Holocene development of Brabrand Fjord, eastern Jylland, Denmark

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The Brabrand Sø area west of Aarhus in eastern Jylland, Denmark, was deglaciated about 18 000 to 17 000 years ago. Coring in the present-day lake area revealed Early Holocene stream deposits overlain by marine deposits. The area was transgressed by the sea at *c*. 8500 cal. years BP and a 12 km long, narrow fjord was formed. In the beginning, the fjord housed a species-poor marine or brackish-water fauna with molluscs *Hydrobia* sp. (mudsnail), *Littorina littorea* (winkle), *Mytilus edulis* (blue mussel) and *Cerastoderma* sp. (cockle). This phase was followed by a phase during which the fjord housed a species-rich fauna that included *Ostrea edulis* (European flat oyster) and *Ruditapes decussatus* (palourde clam). During this phase the salinity and summer water temperatures were higher than in present day Aarhus Bugt and we also see evidence for strong bottom currents. This phase was probably characterised by a fairly large tidal amplitude. Two radiocarbon ages of *O. edulis* shells of *c*. 6250 and 6700 cal. years BP indicate that such conditions peaked during the period of the Ertebølle culture. The high-salinity phase was followed by a phase with a more species-poor fauna, this phase was also characterised by a high sedimentation rate – a feature seen in other fjords in the region. We suggest that the shift could be due to a decrease in tidal amplitude. Brabrand Fjord was eventually transformed into a lake due to land uplift and closure of the connection to Aarhus Bugt due to longshore sediment transport but the timing of the transition from fjord to lake is still unknown.

Keywords: Quaternary, Brabrand Sø, Littorina Sea, relative sea-level changes, tidal amplitude, *Ostrea*.

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During the Last Glacial Maximum, huge amounts of water was stored in continental ice sheets and global sea level was lowered by *c*. 130 m compared with the present (Lambeck *et al*. 2014). About 20 000 years ago, the sea level began to rise, and vast shallow-water areas were flooded. In Denmark, Storebælt, Lillebælt, Øresund and the North Sea were inundated. Large areas that were dry land or occupied by lakes were transgressed by the sea (e.g. Jensen *et al*. 2002; Bennike *et al*. 2021a). Stone Age settlements, forests and mires were flooded by the sea. However, in the northern part of Denmark, the glacio-isostatic uplift surpassed the eustatic sea-level rise and raised marine deposits are widespread. In the Aarhus Bugt area, the marine limit is *c*. 2.5 m above present sea level (Mertz 1924). According to the deglaciation chronology of Denmark, the last active glacier ice disappeared from the Brabrand Sø region about 18 000 to 17 000 years ago (Houmark-Nielsen *et al*. 2012).

The Holocene history of Denmark has been studied for almost two centuries, but many details are still unknown. Development of radiocarbon dating by means of accelerator mass spectrometry means that it is now possible to date a single shell of a mollusc, small remains of plants or even a single test of a foraminifer. Therefore, the timing of events in the Holocene history of Denmark can be better constrained than earlier. Detailed, high-resolution studies of continuous records are crucial for understanding the late Quaternary palaeogeographical evolution of southern Scandinavia. Here we report on studies of two sediment cores from the former Brabrand Fjord in eastern Jylland, Denmark (Figs 1, 2). We studied macroscopical remains of plants and animals and determined the age of selected samples to provide information on local environmental changes, which must have had a crucial impact on pre-historic people.

In 1900 Stone Age artefacts were found during digging of a ditch near Rugholm at the south-eastern end of Brabrand Sø and in 1903–1904 excavations were conducted by the Danish National Museum and the Geological Survey of Denmark (Thomsen & Jessen 1906). The artefacts were referred to the Ertebølle culture; they came from shallow-water, marine deposits. The deposits located in 1900 were dated by means of pollen analysis by Troels-Smith (1937). Troels-Smith dated the deposits to the late part of pollen zone VII and the early part of pollen zone VIII in the zonation scheme of Jessen (1935) and Troels-Smith (1937, 1942) concluded that the Ertebølle culture was partly contemporaneous with the Early Neolithic.

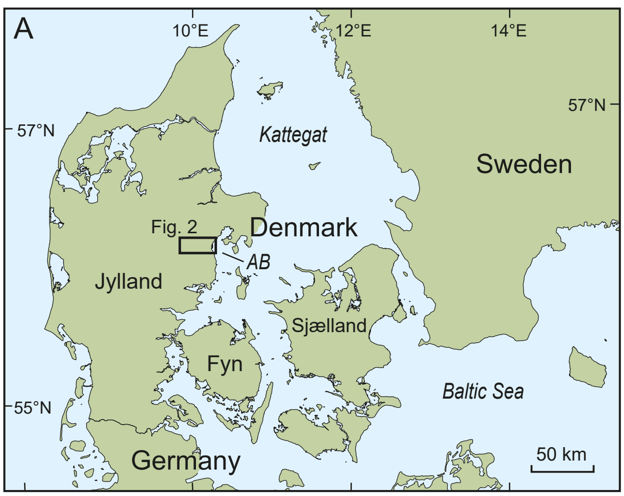

Fig. 1. Map of Denmark showing the location of the study area. AB: Aarhus Bugt. The position of Fig. 2 is indicated.

More recent radiocarbon dating indicates that the artefacts belong to the Ertebølle culture, which is now referred to the Late Mesolithic (Table 1; Fig. 3). The bone assemblage was dominated by *Cervus elaphus* (red deer) but included *Sus scrofa* (wild boar), *Bos primigenius* (aurochs), *Capreolus capreolus* (roe deer), *Martes martes* (pine marten), *Halichoerus grypus* (grey seal), *Alces alces* (elk), *Lagenorhynchus albirostris* (white-beaked dolphin), *Vulpes vulpes* (red fox), *Felis silvestris* (wild cat), *Ursus arctos* (brown bear), *Cygnus cygnus* (whooper swan), *Cygnus columbianus* (tundra swan), *Tetrao urogallus* (capercaillie), *Phalacrocorax carbo* (great cormorant), *Uria aalge* (common guillemot), *Morus bassanus* (gannet) and *Pelicanus crispus* (dalmatian pelican). The bones were identified by Herluf Winge and the results published by Thomsen & Jessen (1906).

