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Late glacial to early Holocene development of southern Kattegat

Carina Bendixen, Jørn Bo Jensen, Ole Bennike and Lars Ole Boldreel

The Kattegat region is located in the wrench zone between the Fennoscandian shield and the Danish Basin that has repeatedly been tectonically active. The latest ice advances during the Quaternary in the southern part of Kattegat were from the north-east, east and south-east (Larsen *et al.* 2009). The last deglaciation took place at *c.* 18 to 17 ka BP (Lagerlund & Houmark-Nielsen 1993; Houmark-Nielsen *et al.* 2012) and was followed by inundation of the sea that formed a palaeo-Kattegat (Conradsen 1995) with a sea level that was relatively high because of glacio-isostatic depression. Around 17 ka BP, the ice margin retreated to the Øresund region and meltwater from the retreating ice drained into Kattegat. Over the next millennia, the region was characterised by regression because the isostatic rebound of the crust surpassed the ongoing eustatic sea-level rise, and a regional lowstand followed at the late glacial to Holocene transition (Mörner 1969; Thiede 1987; Lagerlund & Houmark-Nielsen 1993; Jensen *et al.* 2002a, b).

Major parts of Kattegat are characterised by thick successions of Late Weichselian and Holocene sediments (Mörner 1969; Bergsten & Nordberg 1992; Gyldenholm *et al.* 1993). At around 9.6 ka BP, a large lagoon–estuary environment in southern Kattegat was partly blocked by transgressive, coastal barrier islands and spits (Bennike *et al.* 2000; Jensen *et al.* 2002a).

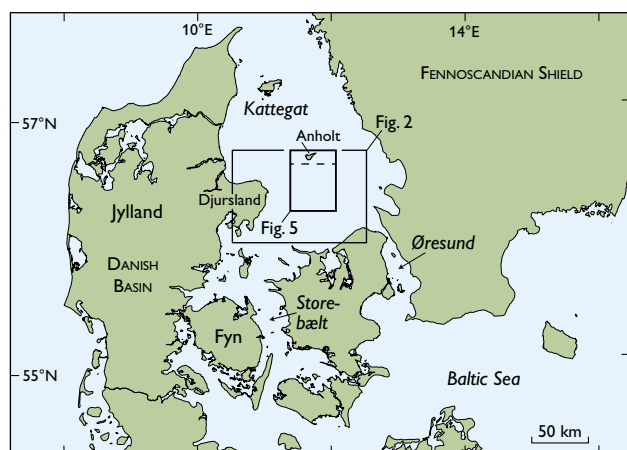


Fig. 1. Map of Denmark showing the location of the study area of Fig. 5 in southern Kattegat.

The aim of this paper is to describe the late glacial and early Holocene development of southern Kattegat, based on a recent study (Bendixen 2012). The study area covers 1696.5 km² and is located south of the island of Anholt in the southern part of Kattegat (Figs 1, 2). The south-western part of the area is shallow but water depths increase to the north-east where depths over 40 m are found (Fig. 2). Two distinct submarine channels running nearly N–S and NE–SW were probably formed by subglacial meltwater erosion; these channels are partly filled by late glacial and Holocene sediments. The area can be seen as a transitional shallow-water area at the entrance to the Baltic Sea (Bennike *et al.* 2000). Detailed 2D seismic work will be conducted in the region over the next years, which will improve the basis for interpretations in the coming years.

Methods

The data used in this study consist of shallow single-channel seismic profiles and sediment cores. The seismic data comprise boomer data acquired by R/V *Alexander von Humboldt* from 1997 to 1999 and sparker data acquired in 2011 using M/V *Laura*. Navigation was based on differential GPS. The sediment cores were collected with a 6 m long vibrocorer

