to old carbonate sediments in the region (Heier-Nielsen *et al.* 1995b; Philippsen *et al.* 2013). However, because we do not know what the former reservoir age was at different sites in Limfjorden, we have used the standard value of 400 years. Another factor is that some mollusc species, such as *Macoma balthica* that has been used for dating, can take up old carbon from the sediment, and dating of such species can therefore also produce ages that are several hundred years older than contemporaneous terrestrial samples (Mangerud *et al.* 2006). Compaction of sediment, in particular peat layers also add another source of error (Baeteman *et al.* 2012). Finally, and perhaps most important, marine shells and foraminifera may survive reworking. These factors mean that ages based on marine material may be somewhat too old. We consider the latter factor the most likely reason that some shell ages fall above the proposed relative

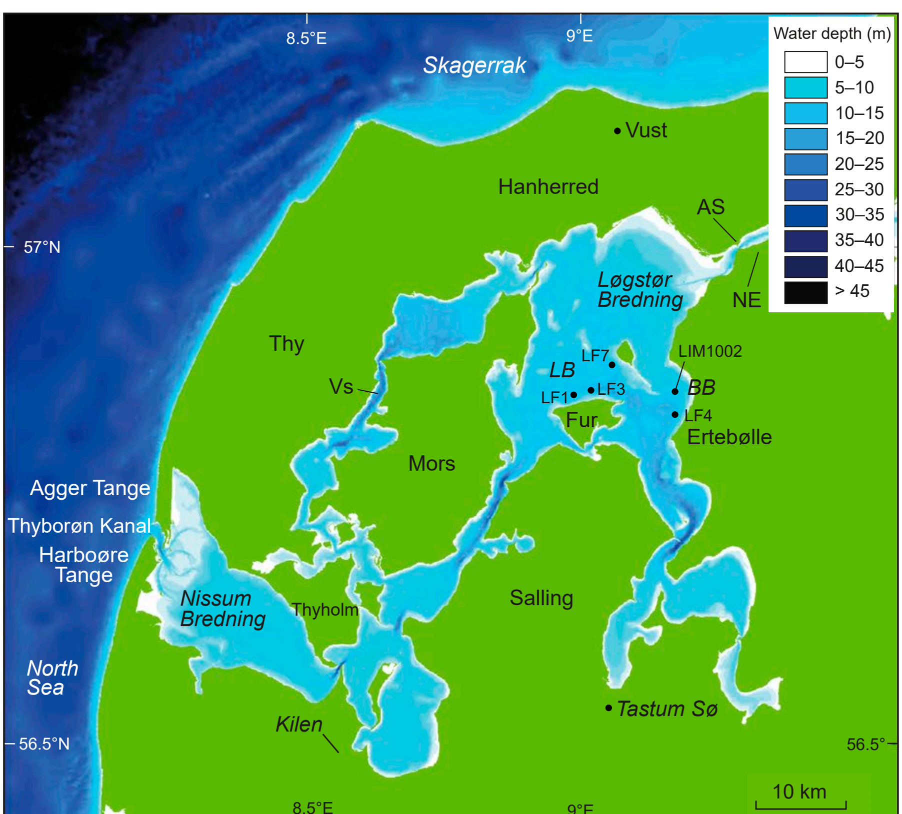

Fig. 3. Map of Limfjorden showing the bathymetry and the location of selected vibrocores. Thyborøn K: Thyborøn Kanal, Vs: Vilsund, LB: Livø Bredning, BB: Bjørnsholm Bugt, AS: Aggersund, NE: Nørrekær Enge. Prior to 1825, Nissum Bredning was separated from the North Sea by a sand bar known as Limfjordstangen, it is now divided into Agger Tange and Harboøre Tange. LF3, LF4, LF7: location of selected sediment gravity cores. The seismic lines are so short that they correspond to the dots.

sea curve. The nomenclature of marine species in this paper follows the World Register of Marine Species (2017), where synonyms are also listed.

Results: Late Quaternary stratigraphy

Unit 1

Based on the interpretations of the shallow seismic data (Fig. 4) and comparison of these seismic profiles to the sediment in the cores (Fig. 5), the submarine Late Quaternary succession in Limfjorden can be divided into four units. The oldest Quaternary unit (Unit 1; Fig. 2) consists of glacial deposits, which form the acoustic basement. On the seismic profiles, the unit is characterised by an internal hummocky or chaotic appearance and a sharp uneven upper boundary (Fig. 4). In core samples clayey till dominates, but glacio-

Table 1. Selected new and published radiocarbon ages from Limfjorden, Denmark. We have selected ages that are relevant for reconstructions of past sea-level changes and environmental changes

Core/ site	Latitude °N	Longitude °W	Laboratory number	Material	Altitude (m)	Age (^{14}C years BP)[1]	Cal. age (years BP)[2]	Reference
LF2	56.849	8.997	Beta-473553	*Mytilus*	–9.5	2210 ± 30	7111–1890	a
LF3	56.855	9.012	Beta-473554	*Aporrhais*	–13.6	7600 ± 30	7975–8147	a
LF4	56.831	9.178	Beta-473555	*Mytilus*	–9.5	2300 ± 30	1820–1994	a
LF6	56.834	9.161	Beta-473556	*Mytilus*	–10	1950 ± 30	1402–1588	a
LF7	56.881	9.063	Beta-473568	*Corylus* nut	–12.6	8730 ± 30	9557–9885	a
Skrandrup	56.933	8.833	K-2474	*Tilia* wood	+0.5	7040 ± 110	7656–8052	b
Skrandrup	–	–	K-2476	*Ulmus* stump	0	7460 ± 120	8011–8458	b
Gjøttrup H	57.067	9.233	K-2480	*Ostrea, Cerast.*	+3.5	6980 ± 110	7609–8054	b
Kovad Bro	57.083	9.217	K-2384	*Donax vittatus*	0	1910 ± 100	1677–2194	b
Vust	57.102	9.073	K-3281	Cirripedia	–24.75	7860 ± 115	8482–9098	c
Vust	–	–	K-2875	Peat	–25.75	9830 ± 115	10790–11715	c
Tastum Sø	56.503	9.058	K-3155	*V. pullastra*	–4	5320 ± 70	5955–6274	d
Tastum Sø	–	–	K-3156	*Mytilus*	–2	3420 ± 80	3556–3982	d
Agger I	56.724	8.242	AAR-1827	*L. littorea*	–24	9270 ± 90	9761–10283	e
Agger II	56.743	8.229	K-4291	*Corbula gibba*	–23	7290 ± 110	7939–8364	f
Agger II	–	–	AAR-1828	*M. balthica*	–33	9900 ± 140	10527–11175	e
Ertebølle	56.789	9.190	K-4340	*Ostrea edulis*	+1	6000 ± 100	6652–7141	g
Ertebølle	–	–	K-3680	*Cerastoderma*	+1.5	5280 ± 90	5898–6270	g
Ertebølle	–	–	K-3679	*Cerastoderma*	+0.5	3690 ± 80	3912–4376	g
Strande I	56.571	8.154	K-6147	*Ostrea edulis*	–3.75	6020 ± 100	6667–7151	e
Strande I	–	–	K-6148	*Ostrea edulis*	–4.25	6090 ± 140	6657–7286	e
Strande I	–	–	K-6149	*Ostrea, Cerast.*	–11.75	7780 ± 155	8344–9094	e
Strande II	56.589	8.170	K-6150	Lake gyttja	–10.5	8400 ± 140	9016–9626	e
Core 95	56.988	9.113	AAR-211	Mollusc shell	–15.5	8615 ± 110	9001–9478	h
562002	57.003	7.204	AAR-1818	*L. littorea*	–46	9330 ± 150	9690–10527	i
562003	56.887	7.472	AAR-1819	*Tellina fabula*	–33.25	8320 ± 110	8562–9184	i
562010	67.741	7.697	AAR-1820	*Cerastoderma*	–33.6	9480 ± 90	10160–10555	i
562011	56.760	7.701	AAR-1822	*Cerastoderma*	–34.45	9750 ± 100	10402–10984	i
Krabbesh.	56.570	9.425	LuS-6138	*P. groenlandica*	–14.5	4395 ± 60	4403–4771	j
NK Enge	57.013	9.230	AAR-13957	*Cerastoderma*	–9.4	8560 ± 40	9058–9346	k
NK Enge	–	–	AAR-13958	Plant material	–9.5	8520 ± 40	9474–9544	k
NK Enge	–	–	AAR-13959	Plant material	–10.1	10070 ± 40	11391–11820	k
DGU22.547	57.098	8.627	AAR-7843	Marine shell	–7.5	8810 ± 100	9235–9728	k
Aggersborg	56.995	9.255	KIA-42408	Peat	–1.15	7645 ± 45	8383–8539	k
Rønbjerg	56.893	9.167	K-6375	Peat	+1.0	7170 ± 120	7721–8290	l

[1] Radiocarbon ages are reported in conventional radiocarbon years BP (before present = 1950; Stuiver & Polach (1977)).