An updated list of vertebrate remains from Ertebølle sites in Brabrand Fjord was published by Laursen (2012), based on information from Kim Aaris-Sørensen from the Natural History Museum of Denmark. The list published by Laursen includes *Pagophilus groenlandica* (harp seal), *Aquila chrysaetos* (golden eagle) and *Pinguinus impennis* (great auk). *P. groenlandica* is an arctic species that was common in Danish waters

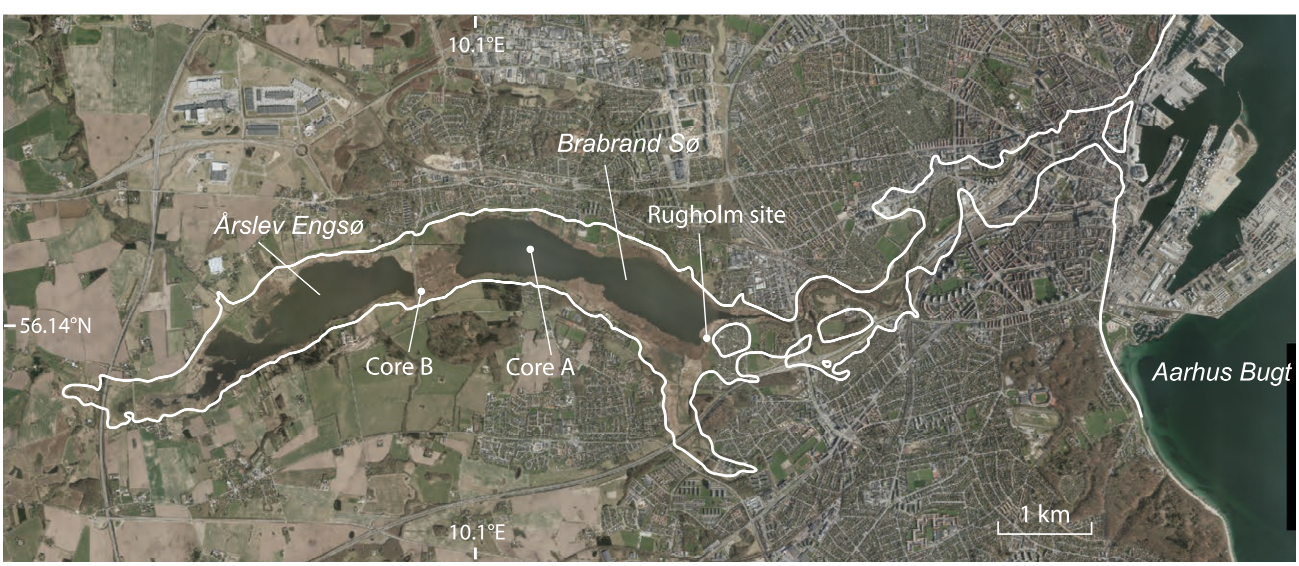

Fig. 2. Orthophoto with the former extension of Brabrand Fjord indicated, based on Rasmussen (2017).

Table 1. Selected radiocarbon ages from Brabrand Fjord and Aarhus, Denmark

Core/ site	N. lat. °	E. long. °	Laboratory number	Material	Depth (m)	Age (^{14}C years BP)[1]	Cal. age (years BP)[2]	Cal. age (y BP)[3]	Ref.
A	56.146	10.109	AAR-30714	*S. lacustris*	2.22	148 ± 25	2–282	142	a
A	56.146	10.109	AAR-30713	*S. lacustris*	2.74	134 ± 23	9–272	112	a
A	56.146	10.109	AAR-30712	Leaf fragments	3.54	4554 ± 29	5052–5431	5169	a
A	56.146	10.109	AAR-30711	Leaf fragments	4.62	4729 ± 32	5326–5579	5470	a
A	56.146	10.109	AAR-30710	Leaf fragments	5.58	4755 ± 33	5330–5584	5519	a
A	56.146	10.109	AAR-30709	Leaf fragments	6.54	4922 ± 27	5592–5716	5638	a
A	56.146	10.109	AAR-30708	*Ostrea edulis*	7.10	6260 ±31	6495–6836	6669	a
A	56.146	10.109	AAR-30707	*Ostrea edulis*	8.65	5862 ± 34	6079–6395	6240	a
A	56.146	10.109	AAR-30706	*Mytilus edulis*	8.77	8512 ± 40	8967–9310	9130	a
A	56.146	10.109	AAR-30705	Twig	8.90	9249 ± 40	10262–10560	10418	a
A	56.146	10.109	AAR-30704	*Populus tremula*	8.98	9377 ± 37	10500–10702	10603	a
B	56.143	10.090	AAR-30093	*S. lacustris*	0.58	2831 ± 32	2853–3058	2934	a
B	56.143	10.090	AAR-30092	*Cerastoderma* sp.	0.62	5428 ± 33	5602–5909	5769	a
B	56.143	10.090	AAR-30091	*Littorina littorea*	2.16	7274 ± 36	7564–7848	7702	a
B	56.143	10.090	AAR-30090	Root, woody plant	2.24	6895 ± 39	7624–7834	7725	a
Rugholm	56.138	10.139	K-2651	*Equus ferus*		5500 ± 75	6016–6450	6299	b
Rugholm	56.138	10.139	Ua-32311	*Bos primigenius*		5425 ± 75	5999–6391	6216	c
Åby rens.	56.152	10.178	Aar-12828	*Cerastoderma* sp.	1.0	5179 ± 39	5325–5648	5503	d
Pustervig	56.158	10.208	Ua-4161	*Littorina* sp.	0.36	4885 ± 50	4943–5366	5167	e

[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 IntCal20 and Marine20 data (Reimer *et al.* 2020; Heaton *et al.* 2020).