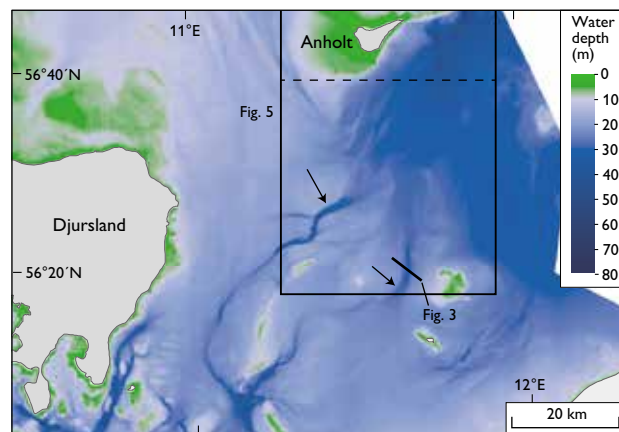


Fig. 2. Bathymetric map of the study area in southern Kattegat showing the two incised palaeo-channels from Storebælt (arrows) that drained into the Kattegat and the location of the shallow seismic profile shown in Fig. 3. The white areas to the east are Swedish territorial waters.

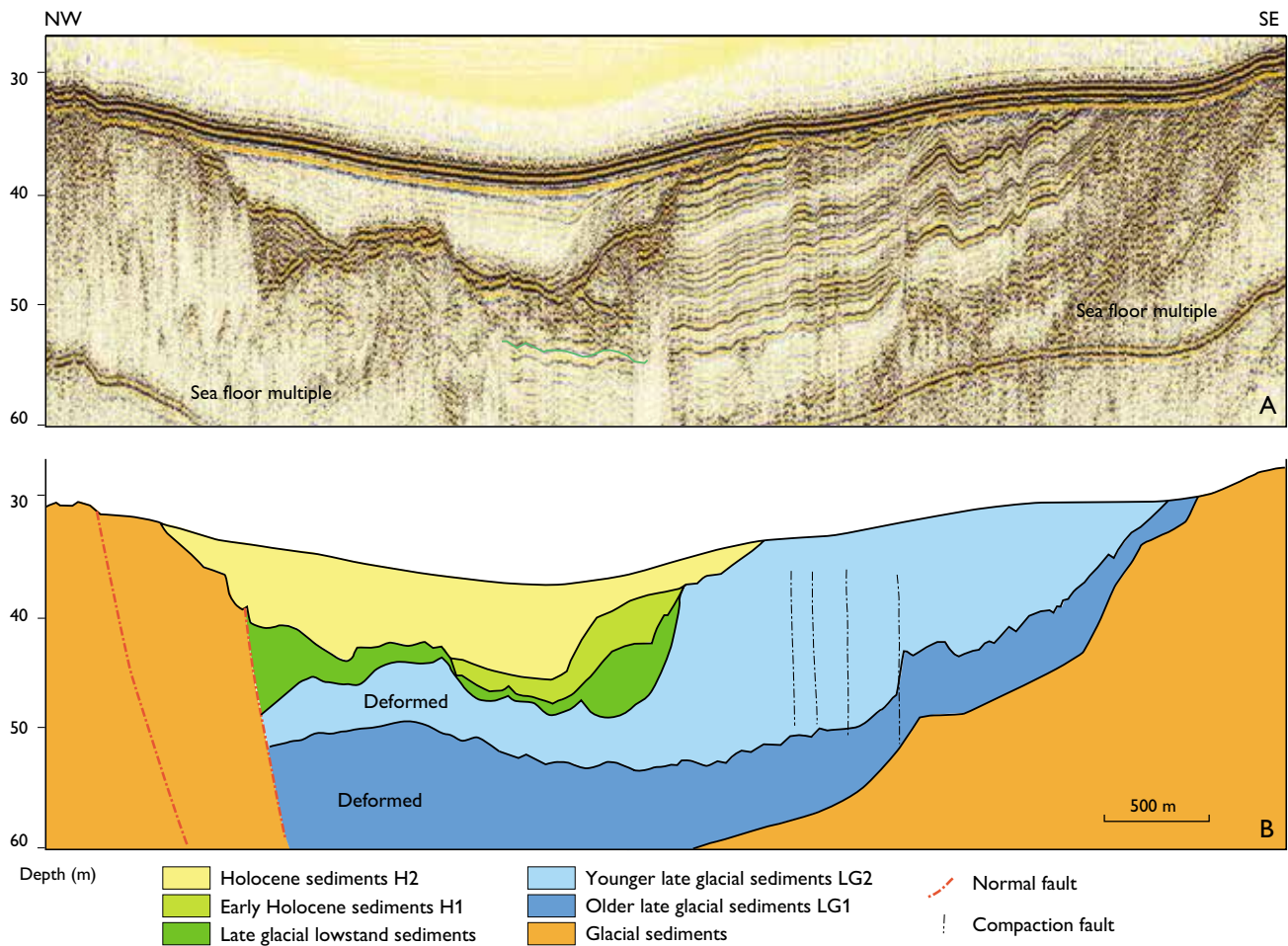


Fig. 3. A: Selected part of shallow seismic profile R3_021a obtained by a boomer. B: Preliminary interpretation. For location see Fig. 2.