[2] Calibration to calendar years BP (2 sigma) is according to the INTCAL13 and MARINE13 data (Reimer *et al.* 2013).

References a: this study, b: Petersen 1976, c: Petersen 1981, d: Rasmussen & Petersen 1980, e: Petersen 1998, f: Petersen 1985, g: Petersen 1986b, h: Nielsen 1992, i: Leth 1996, j: Bennike *et al.* 2008, k: Jessen *et al.* 2019, l: Hylleberg 1998.

fluvial and glaciolacustrine deposits are also found. Clayey till was also found in the Vust borehole (Fig. 3) below a peat unit (Unit 3, see below). The top of the glacial deposits defines a distinct palaeo-surface with channels and depressions, as well as highs reaching the present day seafloor (Fig. 4).

Unit 2

Within the depressions un-fossiliferous clay and silt may occur (Unit 2). Unit 2 is characterised by transparent to subparallel continuous low-amplitude reflections. At the edges of the depressions, onlap is typically observed (Fig. 3B) whereas a draping pattern dominates the central areas of the depressions (Fig. 4A). In the 2017 survey, only core LF3 penetrated the Holocene sediments (Fig. 5). In this core we found brownish homogeneous Lateglacial clay (Unit 2) below an Early Holocene layer of sand and gravel with shells of marine molluscs. This clay is barren of marine fossils and we suggest that it accumulated in a glaciolacustrine environment, which is also known from south-western Vendsyssel, Thy, and the Aalborg area. Previously, such deposits were referred to as Yoldia-clay but Berthelsen (1987) suggested the name Aalborg-ler (Aalborg clay) for deposits without marine fossils in the Aalborg area. This name was already used by A. Jessen in his field notes during mapping of the region more than a century ago (Berthelsen 1987).

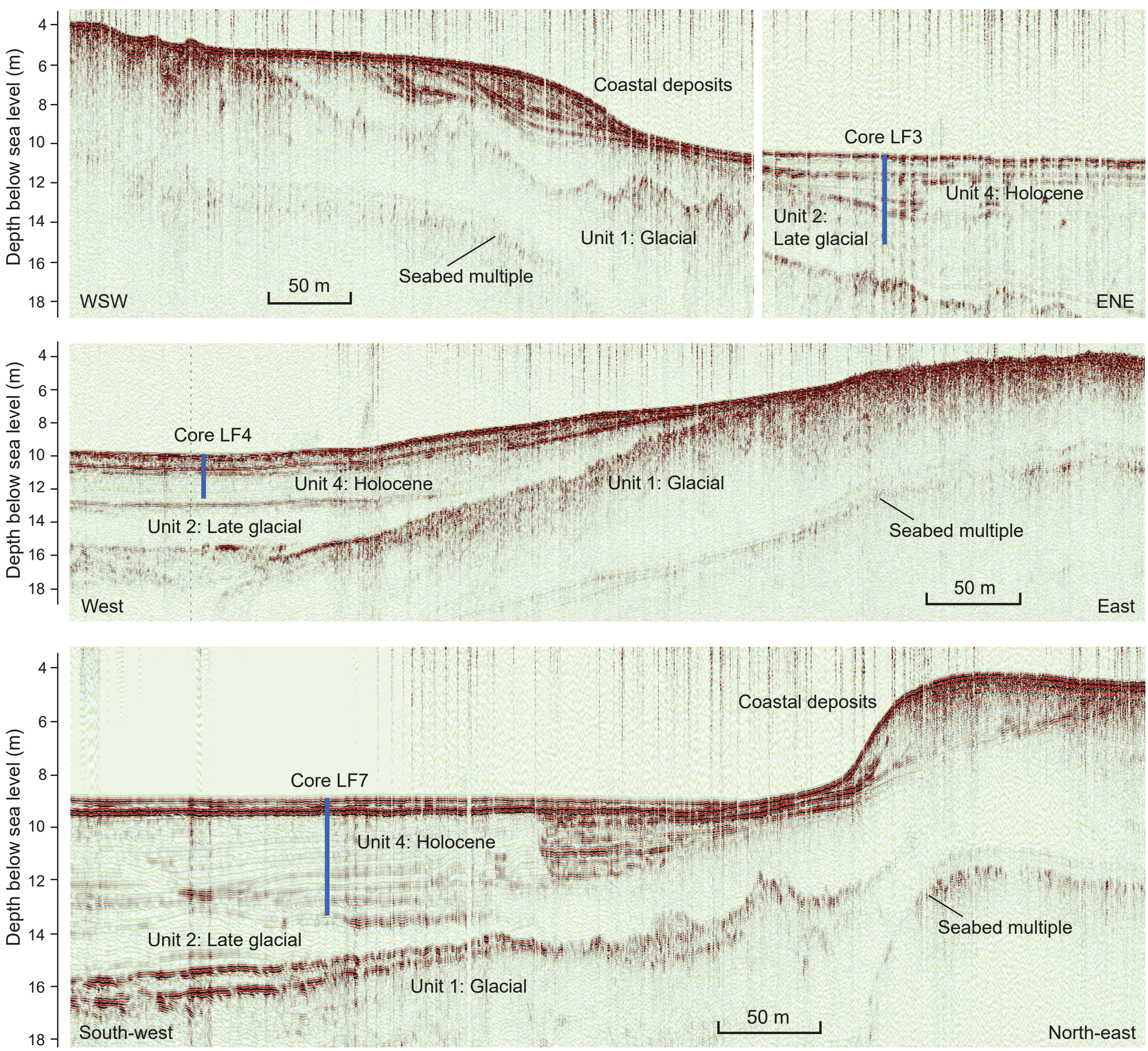

Fig. 4. Three examples of seismic profiles at gravity core positions. Glacial sediments (Unit 1) are overlain by Lateglacial (Unit 2) and Holocene (Unit 4) sediments. Unit 3 (Holocene peat) is a thin unit and not indicated on the profiles. Fossil coastal deposits with inclined reflections are seen on A and C.

The Aalborg-ler was probably deposited in a glaciolacustrine environment with turbid water. Glaciolacustrine clay and silt, presumably of Lateglacial age, have also been reported from core samples collected during geotechnical investigations prior to the construction of bridges in the region (Mertz 1937; GEUS 2019). Lateglacial un-fossiliferous clay (the Morild Formation) has also been described from a large number of wells in Vendsyssel (Krohn *et al.* 2009).

Unit 3

Unit 3 is terrestrial peat, which was sampled in sediment core LF7 (Figs 4, 5). The peat consists of humified forest peat with wood fragments, twigs, radicells, a few sclerotia of the soil fungus *Cenococcum geophilum*, a fruit of *Carex* sp. and a fragment of a nutshell of *Corylus avellana* (hazelnut). The nutshell was dated to *c.* 9680 years BP (Table 1). As mentioned above, peat and lake deposits have been recorded