[3] Median probability ages.

References. a: this study, b: Sommer *et al.* 2011, c: Gravlund *et al.* 2012, d: Kveiborg 2014, e: Heinemeier 1999.

during the Middle Holocene (Bennike *et al.* 2008). *P. impennis* is extinct but its bones are well known from Ertebølle sites in Denmark. *P. crispus* is a southern species that no longer lives in Denmark (Hatting 1963).

The bone material excavated by Thomsen & Jessen included two bones of horse, but Winge did not include this species in his list, presumably because he considered the age of them doubtful. Degerbøl (1933) discussed these horse bones and suggested that they represent *Equus ferus* (wild horse). This viewpoint has been confirmed by direct radiocarbon dating of one of the bones, which gave an age of *c.* 6300 cal. years BP, and which fits into a general central European repopulation of wild horse tracing the Neolithic expansion (Table 1; Sommer *et al.* 2011). Degerbøl & Fredskild (1970) discussed if some of the ox bones from Rugholm represent domestic cows but concluded that the bones likely come from *B. primigenius*. One of these bones has been dated to *c.* 6220 cal. years BP (Table 1; Gravlund *et al.* 2012), which predates the arrival of domestic cattle to Denmark (Sørensen 2015).

Data on the fossil marine mollusc fauna from a gyttja layer from the Rugholm excavation were provided by Thomsen & Jessen (1906). They reported the following 13 species of molluscs: *Ostrea edulis* (European flat oyster), *Mytilus edulis* (blue mussel), *Cerastoderma edule* (common cockle), *Parvicardium exiguum*, *Venerupis corrugate* (= *Tapes pullastra*), *Ruditapes decussatus* (palourde clam), *Scrobicularia plana*, *Macoma balthica*, *Littorina littorea* (winkle), *Hydrobia ulvae*, *Bittium reticulatum*, *Tritia reticulata* (= *Nassa reticulata*) and *Retusa truncatula*. The fauna shows that a fjord with a rich and diverse marine mollusc fauna existed in the area during the Stone Age.

In 1944–1945 new excavations were carried out at the Rugholm site. The aim was to collect material for exhibitions in Aarhus (Haugsted *et al.* 1947), however, new pollen analyses were also carried out (Andersen 1947). The analysed samples were referred to the late part of pollen zone VII, corresponding to the late part of the Atlantic chronozone (Mangerud *et al.* 1974) or to *c.* 6000–7000 cal. years BP.

In recent years, archaeological excavations have been conducted in connection with urban development east of Brabrand Sø (Rasmussen 2009a, b, 2012, 2017; Kveiborg 2014) and it is clear that the Brabrand Fjord area has been an important area for pre-historic people. A shell of a marine bivalve (*Cerastoderma*) from the fjord gave an age of *c.* 5500 cal. years BP, and a shell of a marine gastropod (*Littorina*) from Aarhus, at the entrance to the fjord gave an age of *c.* 5170 cal. ka BP (Table 1). However, so far little information is available on the duration of the fjord stage and no attempt to obtain continuous records of environmental changes has been carried out so far.

Study area

Brabrand Sø is located in a 2–3 km wide buried valley with a Quaternary succession that is over 100 m thick (Lykke-Andersen 1973). This incised valley is interpreted as a tunnel valley, where meltwater has eroded Quaternary and pre-Quaternary strata. The lake is fed by Aarhus Å draining a catchment of 310 km^2. In pre-historic times the Brabrand Sø area (Fig. 2) was a fjord, which was connected to Aarhus Bugt in the east. Brabrand Fjord was *c.* 12 km long, *c.* 700 m wide in the west and more in the east. At present, part of the former fjord is occupied by two lakes, Brabrand Sø and Årslev Engsø. Brabrand Sø is east–west-oriented, 2.8 km long and 300–600 m wide with an area of 154 ha. The maximum water depth was 1.8 m in 1979 (Høy 1979). According to historical maps, 200 years ago the lake was approximately 1 km longer than at present. Lake level lowering and deposition of sediment have reduced the size of the lake. During the period from 1988 to 1995 about 500 000 m^3 of sediment was dredged from the lake, in order to improve the water quality of the eutrophic lake and to prevent overgrowth of the lake. Årslev Engsø is an artificial, shallow lake that was created in 2003. The level of Brabrand Sø is 0.7 m above sea level (Høy 1979). The tidal range in Aarhus is about 40 cm during spring tide (DMI 2021), but sea level variations during stormy weather may exceed 150 cm (Kystdirektoratet 2019).

During the Late Holocene, the former Brabrand Fjord turned into the present lake because the relative sea level gradually fell *c.* 2.5 m (Mertz 1924). Raised marine deposits have been mapped at some sites along the shores of Brabrand Sø (Jupiter 2019).