from *Laura* in 2011. The cores were cut into 1 m long sections that were shipped to the Geological Survey of Denmark and Greenland where they were split, photographed, described and subsampled in the laboratory.

Prior to interpreting the seismic profiles, ProMAX seismic data processing software was used to optimise the data quality. The boomer data were subjected to frequency filtering and the sparker data were subjected to the Kirchhoff time-migration method. Interpretation of the seismic data was carried out using the program SeisVision.

Results and discussion

Two late glacial units (LG1 and LG2) have been identified (Fig. 3); they show high variability in thickness in the area studied. The sediments were deposited during a sea-level highstand period, which can be seen from the internal seismic pattern. The older LG1 unit shows draping parallel reflections of low amplitude whereas the LG2 unit shows parallel reflections of high amplitude (Fig. 3). The units are

divided by an erosional unconformity in the north-eastern parts of the study area, whereas continued deposition occurred in the west where no unconformity is found. A single radiocarbon dating of a shell of *Hiatella arctica* from LG1 gave an age of 16.1–16.6 cal. ka BP, and dating of shells from LG2 gave ages of 13.3–15.5 cal. ka BP (Jensen *et al.* 2002a).

Distinct normal faults cut the late glacial deposits. Detailed interpretations of the seismic profiles show that faulting occurred during the last stage of the deposition of the LG2 unit. This is evident because the uppermost part was not affected by the faulting whereas the lower-lying sediments are cut by the faults. This finding is consistent with the conclusions of Jensen *et al.* (2002b).

The NW–SE-orientated sparker profile R3_021a (Fig. 3) shows major bounding faults that cut the late glacial sediments to the north-west and south-east and hence limit the distribution of the younger sediments. Within the late glacial units, two major faults are interpreted as strike-slip faults. The faulting postdates the uppermost part of the LG2 unit and was possibly a result of the deglaciation of the Kat-

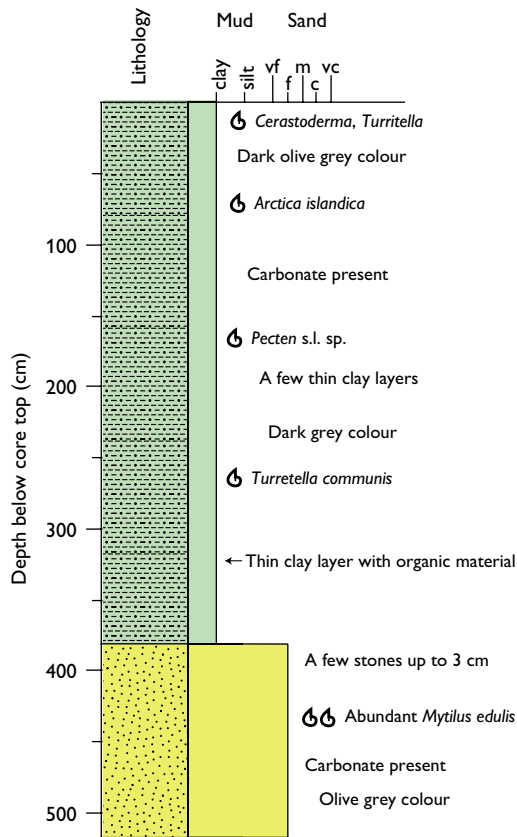


Fig. 4. Sedimentological log of vibrocore DGU 561118.10. For location see Fig. 5.

tegat region that led to isostatic uplift and reactivation of older faults. This tectonic event may have contributed to the opening of Storebælt.

The late glacial units between the faults show an internal pattern with contorted reflectors. The late glacial deposits have been reworked by faulting and a significant erosional unconformity is found between the late glacial and the Holocene sediments. This unconformity formed during the late glacial – early Holocene lowstand period.