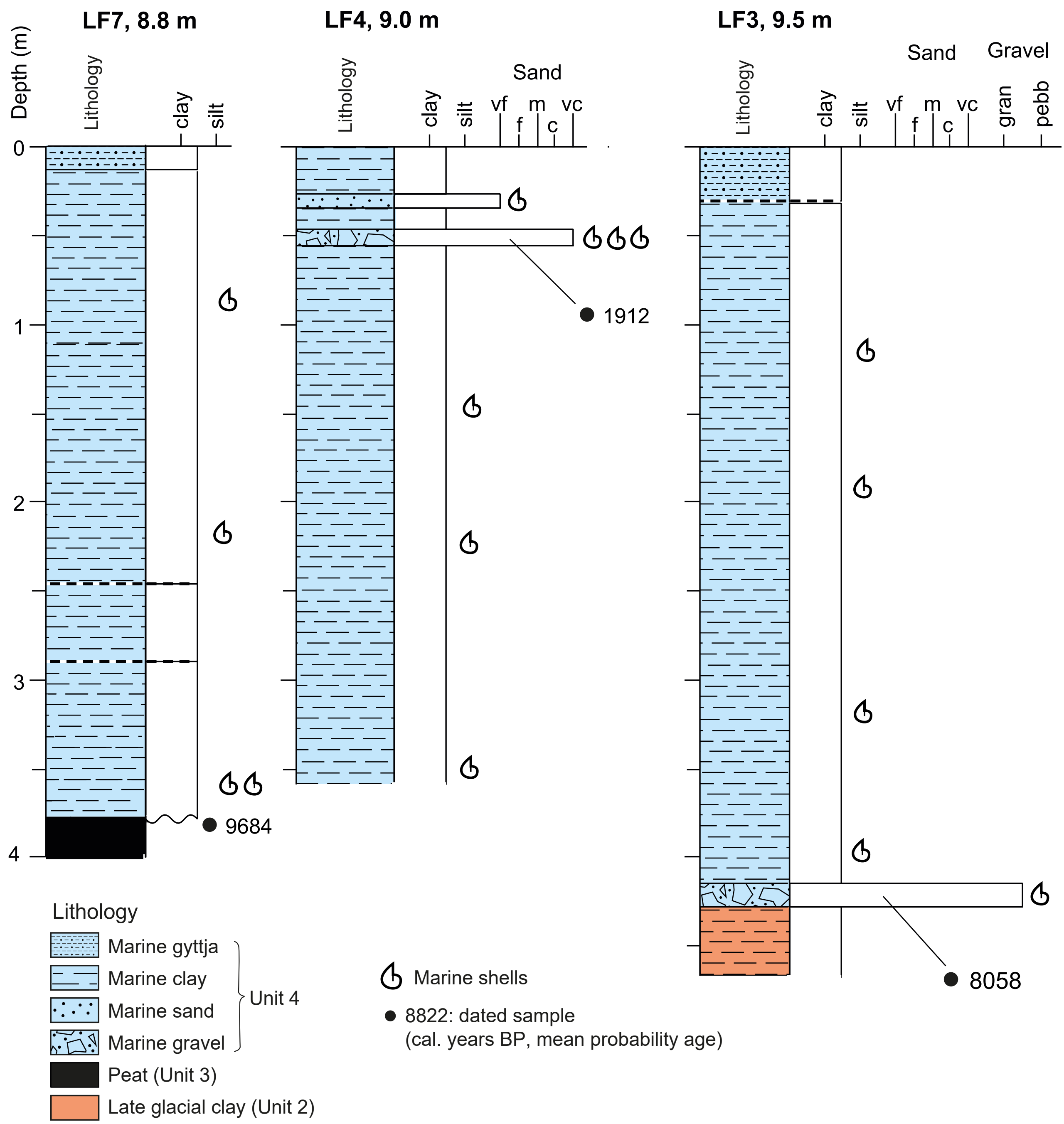

Fig. 5. Selected simplified sedimentological core logs from the western part of Limfjorden. The locations and ages of dated samples are indicated. For details on ages see Table 1. There is probably a hiatus in core LF7 between the peat (Unit 3) and the overlying marine mud (Unit 4), which is younger than 8058 years BP as shown in LF3. The sediment cores are located in Fig. 2.

below marine sediments at several sites in the region and bogs and lakes were probably widespread in Limfjorden during the so-called continental period (Fastlandstiden) in the Early Holocene (Gry 1979; Christensen 1993, 2001; Christensen *et al.* 1997).

Unit 4

Unit 4 consists of Holocene marine and coastal deposits. On seismic profiles this unit is often acoustically semi-transparent, but it may also show high-amplitude parallel, continuous internal reflections as well as inclined sigmoidal reflections, typically representing coastal deposits (Fig. 4). The lower boundary is sharp and is interpreted as a marine transgressive surface, the upper boundary is the sea floor. Basin areas with low seismic penetration (blanking) are interpreted as evidence of gas bubbles in the sediments. Blanking is usually seen when the thickness of the marine mud exceeds 4–5 m, a phenomenon common for organic-rich deposits (Jensen & Bennike 2009). In

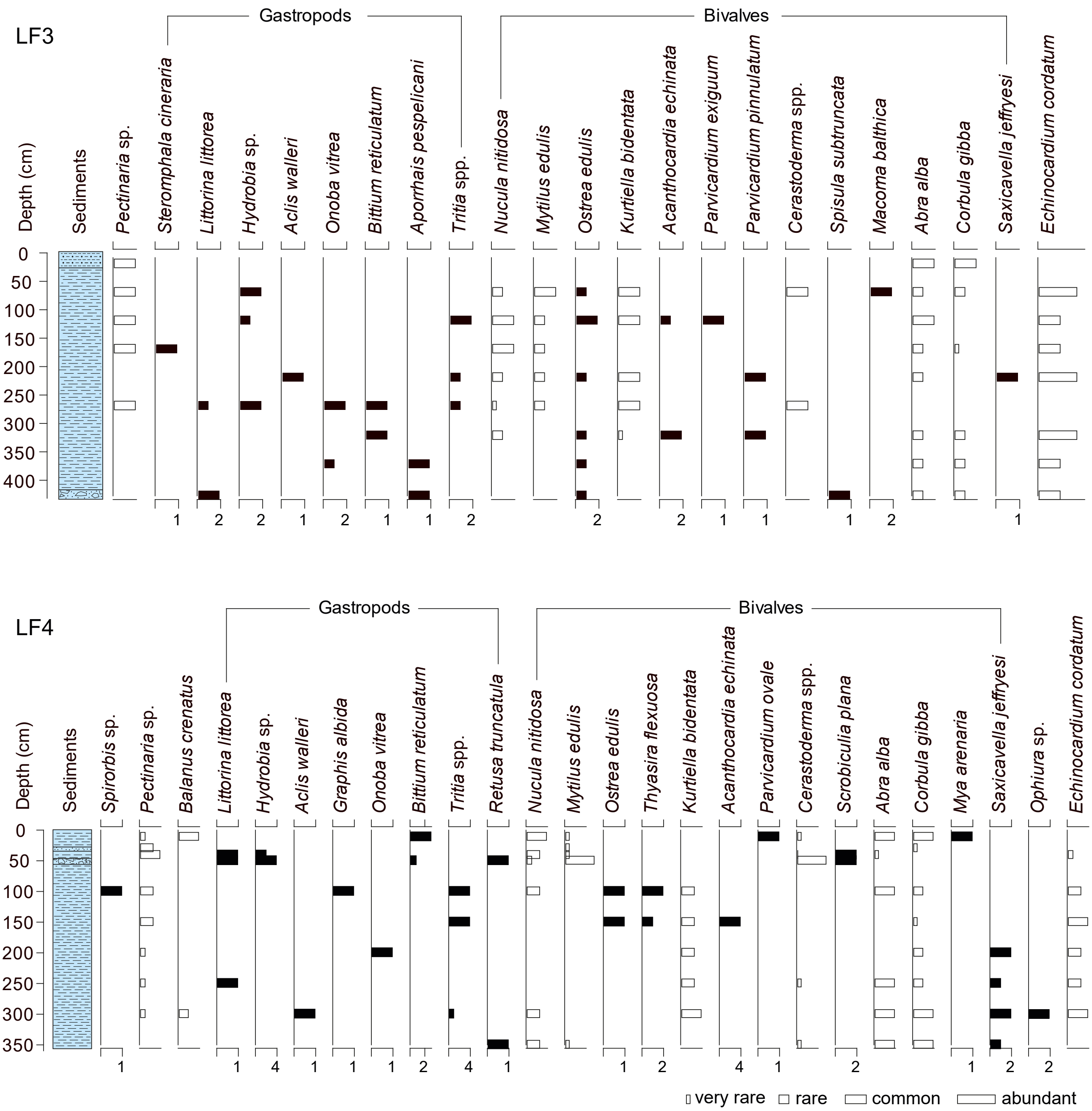

Fig. 6. Simplified macrofossil concentration diagrams of gravity cores LF3 and LF4 from Livø Bredning and Bjørnsholm Bugt in Limfjorden. Black bars: counted fossils, open bars: number of fossils per sample estimated. Sample size: *c.* 500 g.

Nissum Bredning and in an area to the north-west of Agger Tange, Holocene marine clay deposits are referred to as the Agger clay unit (Leth 1996).