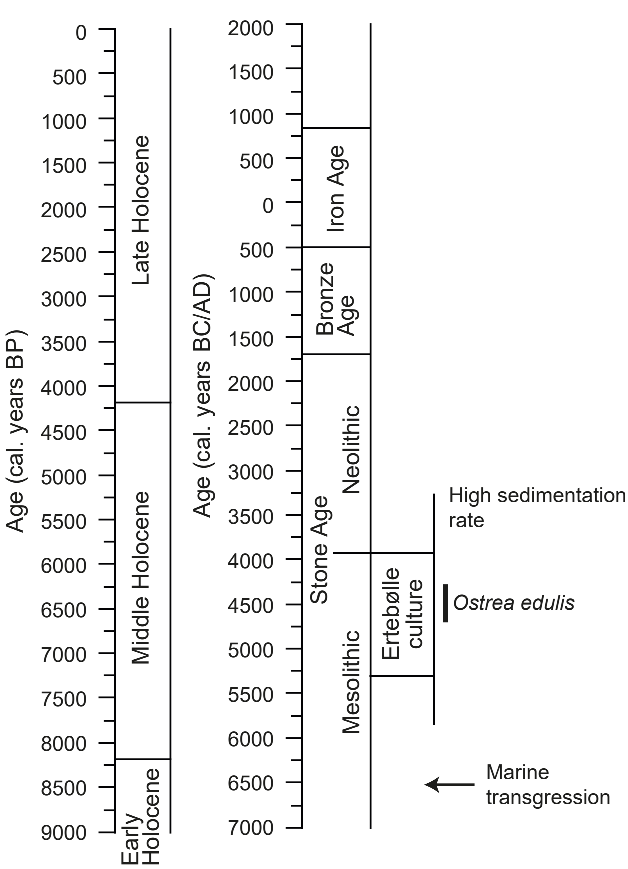

Fig. 3. Chronology and overview of Holocene changes at Brabrand Fjord. The division of the Holocene is from Walker *et al.* 2019 and the archaeological time periods are from Skousen (2008).

Methods

Coring was carried out from a platform on the lake (May 2019) and at a site on land (March 2019), using a Russian peat corer (Jowsey 1966). The chamber was 1 m long and had a diameter of 5 cm. The corer was pushed or hammered into the sediment. The water depth at the lake site was 1.6 m (site A, Fig. 2). The site on land is located south-west of Brabrand Sø, at an elevation of *c.* 1 m above sea level (site B in Fig. 2). Whole cores were brought to the laboratory where they were cleaned and subsampled. Contiguous 4 cm thick samples were taken for macrofossil analyses. Sediment samples were wet sieved on 0.4, 0.2 mm sieves, and the residue left on the sieves was transferred to a petri dish. Macroscopic remains of plants and animals were identified and counted using a dissecting microscope. The numbers in the macrofossil diagrams refer to the number of shells per sample, however, many of the shells represent small juvenile specimens. Many of the shells, especially of *M. edulis*, were fragmented – in this case, hinge fragments were counted. In general, preservation was good to excellent, but at some levels carbonate shells were somewhat dissolved. This means that thin-shelled organisms may be under-represented at these levels. A total of 320 samples were analysed for macrofossils.

Selected remains were dried and submitted for radiocarbon dating using accelerator mass spectrometry. Dating was carried out at the Aarhus AMS Centre, Aarhus University. Radiocarbon ages were calibrated to calendar years before present (BP) using CALIB v. 8.2 with the IntCal20 or Marine20 calibration curves (Reimer *et al.* 2020; Heaton *et al.* 2020). For marine samples, we used a ΔR value of –150 years, which corresponds to a reservoir age of 400 years. However, the local reservoir age may have varied in the past (Olsen *et al.* 2009), and ages of marine shells are therefore more uncertain than ages of remains of terrestrial plant.

Results and discussion

Sediments

Simplified logs are shown in Figs 4, 5. The sediments at core site A consisted, from the bottom upwards, of (1) 40 cm light-grey homogenous clay and silt, (2) 55 cm brown sand, layered fine- and medium-grained sand in the lower part and homogenous coarse-grained sand in the upper part, (4) 39 cm grey, homogenous shell-rich sand, (5) 8 cm grey silt and fine-grained sand. This layer was almost completely lost during coring. It was followed by (6) 100 cm grey, homogenous shell-rich sand, (7) 428 cm dark olive-grey homogenous gyttja with abundant well-preserved leaves of deciduous woody plants and with scattered marine shells, (8) 80 cm dark-grey homogenous detritus gyttja.

At core site B we found (1) 30 cm grey poorly sorted sand and fine gravel with *in situ* roots in the upper part, (2) 155 cm marine sediments consisting of brown shell-rich sand in the bottom, dark-brown homogenous sandy gyttja with shells and homogeneous gyttja with marine shells and remains of *Phragmites*, (3) 85 cm alternating layers of fine-grained sand and coarse detritus gyttja, and (4) 75 cm brown peat, decomposed in the upper part.

Radiocarbon ages and sedimentation rates

A total of 15 samples were dated (Table 1; Figs 4, 5). At site A a *Populus tremula* (aspen) bud scale and a twig provide ages of the terrestrial vegetation that covered the deeper parts of the fjord before it was inundated by the sea; these samples gave ages of *c.* 10 400 and 10 600 cal. years BP. The oldest dated marine shell yielded an age of *c.* 9100 cal. years BP, however, this age appears to be somewhat too old, according to the relative sea-level curve for the area (Bennike *et al.* 2021b). It is possible that the local reservoir age was