Above the erosion surface, two Holocene units can be separated on the basis of their difference in reflection pattern and infill direction, with H1 showing infill from the south-east and H2 from the north-east. Two lithological units presumably of Holocene age were also found in sediment core no. DGU 561118.10 collected at 56°23.165'N, 11°22.0'E from a water depth of 38.0 m (Fig. 4). The core was 518 cm long and consisted of 136 cm sand with abundant shells of the common blue mussel *Mytilus edulis* that is

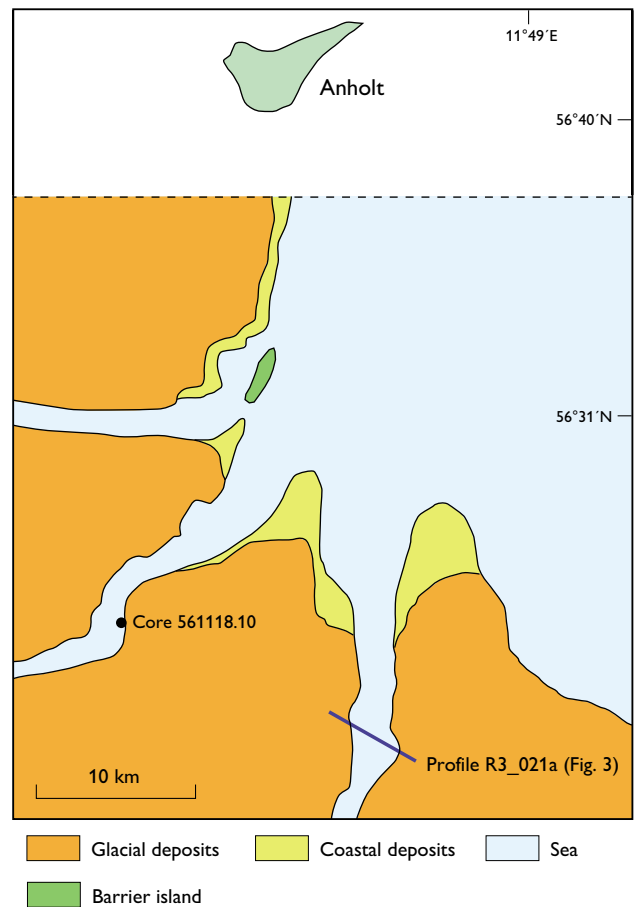


Fig. 5. Palaeogeographic map of the area south of Anholt in Kattegat in early Holocene showing glacial deposits to the south and west, coastal sandy deposits formed by prograding shorelines and a barrier island. The present-day form of Anholt is included to show the location of the map.

characteristic of shallow water, overlain by 328 cm of mud with shells of *Turrítella communis*, *Arctica islandica*, *Pecten s.l. sp.* and other marine molluscs that are characteristic of deeper water. The marked lithological change 382 cm below the core top probably corresponds to the boundary between units H1 and H2 (Bendixen 2012). We suggest that the sand was deposited during the early Holocene when sea level was low, whereas the mud was deposited after the relative sea level had increased. Radiocarbon dating of Holocene sub-littoral sand deposits in the region has yielded ages of c. 11–10 cal. ka BP (Bennike *et al.* 2000; Jensen *et al.* 2002a).

A palaeogeographic map of the region illustrates northward coastal progradation with spits and barriers with back-barrier-enclosed environments in which finer-grained sediments were deposited (Fig. 5).

Conclusions

The late glacial sediments in southern Kattegat consist of a lower and an upper sequence deposited during relatively high sea level; the boundary between the sequences shows an erosional surface towards the north-east. The distribution of the sediments is limited by major faults which were initiated during deposition of the uppermost part of the youngest late glacial unit.

Major faults bounding the late glacial sediments were active during the deposition of the uppermost part of the youngest late glacial unit. We suggest that strike-slip movements occurred due to isostatic reactivation of the Fennoscandian Border Zone and upward movement of the late glacial sediments. An early Holocene lowstand level is identified as an erosional surface, underlying units H1 and H2. Initial transgression resulted in coastal progradation and back-barrier-enclosed environments with deposition of finer-grained sediments (H2) in the former incised valleys.

Acknowledgement

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