Sediment core LF3 contained a basal layer of gravel with shells of *Aporrhais pespelicani* and *Spisula subtruncata* (Fig. 5). Core LF1 (not shown) contained sand with some gravel in the lower part with a macrofauna that included *Ostrea edulis*, *Achantocardia echinata*, *Mytilus edulis* and *Virgularia mirabilis*. These coarse-grained sediments accumulated during the initial marine transgression, as littoral or sub-littoral deposits.

Coarse-grained sediments are probably widespread in the region, but Unit 4 is dominated by clay and bioturbated clayey and silty organic mud, sometimes with marine sand and shell layers in the upper part (Fig. 5). The macrofauna in the marine mud is dominated by the bivalves *Corbula gibba*, *Abra alba* and *Mysella bidentata* and the irregular sea urchin *Echinocardium cordatum* (Fig. 6). More rare species included the molluscs *Nucula nitidosa*, *Chamelea striatula*, *Achantocardia echinata*, *Parvicardium pinnulatum* (= *P. ovale*), *Phaxas pellucidus*, *Ostrea edulis* (European flat oyster), *Saxicavella jeffreysi*, *Thyasira flexuosa*, *Tritia incrassata*, *Steromphala cinerea* (= *Gibbula cinerea*), *Aclis walleri*, *Retusa truncatula*, the polychate worm *Pectinaria* sp., the octocoral *Virgularia mirabilis* and the regular sea urchin *Psammechinus miliaris*. This fauna is similar to that reported by Christensen *et al.* (2004) from their zone 1, which represented marine mud from the same area. The fauna indicates fully marine conditions.

The shell layers in the upper part of the sediment cores were dominated by paired shells of *Mytilus edulis* (blue mussel) and *Cerastoderma glaucum* (= *Cerastoderma lamarcki*, *Cardium lamarcki*¸ edible cockle or common cockle). Additional species included *Littorina littorea* (periwinkle), *Macoma balthica* and the small fish *Gasterosteus aculeatus* (three-spined stickleback). This fauna can be characterised as a littoral or sub-littoral fauna and we suggest that the shells were transported from shallow waters to deeper waters during storm surges, perhaps in connection with wind-stowing of waters in Limfjorden, which is a fairly common phenomenon during stormy weather at present. The species in the shell-rich layers are rare in the underlying sediments and have not been concentrated by erosion of the muddy sediments.

Similar shell-rich layers were reported by Hylleberg (1992, 1993). Hylleberg suggested that low oxygen levels led to mass mortality of bivalves. Low oxygen levels could be a result of long lasting sea ice cover during winter or warm summers with stratified water. Hylleberg speculated that the bivalves died during a period with abnormal weather conditions and suggested that the layers were formed by bivalves that died *in situ*. However, if this was the case a fauna dominated by sub-littoral species would be expected in the shell layers. We also consider it unlikely that the waters became stratified because of the shallow water depth.

Top Unit 4: Rumohr Lot core data

In several Rumohr Lot cores sampled in 2017 we found a thin layer of gyttja close to the sediment surface, i.e. near the very top of Unit 4 (Fig. 7). This gyttja layer was not preserved in the gravity cores. The LF7 Rumohr Lot comprised from the core top:

1) 16 cm of black marine mud with a fauna that included the bivalves *Abra alba*, *Corbula gibba*, *Parvicardium pinnulatum*, *Mytilus edulis* and *Nucula nitidosa*, rare shells of the gastropods *Bittium reticulatum* and *Rissoa parva*, remains of the barnacle *Balanus crenatus* and un-identified hydroids as well as tests of the foraminifers *Elphidium* spp. and *Ammonia beccarii*. This fauna is similar to the present-day fauna in the deeper parts of the western Limfjord region.

2) 13 cm of dark olive-grey gyttja. The upper part of this layer did not contain carbonate fossils; we found rare oospores of charophytes (*Chara* sp. and *Tolypella* sp.), numerous head capsules of the non-biting midge *Chironomus* sp., rare jaws of the polychaete worm *Nereis* sp., linings of foraminifers, rare skeletal remains of hydroids and rare ephippia of the cladoceran *Daphnia* cf. *pulex*. The invertebrate remains are made of chitinous material. The assemblage indicates low salinity and low oxygen level,

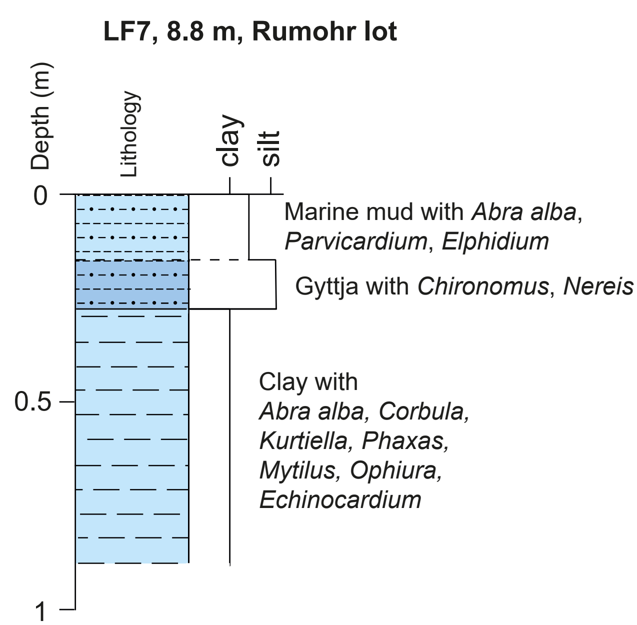

Fig. 7. Simplified sedimentological core log of Rumohr lot LF7. The sediment core is located in Fig. 2.

corresponding to the brackish-water period prior to 1825 CE known from historical sources. The layer is sandy in the lower part, and this part contained some shells of marine molluscs, such as *Abra alba*, *Corbula gibba*, *Mytilus edulis*, *Nucula nitidosa* and *Littorina littorea*, indicating that the periods of marine conditions alternated with periods of brackish conditions during the formation of Limfjordstangen.

3) 61 cm of dark greenish grey clay with a more species-rich fauna that includes the bivalves *Abra alba*, *Corbula gibba*, *Kurtiella bidentata* (= *Mysella bidentata*), *Phaxas pellucidus*, *Mytilus edulis* and *Nucula nitidosa* as well as remains of *Ophiura* sp. and *Echinocardium cordatum*. This fauna indicates fully marine conditions.

Holocene relative sea-level changes of the Limfjord region

Based on data from a borehole south of the village Vust (location see Fig. 3), radiocarbon dated shells from raised marine deposits, an *in situ Ulmus* sp. stump and *Tilia* sp. wood fragments from a peat deposit, Petersen (1981) proposed a relative sea-level curve for the western Limfjord. The curve was extremely steep and it was estimated that the sea-level rose by 28 m in 850 calendar years (Petersen & Rasmussen 1995). The lower part of the curve was fixed by pollen dating of a fresh to brackish water gyttja. No details on the results of the pollen analysis were published, but Petersen (1981, p. 502) noted that "the pollen spectrum