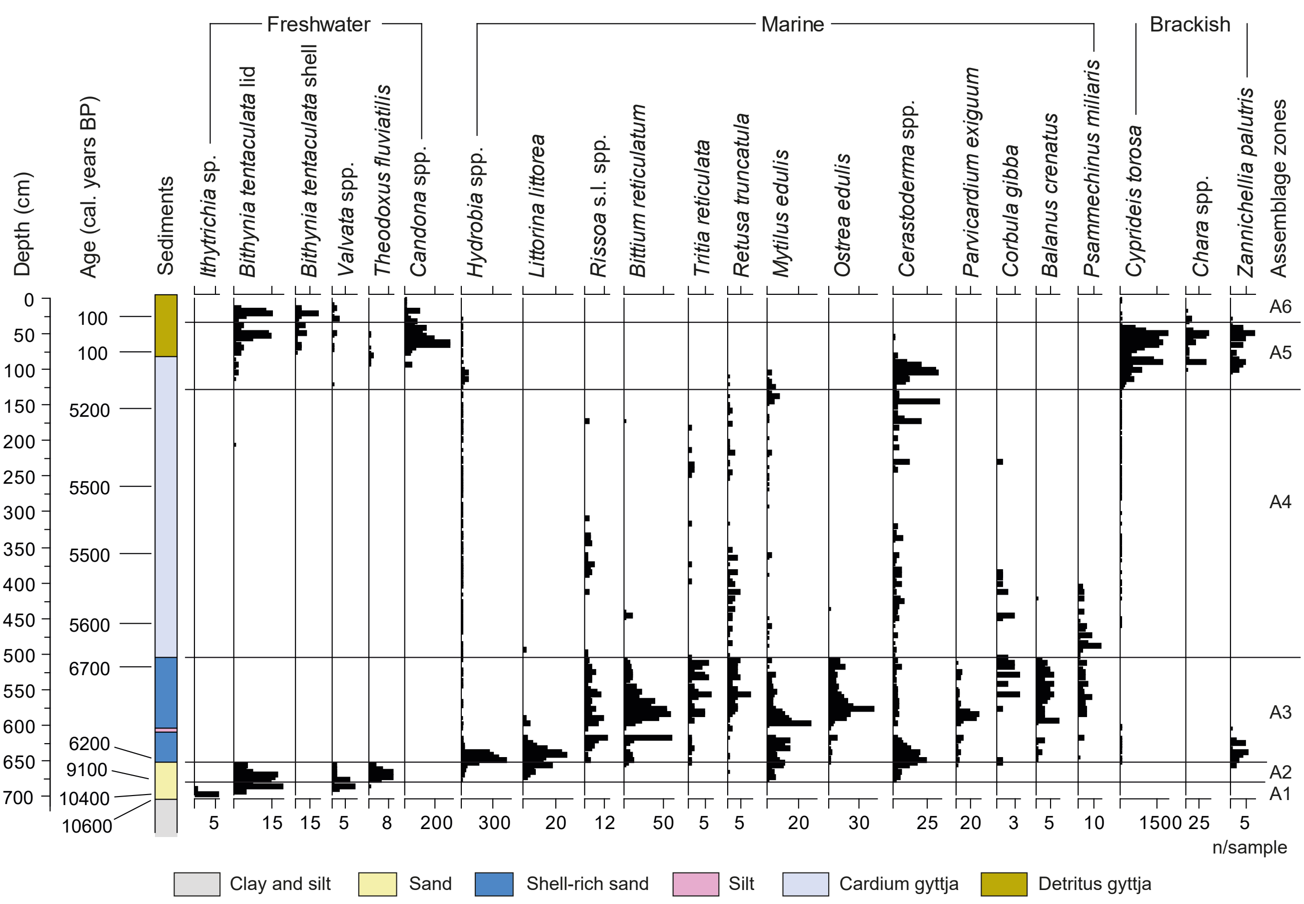

Fig. 4. Simplified macrofossil concentration diagram for core site A from Brabrand Fjord. Note different scales for different taxa.

larger than 400 years during the initial marine transgression and we suggest that the fjord was inundated *c.* 8500 cal. years BP. Dating of two shells of *O. edulis* gave ages of *c.* 6300 and 6700 cal. years BP, however, the ages are reversed, indicating that the shell-rich sandy sediment was deposited during a time period with strong currents that led to reworking of shells. Four samples of leaves from the next layer gave ages between *c.* 5600 and 5100 cal. years BP, indicating a very high sedimentation rate. The high sedimentation rate may be the reason that the leaves were well-preserved. Thus usually, only the veins of the leaves are found in Holocene sediments. Finally, two samples from the upper part of the succession gave young ages. The ages show that the succession is characterised by major hiati and it was not possible to reconstruct an age-depth curve from the dated samples.

At site B a small *in situ* root and a shell of *L. littorea* both gave ages of *c.* 7700 cal. years BP, indicating that the site was inundated by the sea at that time. The youngest shell from the site was dated to *c.* 5800 cal. years BP and a sample of achenes of the reed plant *Schoenoplectus lacustris* (bulrush) gave an age of *c.* 2900 cal. years BP. This shows that a major hiatus is also found at site B.

Macrofossils

Core site A. The macrofossil diagram from core site A was divided into six local assemblage zones (A1–A6; Fig. 4).

Zone A1 is characterised by sand with a mixture of terrestrial, wet-ground and limnic plants such as *P. tremula*, *Betula* sect. *Albae* sp. (tree birch), *Schoenoplectus* spp., *Carex* sp. (sedge), *Urtica dioica* (common nettle), *Filipendula ulmaria* (meadowsweet), *Eupatorium cannabinum* (hemp-agrimony), *Menyanthes trifoliate* (bogbean) and *Nymphaea alba* (white water lily). A single tooth of a small rodent was also found. The lowest fossiliferous samples contained remains of larvae of the caddisflies *Ithytrichia* sp. (probably *Ithytrichia lamellaris*), *Hydropsyche pellucidula* and *Lepidostoma hirtum* and head capsules of larvae of Simuliidae (blackflies; Table 2). Larvae of the recorded caddisflies and blackflies are typical inhabitants of rivers and streams with fairly fast-flowing water (Wiberg-Larsen *et al*. 2001; Bennike & Wiberg-Larsen 2002), and the sandy sediment is interpreted as a stream deposit. Larvae of non-biting midge *Stenochironomus* sp. are miners of macrophytes (Brooks *et al*. 2007). A bit higher up follows shells of the gastropods *Valvata cristata*, *Valvata piscinalis*, opercula of the freshwater gastropod *Bithynia tentaculata*, shells of the small bivalve *Pisidium* sp. and statoblasts of the bryozoan *Cristatella mucedo*. The gastropods are primarily inhabitants of lakes, but the presence of sandy sediment may indicate a at least partly lotic environment.

Zone A2 contains shells of the freshwater gastropods *V. cristata*, *V. piscinalis*, rare shells and common opercula of *B. tentaculata* and shells of *Pisidium* sp. Shells of the gastropod *Theodoxus fluviatilis* (river nerite) are common; this species is usually classified as a freshwater species and it is nowadays widely distributed in Aarhus Å (Wiberg-Larsen, unpubl.), but it also lives in brackish water. Zone A2 also contains shells of marine or brackish-water mollusc species, such as *Hydrobia* sp., *L. littorea*, *M. edulis* and *Cerastoderma* sp. The mixture of freshwater species and marine species may indicate that the salinity alternated between marine and freshwater conditions during the earliest stage of the marine inundation. It is also possible that the remains of freshwater species were transported into the fjord from a nearby stream (no doubt being a former Aarhus Å and its major tributary Lyngbygaards Å), but we consider this option less likely because the shells of the freshwater species are thin and hardly survives transport. The zone forms a transition from freshwater conditions to marine conditions.

Zone A3 contains numerous shells of marine molluscs, whereas shells of fresh-water species are absent. Remains of land plants and limnic plants are also absent. The fauna is dominated by the gastropods *Hydrobia* sp., *L. littorea*, *Rissoa* spp. (*R. parva* and *R. membranacea*) and *B. reticulatum* and the bivalves *M. edulis*, *O. edulis* and *Cerastoderma* sp. The fauna also comprises for example *Musculus discors*, *Mysella bidentata*, *Spisula subtruncata*, *Abra alba*, *R. decussatus*, *P.*

Table 2. Arthropod remains from assemblage zone A1, core site A from Brabrand Fjord, Denmark

Order/family	Genus/species	694 cm	698 cm
Oribatida	*Hydrozetes*?		2 exoskeletons
Trichoptera, Hydropsychidae	*Hydropsyche pellucidula*		1 frontoclypeal apotome
Trichoptera, Hydroptilidae	*Ithytrichia* sp.	1 case	7 cases
Trichoptera, Lepidostomatidae	*Lepidostoma hirtum*	2 genae, 1 pronotum	
Diptera, Simuliidae		6 head capsules	13 head capsules
Diptera, Chironomidae	*Stenochironomus* sp.	1 head capsule	1 head capsule
Diptera, Chironomidae	*Micropsectra* sp.		2 head capsules

exiguum, *Corbula gibba*, *T. reticulata*, *Triphora adversa*, *R. truncatula*, *Onoba semicostata*, *Lacuna divaricata*, the barnacle *Balanus crenatus*, the crab *Carcinus maenas*, the sea urchin *Psammechinus milliaris* and the polychaete worm *Pomatoceros triqueter*. Remains of crabs are rarely reported from Quaternary sediments, but the samples from Brabrand Fjord contained a few dactyls (moveable fingers from the claw) of crabs.

The lower part of the zone is characterised by abundant shells of *Hydrobia* spp., many shells of *L. littorea and Cerastoderma* sp., whereas shells of *O. edulis* are rare; the species becomes common in the upper part of the zone. The fauna is rich and diverse with a total of 24 taxa of molluscs. The fossil assemblage indicates shallow water influenced by currents and increasing salinity and water depth. The presence of *O. edulis* and *R. decussatus* is noteworthy as these species no longer live in the inner Danish waters; they indicate salinities and summer temperatures higher than pre-industrial values. Water plants are represented by fruits of *Zannichellia palustris* in the lower part of the zone and by rare fruits of *Ruppia* sp., both being common in shallow marine or brackish waters.

Zone A4 is characterised by gyttja with *Cerastoderma* sp., *M. edulis* and *Hydrobia* spp., whereas *Rissoa* spp., *B. reticulatum*, *T. reticulata*, *R. truncatula* and *C. gibba* are rare or fairly rare. The fauna also comprises for example *S. subtruncata*, *M. bidentata*, *M. balthica*, jaws of the polychaete worm *Nereis* sp. A total of 15 taxa of molluscs were found in this zone. The fine-grained sediment indicates a low energy environment and the fauna indicate somewhat lowered salinity, although *B. reticulatum* indicates a salinity above 25 ‰.

Zone A5 is characterised by huge numbers of the ostracod *Cyprideis torosa*, fairly high numbers of *Cerestoderma* (in the lower part of the zone), *Chara* sp., *Z. palustris*, *B. tentaculata* and *Candona* sp. *Cyprideis torosa* is typical of brackish-water environments with fluctuating salinities (Pint *et al.* 2012), and we suggest that the sediments accumulated during the transition from fjord to lake. The plants *Chara* and *Zannichellia* are also typical of brackish water, although they may also grow in freshwater. *B. tentaculata* is a freshwater species, whereas some *Candona* species can live in brackish water. This zone marks a transition from fjord to lake.