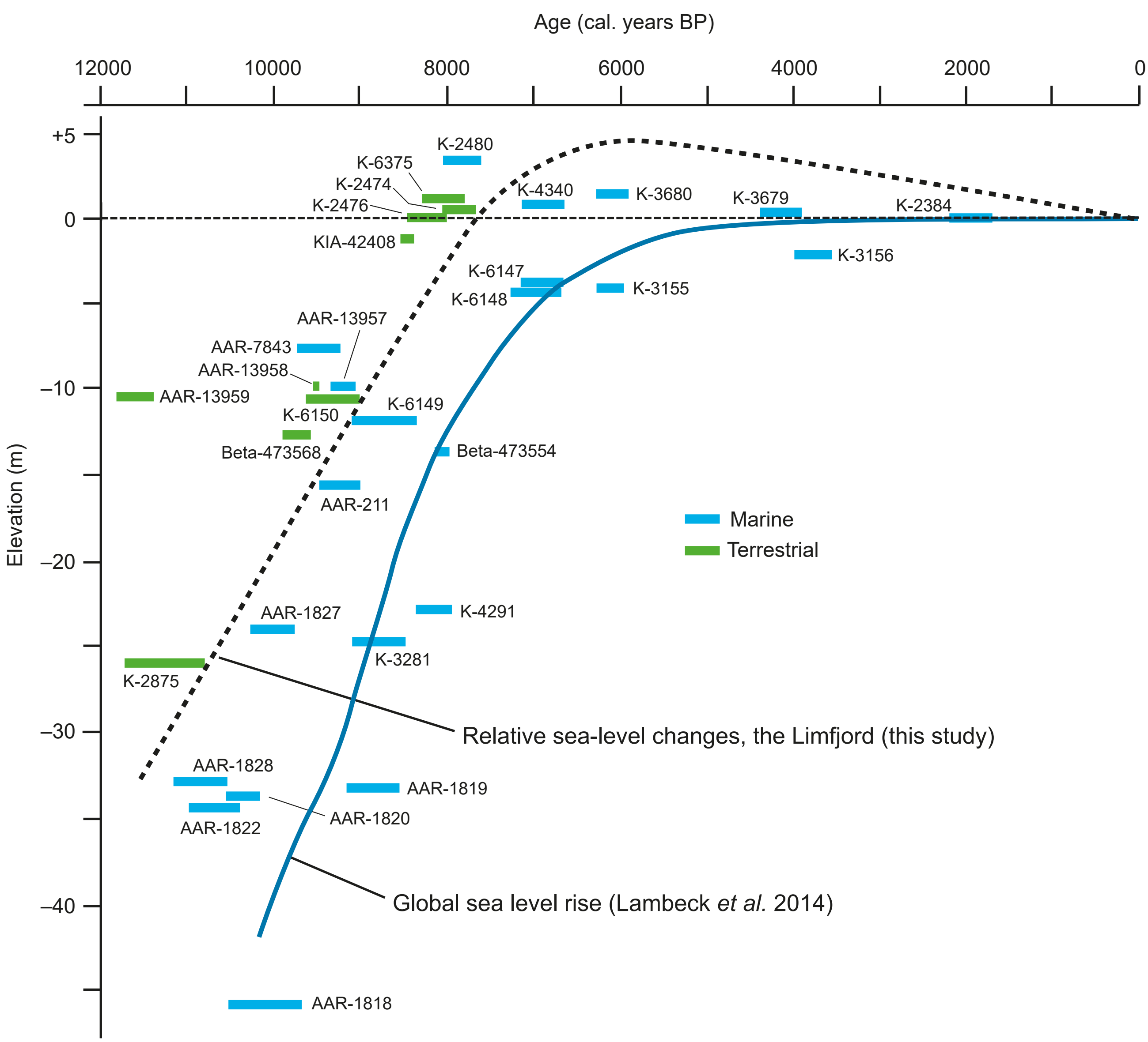

Fig. 8. Tentative curve showing relative sea-level changes in Limfjorden during the Holocene based on radiocarbon dated samples (Table 1). The relative sea-level changes are compared with a curve showing global eustatic sea-level rise (Lambeck *et al.* 2014).

was dominated by *Corylus*, *Pinus* and *Betula*. *Alnus* and trees of the oak mixed forest were lacking". Petersen suggested that the pollen spectrum indicated an age of *c.* 8750 years BP (Petersen 1981). At present, a pollen spectrum dominated by *Corylus*, *Pinus* and *Betula* and without *Ulmus*, *Alnus* or other elements of the 'oak mixed forest' would indicate an older age, perhaps about 9900–10200 years BP (Odgaard 2005; Jessen *et al.* 2019).

Petersen (1981) also proposed that the marine transgression began with a littoral fauna. The fauna in the lowermost sample was dominated by *Ostrea edulis* and comprised the bivalve *Mytilus edulis*, the gastropod *Littorina* sp. and Cirripedia. *Mytilus* and *Littorina* are most abundant in the littoral zone, but they can also live in deeper waters, if they can find hard or firm substrates. Petersen did not identify the Cirripedia species, but Jessen *et al.* (2019, p. 124) noted that "the preferred living position of this genus is close to the coastline". Cirripedia is not a genus, it is usually considered an infraclass in the subphylum Crustacea. Cirripedia includes some littoral species but the most common Cirripedia species in Holocene deposits in the region is the barnacle *Balanus crenatus* (Bennike *et al.* 2000). *Balanus crenatus* is also by far the most common *Balanus* species in Danish waters at the present; it lives at water depths down to 100 m or more (Stephensen 1933; Poulsen 1935). The marine fauna from the lowermost part of the Vust borehole (Fig. 3) comprised 26 taxa of which the majority definitely are non-littoral species.

A new curve

Here we propose a new relative sea level curve for the western Limfjord (Fig. 8). It is partly based on the same data as used by Petersen (1981) and Jessen *et al.* (2019), partly on new data from this study (Table 1). We use the INTCAL13 curve for calibration of terrestrial samples and the MARINE13 curve for calibration of marine samples (Reimer *et al.* 2013). The new curve shows that relative sea-level rose from *c.* 30 m below present sea level at *c.* 11000 years BP to present level at *c.* 8000 years BP, corresponding to a rise of 1 m/100 years. This is similar to the relative sea-level rise in Øresund (Bennike *et al.* 2012). Øresund is at about the same isobase as western Limfjord and we agree with Jessen *et al.* (2019) that such an estimate is more realistic than the extremely steep rise suggested by Petersen (1981). We note that the relative sea-level curve for western Limfjord is poorly constrained, and one could argue that there is room for minor regressions and transgressions (wiggles) during the Early Holocene rise. However, no such wiggles are seen on the global eustatic sea-level curve (Lambeck *et al.* 2014). Our curve shows large similarities to the curve recently published by Jessen *et al.* (2019) but it is supported by new data from this study, as well as other published data points not included by Jessen *et al.* (2019).

The relative sea-level curve by Jessen *et al.* (2019) covers the time span from 12400 to 7400 years BP. The older part of their curve shows a marked fall of the relative sea level, which was attributed to a high rate of isostatic uplift. However, no data were provided to constrain this part of the curve and as mentioned above no Lateglacial deposits with marine fossils have been reported from Limfjorden. Furthermore, Lateglacial marine fossils are not known from the adjacent part of the North Sea. Therefore we consider reconstruction of Lateglacial sea-level changes to be speculative and refrain from extending the new relative sea-level curve back to the Lateglacial time period.

During the Mid-Holocene, large wide connections existed between the current Limfjord, the North Sea, Skagerrak and Kattegat (Jessen 1920; Fig. 9). The relative sea-level was between 2 and 5 m higher than at present in the western part of Limfjorden (Mertz 1924). The marine samples should fall below the line, and the terrestrial samples should fall above the line. However, it is not possible to draw the line so that this is fulfilled – a few of the marine samples are located above the line. The samples come from a fairly large

Fig. 9. Palaeogeographical coast-line map of northern Jylland, which was an archipelago during the Middle Holocene (Littorina Sea or Tapes Sea) when the relative sea-level in the region was at its highest. Redrawn after Jessen (1920).

region, which experienced different isostatic uplift, but these differences would only shift the elevation of the plotted samples a few metres at the most.

Changes in relative sea level results from a combination of global eustatic sea-level rise due to ocean volume increase and local land uplift due to isostatic unloading by ice. By adding the curve showing relative sea-level changes and the eustatic sea-level curve (Lambeck *et al.* 2014) we propose a curve showing glacio-isostatic changes in the western Limfjord area (Fig. 10). Although this curve is not well constrained, it indicates that the western Limfjord region has been uplifted by 25–30 m during the Holocene. The Limfjord region experienced regression in the Late Holocene because isostatic uplift surpassed the eustatic sea-level rise.

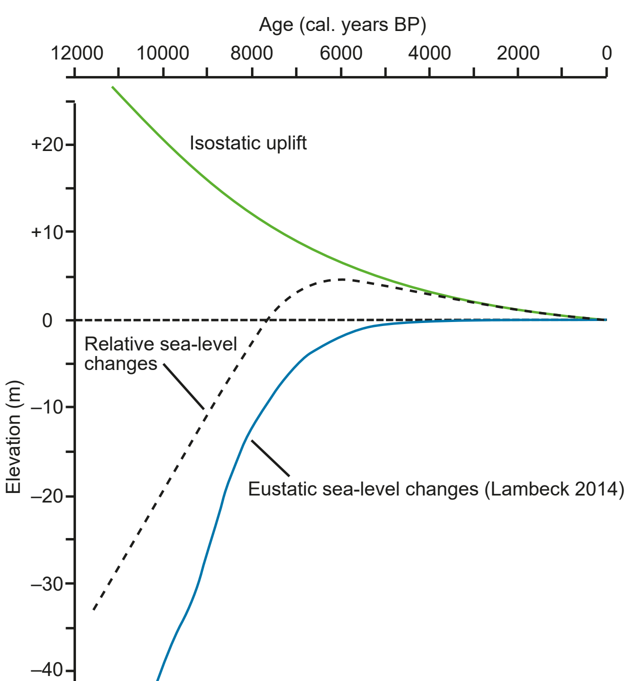

Fig. 10. Conceptual model showing relative sea-level changes in the western Limfjord region (this study), global eustatic sea-level rise (Lambeck *et al.* 2014) and modelled isostatic uplift (this study). The isostatic uplift is the difference between the relative sea-level changes and the eustatic sea-level rise. In the Early and Mid-Holocene eustatic sea-level rise dominated the sea-level history in the Limfjord region, whereas in the Late Holocene isostatic uplift dominated. There is no indication that the eustatic sea level was higher than at present during the Holocene.