Zone A6 contains shells of molluscs such as *B. tentaculata*, *V. cristata*, *V. piscinalis*, *Anisus contortus*, *Acroloxus lacustris*, *Pisidium* sp., shells of ostracods (*Candona* sp., *Darwinula stevensoni*, *Cyclocypris laevis*), the caddisfly *Orthotrichia* sp., the bryozoans *Cristatella mucedo* and *Fredericella* sp., the water plants *Ranunculus* sect. *Batrachium* sp., *Potamogeton perfoliatus* and *Callitriche* sp. This assemblage represents a limnic or

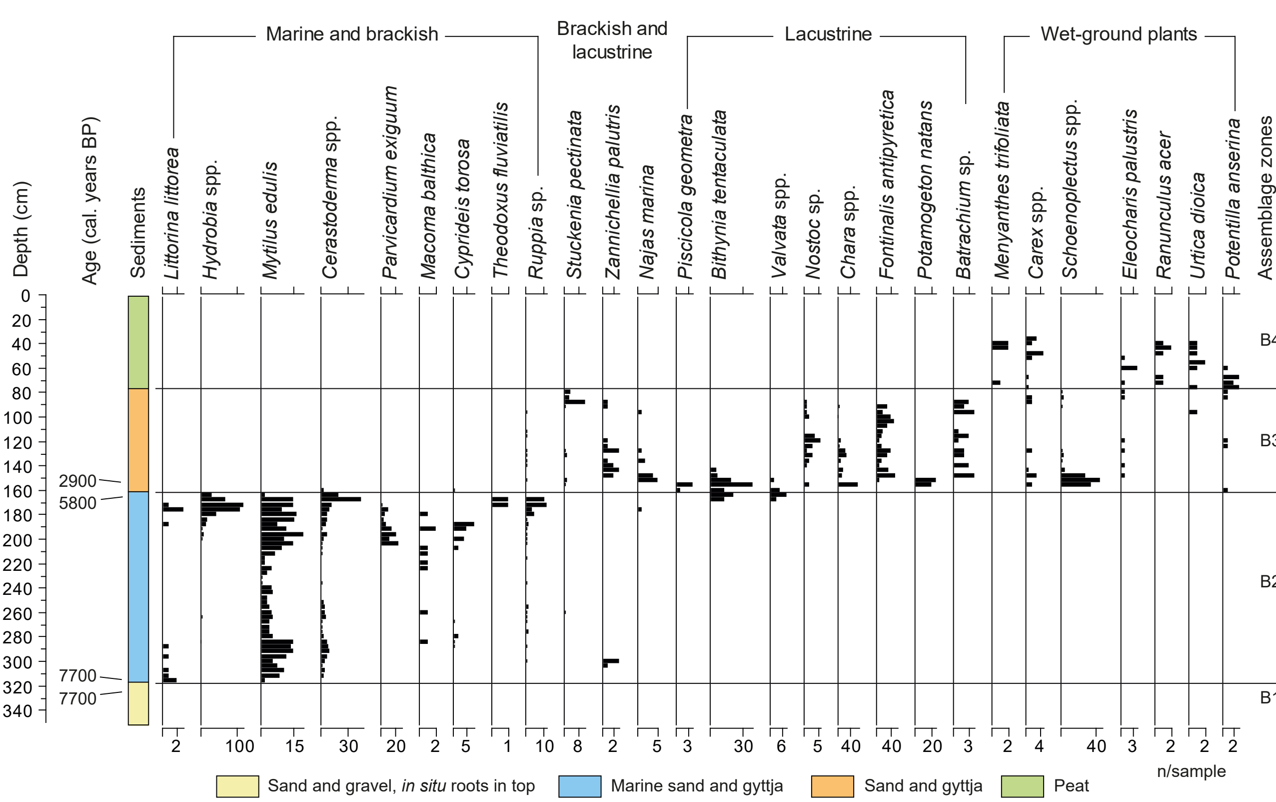

Fig. 5. Simplified macrofossil concentration diagram for core site B from Brabrand Fjord. Note different scales for different taxa.

lentic environment with macrolimnophytes and a rich fauna of invertebrates. The zone contains low numbers of *C. torosa* shells, which we interpret as reworked from zone A5.

Core site B. The macrofossil diagram from core site B was divided into four local assemblage zones (B1–B4; Fig. 5).

Zone B1 contains roots of woody and non-woody plants.

Zone B2 is characterised by shells of marine bivalves and gastropods, in particular *M. edulis* and *Cerastoderma* spp. Rare shells of *L. littorea* occur in the bottom and top of the zone, and shells of *Hydrobia* spp. are abundant in the top. Other marine molluscs comprised the bivalves *P. exiguum* and *M. balthica* and the gastropods *B. reticulatum* and *Aclis walleri*. There is a small peak of the ostracod *C. torosa* below the top of the zone, and two shells of the gastropod *T. fluviatilis* were found near the top of the zone. Remains of water plants are rare but fruits of the vascular plants *Ruppia* sp. and *Zannichellia palustris* were recorded. Shells of freshwater gastropods are found in the uppermost part of the zone. A total of 9 taxa of marine molluscs are recorded in zone B2.

Zone B3 is dominated by remains of water plants such as the vascular plants *Ruppia* sp. (rare), *Stuckenia pectinata*, *Z. palustris*, *Najas marina*¸ *Batrachium* sp., *Ceratophyllum demersum*, *N. lutea*, *Myriophyllum spicatum*, *Potamogeton perfoliatus*, the algae *Nostoc* sp. and *Chara* spp. and the bryophyte *Fontinalis antipyretica*. In the lower part of the zone shells and opercula of freshwater molluscs are found, the most common species are *B. tentaculata*, *V. cristata* and *V. piscinalis*. The zone also contains fruits of wet-ground plants such as the *Scirpus* s.l. spp., *Carex* spp. and *Eleocharis palustris*.

Zone B4 is dominated by vegetative remains of *Phragmites australis*. In the lower part rare fruits and seeds of wet-ground plants such as *Eleocharis palustris*, *Carex* spp., *M. trifoliata*, *Alisma plantago-aquatica*, *Ranunculus flammula*, *Ranunculus acer*, *U. dioeca*, *Caltha palustris* and *Cicuta virosa* occurred. Achenes of *Potentilla anserina* were also fairly common at the base of zone B4, perhaps due to trampling by domestic animals near the core site. The upper part of the peat did not contain fruits or seeds because the peat was decomposed.