Discussion

When did Limfjorden form?

No fossils indicate that marine Late Weichselian deposits (Yoldia clay) occur in the western Limfjord. This is somewhat surprising because Lateglacial marine deposits are widespread in Vendsyssel to the north but it is in accordance with palaeogeographical reconstructions by for example Larsen *et al.* (2009). During the Lateglacial the relative sea level decreased from *c.* 30 m above present sea level to *c.* 20 below present sea level in northern Sjælland, according to Houmark-Nielsen (2017). Northern Sjælland is at about the same isobase as Limfjorden, so a similar relative sea-level history should be expected here. However, the Lateglacial sea-level history for northern Sjælland is poorly constrained. There is only a single radiocarbon dated Lateglacial marine fossil from that region: a vertebra of a *Pusa hispida* (ringed seal; Lagerlund & Houmark-Nielsen 1993). The relation of this bone to sea level is unknown. Terrestrial environments in northern Sjælland and southern Kattegat are indicated by palaeogeographical maps (Jensen *et al.* 2002; Houmark-Nielsen *et al.* 2005), but the factual basis for these maps is fairly weak. Submarine lake deposits dated to the Younger Dryas have been reported from southern Kattegat at a depth of *c.* 24 m below present sea level (Wiberg-Larsen *et al.* 2019). This shows that the relative sea level was lower than 24 m below the present during the Younger Dryas; lower than suggested by Houmark-Nielsen (2017).

Little is known about the Early Holocene environment in Limfjorden prior to the marine transgression. However, peat is found below marine sediments in core LF7 reported here, near Vust, at Agger Tange, in Vilsund and in Nørrekær Enge (Petersen 1981, 1985, 1998; B. Andersen 1992; Jessen *et al.* 2019) and Holocene lacustrine deposits overlain by marine deposits have been reported by Fredningsstyrelsen (1981).

The rising relative sea level during the Early Holocene led to flooding of low-lying parts of Denmark. Continuous marine sedimentation took place in the deeper parts of the Kattegat, Skagerrak and at the Skagen spit (Gyllencreutz & Kissel 2006; Knudsen *et al.* 2009; Larsen *et al.* 2009). Dating of shells of marine molluscs shows that marine waters had inundated northern Øresund by 10300 years BP (Bennike *et al.* 2012), Aarhus Bugt by 8700 years BP (Jensen & Bennike 2009), the central part of Storebælt by 8200 years BP (Bennike *et al.* 2004), Mecklenburg Bugt by 8000 years BP (Bennike & Jensen 1998) and western Arkona Basin by 7600 years BP (Rößler *et al.* 2011; Fig. 11).

At the western entrance to Limfjorden, the oldest shells of marine molluscs have been dated to *c.* 10400 years BP (Petersen 1998; Fig. 11). From the western part of Limfjorden the oldest ages are *c.* 9300 years BP from sediment core 95 from Løgstør Bredning (Nielsen 1992) and *c.* 8800 years BP near Vust in the area separating western Limfjord from Skagerrak (Petersen 1980, 1981; Fig. 11). The chronology of core 95 is fairly uncertain, even though it is based on no less than 22 dated samples. Several age determinations of foraminifera gave older ages than 9300 years BP, but Nielsen (1992) suggested that this could be due to reworking of pre-Holocene material. Thus we conclude that Limfjorden began to form *c.* 10400 years ago.

Mid-Holocene environment: changes in relative sea level and in marine inundation

During the Mid-Holocene large parts of northern Jylland, in particular the Vendsyssel area, was inundated by the sea because the eustatic sea level rose faster than the istostatic uplift (Penney 1985). This also led to a significant expansion of the Limfjord waters past its present shorelines during the Littorina Sea stage (Jessen 1920; Fig. 9). The inundated regions surrounding the present Limfjord were generally characterised by shallow-water foraminifera tolerating somewhat reduced salinities such as *Ammonia beccarii batava* (reported as *Ammonia batavus*) and *Haynesina germanica* (reported as *Protelphidium anglicum*), but also species that require higher salinities such as *Elphidium margaritaceum* and miliolids (Knudsen 1971, 1973; Kristensen *et al.* 1995) as well as the ostracod *Callistocythere littoralis* (now *Sagmatocythere littoralis*; Penney 1985, 1987).

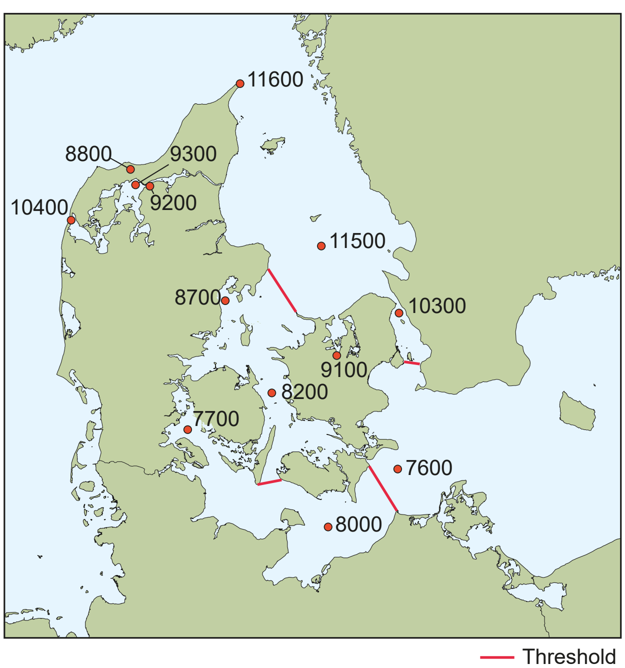

Fig. 11. Oldest Holocene ages in cal. years BP of shells of marine molluscs from Danish waters. Sources: Heier-Nielsen *et al.* (1995a), Bennike & Jensen (1998, 2011), Jensen *et al.* (2002), Bennike *et al.* (2004, 2012), Jensen & Bennike (2009), Olsen *et al.* (2009), Rößler *et al.* (2011) and Table 1. The presence of thresholds in the Danish waters means that the transgression was step-wise.

Also a rich marine mollusc fauna existed in Limfjorden during the Mid-Holocene (Petersen 1976, 1986a, b, 2004). According to Petersen (2004) the fossil Holocene mollusc fauna comprises 147 species, whereas the modern-day fauna comprises 85 species. The more diverse fossil fauna is probably due to higher salinity and higher temperatures compared to the present and it has also been suggested that there were significant tides in Limfjorden at this time (Petersen 2004). The fossil fauna comprises a few species that are no longer part of the Danish fauna, notably the bivalves (*Polititapes aureus* (= *Tapes aureus*, *Paphia aurea*) and *Ruditapes decussatus* (= *Tapes decussatus*). These species indicate higher salinities in the Limfjord area in the past than at present – presumably due to large open connections to the North Sea in the west, Skagerrak in the north and Kattegat in the east. *Paphia aurea* has even been recorded from Tastum Sø (Fig. 3) in the southernmost part of Limfjorden (Rasmussen & Petersen 1980; Petersen 1992). Its occurrence at that locality was dated to the time interval 3700–6100 years BP, corresponding to the most saline period in this part of Limfjorden. In Tastum Sø, *Ostrea edulis* was most common around 6100 years BP, corresponding to peak Mid-Holocene temperatures in Denmark according to Iversen (1973) and Brown *et al.* (2011). The Mid-Holocene fish fauna in Limfjorden included several southern species such as *Mustelus* sp. (smoothhound), *Dasyatis pastinaca* (common stingray), *Engraulis encrasicolus* (anchovy), *Dicentrarchus labrax* (European seabass) and *Spondyliosoma cantharus* (black sea bream) that are now rare stragglers in Danish waters (Enghoff 1991; Enghoff *et al.* 2007).

The fossil fauna of marine molluscs does not include southern species that no longer live in Denmark. However, the warmth-demanding *Ostrea edulis* was much more common and widespread in Danish waters during the Mid-Holocene compared with the present (Spärck 1942). Vork & Thomsen (1996) reported two Lusitanian/Mediterranean marine ostracod species, *Callistocythere badia* and *Xestoleberis rubens* from Mid-Holocene deposits in the eastern part of Limfjorden and suggested that the coldest month sea-surface temperatures in northern Denmark between 6800 BP and 5900 BP were more than 5–6°C above present values, which is higher than other estimates. Thus Burman & Schmitz (2005) concluded that summer surface-water temperatures in the coastal zone of Limfjorden were 2–4°C higher during the Mid-Holocene than at present, based on δ^{18}O values in shells of *Littorina littorea*. *Callistocythere badia* is widespread in Britain (Vork & Thomsen 1996; Hull 1999) and *Xestoleberis rubens* is known from Wales, so they are apparently not exclusively Lusitanian/Mediterranean.

Other warmth-demanding species recorded in Denmark

The Mid-Holocene Danish fauna also included for example the vertebrates *Emys orbicularis* (pond turtle) and *Pelicanus crispus* (Dalmatian pelican). *Emys orbicularis* requires high summer temperatures for the eggs to develop (Degerbøl & Krog 1951); no remains of the species are known from the Limfjord region but there are many finds from central and south-east Denmark. *Pelicanus crispus* is currently found in south-eastern Europe; its former occurrence in Denmark is seen as an indication of higher-than-present summer temperatures (Hatting1963; Nikulina & Schmölcke 2015). Several southern beetle species and terrestrial gastropod species that no longer live in Denmark were also part of the fauna (Johansen & Lynge 1917; Henriksen 1933; Johnsen & Krog 1948; Thomsen & Krog 1949).

The Mid-Holocene flora in Denmark included the small annual fresh- or brackich-water plant *Najas minor* that now has a northern geographical range limit in northern Germany (Bennike *et al.* 2001). The widespread occurrence of pollen grains of *Viscum album* (mistletoe), *Hedera helix* (ivy) and *Ilex aquifolium* (holly) from Mid-Holocene deposits in Denmark indicates that the temperature was 2–3°C higher than at present (Iversen 1944, 1973). More recent analyses of pollen data indicate that the mean July temperature during the Holocene thermal maximum was *c.* 2°C higher than modern values in Denmark and that the mean January temperature was *c.* 2.5°C higher than at present (Brown *et al.* 2011). These data indicate that the mean July temperature in western Limfjorden was 2–3°C higher than pre-industrial values during the Holocene Thermal Maximum.

Harp seals and other vertebrates

The Mid-Holocene Danish fauna also included *Pagophilus groenlandica* (harp seal) and one bone from an archaeological site at Krabbesholm has been dated to the Neolithic (Table 1, LuS-6138; Bennike *et al.* 2008). Bones of *P. groenlandica* have also been reported from other archaeological sites in Limfjorden (S.H. Andersen 1992). The harp seal is currently an arctic species; its former occurrence in Danish waters during the Holocene thermal maximum is surprising, but probably reflects that the waters were characterised by a high biological productivity and large fish populations (Petersen 1922; Andersen 2001).

The bird fauna of the Limfjord region comprised the extinct *Pinguinus impennis* (great auk) and *Tetrao urogallus* (capercaillie). Bones of *P. impennis* have been reported from the Ertebølle midden (Madsen *et al.* 1900) and from a Neolithic midden at Selbjerg west of Aalborg (Marseen 1953); the species may have been breeding on islands in the Kattegat during the Stone Age (Løppenthin 1967). Bones of *T. urogallus* were found to be quite common in the Ertebølle midden (Madsen *et al.* 1900) and bones of the species were also reported from the midden by Andersen & Johansen (1987). The presence of this bird in Mid-Holocene deposits from the Limfjord region may indicate that open areas were fairly widespread in the local forests. Also *Equus ferus* (wild horse), another open landscape indicator, reappeared in Jylland during the Mid-Holocene (Sommer *et al.* 2011). We also note that charcoal assemblage from the Ertebølle midden was completely dominated by *Quercus* sp. (oak), whereas charcoal pieces of *Ulmus*, *Betula*, *Populus tremula* and *Alnus glutinosa* were much rarer (Madsen *et al.* 1900). This charcoal assemblage may also indicate fairly open forests in the region during the Mid-Holocene.

However, midden charcoal assemblages may not be representative of forests in the wider landscape due to, for example, selection bias or bias created by many charcoal fragments from only a few individuals. Pollen diagrams from the region, for example from Skånsø (Odgaard 1994), which are more representative of a wider geographical area, show the dominance of forests – not the very dense forests of the good soils – but the 'lighter' birch/oak forests. There may have been open glades in these forests. Open ground must also have characterised newly formed coastal barriers and beach ridges, which covered large areas between Limfjorden and Skagerrak.

Oysters

Numerous samples of *Ostrea edulis* shells from Stone Age shell middens in the Limfjord area have been radiocarbon dated (Andersen & Johansen 1987). The ages show a peak at about 6200 years BP in layers from the Late Mesolithic Ertebølle culture. This peak corresponds to the warmest part of the Holocene in Denmark (Iversen 1973; Brown *et al.* 2011) and to the timing of the occurrence of warmth-demanding ostracods in eastern Limfjord (Vork & Thomsen 1996). Many shell middens show a marked decline in *Ostrea* shells at the transition from the Mesolithic to the early Neolithic, at about 6000 years BP, where *Ostrea edulis* shells are replaced by shells mainly of *Cerastoderma edulis* and to a lesser degree *Mytilus edulis* (Andersen 1995, 2007).

It has been suggested that the transition from *Ostrea*-rich layers to *Cerastoderma*-rich layers is due to an abrupt, marked decrease in salinity (Rowley-Conwy

1984) or to a decrease in tidal amplitude (Petersen 2004). However, a detailed, well-dated multiproxy study of a sedimentary succession at Kilen showed no evidence of major changes in salinity or other environmental parameters across the Mesolithic–Neolithic transition at about 6000 years BP (Lewis *et al.* 2013, 2016). Another study that used multiple proxies to reconstruct Holocene temperature and salinity changes in Lillebælt also found no marked or abrupt changes about 6000 years ago (Kotthoff *et al.* 2017). It is also possible that the transition from *Ostrea*-rich layers to *Cerastoderma*-rich layers in the shell middens at Limfjorden is not synchronous (Nielsen 2008). At Hjarnø Sund in Horsens Fjord in eastern Jylland, the transition was dated to 7500–7200 years BP, well before the Mesolithic–Neolithic transition (Larsen *et al.* 2018).

The Late Mesolithic Ertebølle culture exploited a wide variety of animals and presumably also plants. Also Ertebølle sites are found in a fairly large region that was characterised by a large salinity gradient from northern Jylland to the south-western Baltic Sea. This means that there are major differences in the relative abundance of fish species at different archaeological sites. Environmental changes can hardly explain why domesticated plants and animals were introduced at the onset of the Neolithic (Ritchie *et al.* 2013).

Salinity changes

Burman & Schmitz (2005) concluded, based on stable isotope values of *Littorina* shells that the Mid-Holocene salinity at the Ertebølle site was *c.* 31 psu, which is 4–6 psu higher than at present. The Ertebølle shell midden is rich in tests of the foraminifer *Elphidium margaritaceum*, which indicates a salinity > 30 psu (Brock *et al.* 1987). The presence of bones in the Ertebølle shell midden of the marine fish *Pollachius virens* (saithe) also indicates higher than present salinity (Enghoff 1986).

The reason for the higher than present salinity during the Mid-Holocene is presumably mainly because Limfjorden was more open to the North Sea, Skagerrak and the Kattegat than at present (Fig. 9). This is partly due to the higher relative sea level and partly due to the fact that longshore sediment transport had not yet started to close the connections between Limfjorden, the North Sea and Skagerrak. Another factor that likely contributed to the higher salinity is that net precipitation was significantly lower during the Mid-Holocene than at present (Kotthoff *et al.* 2017). It is also possible that the tidal amplitude was greater than at present as suggested by Petersen (2004).