Palaeoenvironmental reconstruction of Brabrand Fjord

The light-grey clay and silt at core site A is interpreted as a glaciolacustrine deposit and the poorly sorted sand and fine-grained gravel at core site B as a glaciofluvial deposit. Both sediment types are likely from the last deglaciation of the region.

During the earliest Holocene, the region was covered by open woodland with *Betula*, *Pinus* and *Populus* (Odgaard 1994). A stream, probably the predecessor of present-day Aarhus Å that drained the area west of Aarhus Bugt was found at the bottom of the valley. The stream housed a fauna that included larvae of the caddisflies *Ithytrichia* sp. and *Hydropsyche pellucidula*, confined to rivers and major streams, and *Lepidostoma hirtum*, mainly recorded from major streams. There is no clear indication that a lake existed in Brabrand Fjord prior to the marine transgression, which may indicate that there is no threshold between Brabrand Fjord and Aarhus Bugt. When marine waters began to inundate the area at *c.* 8500 cal. years BP, a brackish-water phase followed, with *Hydrobia* sp., *L. littorea*, *M. edulis* and *Cerastoderma* sp. These taxa are common in shallow-water coastal areas with brackish water in the region at present (Muus 1967).

Somewhat later fully marine conditions with a rich fauna that included *O. edulis* and *R. decussatus*. Thomsen & Jessen (1906) noted that the *O. edulis* shells from the Rugholm site were up to 100–110 mm long. This can be compared with lengths up to 160 mm recorded from the Limfjord (Madsen *et al.* 1900; Nordmann 1903) and a maximum length of 53 mm for shells from southern Lolland (Bennike, unpublished data). The fairly species-rich marine fauna in the former Brabrand Fjord and the large size of *O. edulis* shells indicate favorable conditions with high salinities over 25 ‰, nutrient-rich warm waters and a tidal amplitude larger than at present. However, the conditions were not as favorable for *O. edulis* as in the Limfjord during the Middle Holocene.

Thomsen & Jessen (1906) reported on 13 species of molluscs, and we found a total of 24 taxa of molluscs. Two ages of 6300 and 6700 cal. years BP correspond to the Ertebølle culture (Fig. 3), during which shell middens dominated by *Ostrea edulis* shells accumulated in the region (Andersen 2007). The shell-rich sandy sediments indicate a high-energy environment with strong bottom currents, which was probably caused by a fairly large tidal amplitude.

In the Early Neolithic, fine-grained marine gyttja accumulated in Brabrand Fjord at a high rate, indicating a marked shift to a low-energy environment. A shift to higher sedimentation rates is seen in several other fjords in the region (Lewis *et al.* 2016) and in the former Arrefjord in north-east Sjælland a shift in sedimentation from sand to gyttja occurred (Bennike *et al.* 2017). The shift in Arrefjord was dated to between 6700 and 6200 cal. years BP, apparently earlier than the shift registered in Brabrand Fjord. Lewis *et al.* (2016) discussed if the change in sedimentation rate dated to *c.* 5900 cal. years BP could be due to forest clearance by early farmers. However, only minor changes in soil erosion rates are seen in lake records from the region during the relevant time interval (Bennike *et al.* 2021c). Increased sedimentation rates could also be caused by a relative sea level fall, which could lead to increasing erosion in the streams entering the fjords but it appears that increasing sedimentation rates occurred prior to sea level fall. Lewis *et al*. (2016) suggested that gradually falling temperatures following the Holocene thermal maximum as reconstructed by for example Brown *et al.* (2011) led to increasing sedimentation rates, but we find it difficult to see how falling temperatures could have a strong influence on sedimentation rates. We suggest that a decline in the tidal amplitude could be the factor that allowed fine-grained sediment to accumulate at a high rate in Brabrand Fjord in the Early Neolithic and caused a major shift in sedimentation rate in other fjords in the region.

We have not been able to provide a precise age for the transition from the fjord stage to the current lake stage, but bracketing ages from the core sites indicate that the shift occurred between 5200 and 2900 cal. years BP. The transition was caused by relative sea-level fall and longshore sediment transport along the shores of Aarhus Bugt, closing off the mouth of the fjord. There is a large hiatus in the upper part of the succession from core site A in Brabrand Fjord. This hiatus could be caused by the dredging of sediments from the lake.

The terrestrial fauna during the time of the Ertebølle culture included the mammals *B. primigenius* (aurochs), *E. ferus* (wild horse) and the bird *T. urogallus* (capercaillie). The presence of the latter two species may indicate that the forests in the area were fairly open. By the time of the Ertebølle culture, aurochs had died out on the Sjælland and Fyn, perhaps the forests on these islands had become too closed for this species. The marine fauna included *P. groenlandica* (harp seal) and *P. impennis* (great auk), bones of which have been recorded from many Middle Holocene sites in Denmark. Overall, the marine invertebrate and vertebrate faunas during the Middle Holocene were rich, reflecting higher than present-day temperatures, more salty water – and probably a larger tidal amplitude.

Conclusions

This macrofossil study of the palaeoenvironmental history of Brabrand Fjord shows that the area has a complex Holocene history. A stream drained the region that was transgressed by the sea at about 8500 years BP. The early marine fauna was species-poor, but during the Ertebølle culture a rich marine fauna with *Ostrea edulis* (oyster) was found in the fjord. The fauna and the presence of sandy sediments in the fjord indicate strong bottom currents, which were likely due to a high tidal amplitude. In the Early Neolithic, fine-grained gyttja accumulated rapidly in Brabrand Fjord and other fjords in the region. We suggest that a marked decrease in the tidal amplitude could be the reason. We could not date the transition from fjord to lake, probably because of dredging of sediments in the lake.

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