Another study was conducted by Christensen *et al.* (1998, 2004) based on a 531 cm long sediment core LIM1002 (Fig. 3) also from Bjørnsholm Bugt. The study indicates fully marine conditions prior to 2300 years BP. This was followed by an interval with a salinity around 15 psu that lasted about 960 years. After some time with gradually increasing salinity came a 600 years long interval with a salinity close to 30 psu. The next zone is a brackish-water zone dated to 1220 CE to 1825 CE. Finally there is a zone with intermediate salinity that corresponds to the time period after 1825. The results confirm the study by Kristensen *et al.* (1995), but as noted in the methods section problems related to dating of marine shells in Limfjorden means that the ages are more poorly constrained than indicated.

The most detailed and best dated study of Late Holocene salinity changes in Limfjorden was conducted by Kristensen (1995) based on four sediment cores from Bjørnsholm Bugt. Their record was divided into five zones. Zone 5 (older than 2290 years BP) was characterised by a near fully marine fauna indicating a salinity > 25 psu. Invertebrate remains from Zone 4 (2290–1330 years BP) indicate that salinity increased from *c.* 15 psu to > 20 psu. Zone 3 (1130–730 years BP) indicated almost fully marine conditions. Sediments from Zone 2 (730 years BP to 1825 CE) were rich in remains of brackish-water invertebrates such as the ostracod *Cyprideis torosa*, the midge *Chironomus* sp., the polychaete *Nereis* sp. and the bivalve *Macoma balthica*. Kristensen *et al.* (1995) concluded that the salinity was *c.* 8 psu and referred the zone to the time period with brackish water conditions known from historical sources. Finally Zone 1 (younger than 1825 CE) corresponds to modern day conditions.

Changes in historical time

The timing of the first formation of Limfjordstangen between the North Sea and Nissum Bredning is poorly constrained but it probably formed (or reformed?) around 1100–1220 CE (Kristensen *et al.* 1995). During the Viking Age the sand bar probably had not yet closed the western entrance to Limfjorden from the North Sea (Matthiessen 1941; Wohlfahrt 1994). Most recently, this question was discussed by Eriksen *et al.* (2009). They concluded that the western entrance to Limfjorden closed shortly after the Viking Age, but the entrance was open until then and probably located in the southern part of present-day Harboøre Tange. These authors also discussed the debated escape of the Norwegian king Harald Hårderåde's fleet from the Danish king Sven Estridsen in 1061 CE. According to Sturlason (1948) Harald Hårderåde escaped from the Danish king by dragging the ships over land by night. It has been suggested that the ships were dragged over Agger Tange (e.g. Bricka 1869) or from Løgstør Bredning to the north (Storm 1877). Recently Eriksen *et al.* (2009) suggested that Harald Hårderåde's ships were dragged over the narrow land between Thy and Thyholm (Fig. 3). The question about whether Limfjorden was open to the west or to the north during the Viking Age was also discussed by Nielsen (2013). Written sources indicate that Limfjorden was open to the west during the Viking Age, but closed shortly after. During the Stone Age, Limfjorden was open to the north to Skagerrak (Jessen 1920; Fig. 9), but the presence of Stone Age burial mounds on recurved spits in Hanherred indicates that the connections to the north were already being closed long before the Viking Age (Nielsen 2013) and Nordmann (1905, p. 90) suggested that the northern route was closed by the Bronze Age.

The area between Limfjorden and Skagerrak (Hanherred) was also discussed by Møller (1980, 1986). Møller documented several buried valleys between Limfjorden and Skagerrak. Based on radiocarbon dating of a sample of shells of the marine bivalve *Donax vitatus* reported by Petersen (1976) and discussed by Petersen & Andreasen (1989) that gave an age of *c.* 1900 cal. years BP (Table 1; K-2384) and remains of a *c.* 700 years old ship (Kollerupkoggen) found on land *c.* 400 m from the present coast and finally a buried but un-dated channel that was mapped north of Løgstør Bredning by Andreasen & Grøn (1995) Møller (1986) concluded that if there was a connection between Limfjorden and Skagerrak in historical times, then it must have existed in the eastern part of Hanherred. Our data do not contribute to this 150 years old discussion about when the connections between Limfjorden and Skagerrak closed.

In 1560 or 1561 CE a gap was eroded in Limfjordstangen and it became possible to sail from Limfjorden to the North Sea. In 1566 CE a new gap formed, which was closed due to long-shore sediment transport after 12 to 14 years. During the period from 1572 to 1817 CE at least nine floods are documented (Gram-Jensen 1991). In the western part of Limfjorden salt water intrusion led to mass mortality of fresh water fish in 1624 CE and on other occasions large numbers of dead fish were washed up on the shores of western Limfjord (Berntsen 1650–1654; Matthiessen 1941).

Prior to 1825 CE, Limfjorden was for a long period a fjord connected in the east to Kattegat only. The fauna in the Mors area included the invertebrates *Crangon vulgaris*, *Nereis diversicolor* and *Thedoxus fluviatilis* (Schade 1811). The two first species are euryhaline marine species that can tolerate low salinities. *Thedoxus fluviatilis* is usually classified as a freshwater gastropod, but it can also live in brackish water. Together with data on the fish fauna that included for example *Abramis brama* (bream), *Coregonus lavaretus* (European whitefish), *Perca fluviatilis* (European perch) and *Exos lucius* (pike) the invertebrates indicate that the salinity in Nissum Bredning before 1825 CE was *c.* 6 psu (Johansen 1929).

In 1825 CE Limfjordstangen was flooded twice during strong storms (Gram-Jensen 1991): on the night between 3 and 4 February and again on the night between 27 and 28 November. During the second flooding a large gap in the northern part of Limfjordstangen was created (Fig. 3). As a result, the fish fauna in western Limfjord changed abruptly to a marine fauna with fish species such as *Pleuronectes platessa* (European plaice) and *Gadus morhua* (Atlantic cod; Petersen 1877; Matthiessen 1941; Rasmussen 1968). *Ostrea edulis* also re-immigrated to Limfjorden after it became more salty (the species was noted for the first time in 1851 CE) and soon after it was abundant in the westernmost part of Limfjorden (Collin 1884).

In the following decades the opening created in 1825 CE gradually closed. However, after another storm surge in 1863 CE a new gap formed in the central part of the sand bar and it was decided to artificially maintain an opening between Limfjorden and the North Sea. Since then the western part of Limfjorden has been saline with a salinity in Nissum Bredning around 31 psu.

Conclusions

During the Lateglacial, glaciolacustrine clay was deposited in the Limfjord area. So far, no evidence of Lateglacial deposits with marine fossils have been recorded. During the earliest Holocene, large parts of Limfjorden were dry land with lakes and bogs in depressions and the shore level of the region reached a lowstand. As the relative sea level in the North Sea began to rise, a fjord with brackish water and limited water exchange formed in western Limfjord.

Later, the ongoing relative sea-level rise led to increased salinity and the western Limfjord became larger and was transformed into an area with wide connections to the North Sea and Skagerrak. The oldest dated marine shell from the western entrance to Limfjorden gave an age of 10400 years BP. The oldest dated shells from Løgstør Bredning indicate that this area had become marine at about 9300 years BP; the dated shells come from a depth of about 15.5 m below sea level. New data indicate that the relative sea-level rise was a bit slower than the global eustatic sea-level rise – in agreement with a recent study by Jessen *et al.* (2019).

The relative sea level rose gradually during the Early Holocene, reached a high stand during the Middle Holocene and fell to the present level. The higher than present-day sea level, higher temperatures and perhaps larger tidal amplitude gave rise to a rich marine life in Limfjorden with a fauna that included many species that are now absent. During the Late Holocene, when relative sea level was lowered and when longshore sediment transport of sand closed the northern entrances to Limfjorden, shell-rich layers were deposited in large parts of the Livø Bredning region. Still later, in early Medieval times, the western connection between Limfjorden and the North Sea was closed and Limfjorden became a fjord. The salinity in the western part of the fjord decreased markedly and fully marine species disappeared. After the opening to the North Sea was re-established and maintained after 1825, fully marine animals re-immigrated.

The geological evolution of the western Limfjorden after the last deglaciation has been highly dynamic with large changes in relative sea level and salinity. Environmental changes due to the relative sea-level changes and closing or opening of connections to the North Sea and Skagerrak led to large habitat changes and major shifts in the marine flora and fauna of the region – and on the living conditions. However, more samples of submarine peat or *in situ* tree stumps from different altitudes are needed to better constrain the relative sea-level changes.

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