The geological architecture and development of the Holmsland Barrier and Ringkøbing Fjord area, Danish North Sea Coast

Dennis Anthony & Ingelise Møller

Abstract

The Holmsland Barrier is a 35 km long transgressive coastal barrier located on the Danish North Sea coast, separating the highly dynamic North Sea from the large lagoon Ringkøbing Fjord. In this paper we present new geological and geophysical data from various surveys, including a ground-penetrating radar (GPR) study, several marine shallow-seismic high-resolution surveys, and onshore and marine borehole data. The GPR data has revealed both the large-scale architecture of a part of the barrier as well as small-scale internal structures. From this we conclude that the barrier primarily is built up of sequences of washover deposits, locally interspersed with eolian deposits. The data have been combined in order to construct an evolutionary model of this barrier system. Finally, a large and coherent complex of pre-Quaternary deposits is found at or close to the seabed offshore. This complex also underlies the northern part of the Holmsland Barrier, and is believed to control the position of the present shoreline, as well as its seaward convexity.

Keywords

Barrier, Denmark, coastal evolution, ground-penetrating radar (GPR), sedimentary structure, seismic, washover.

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The west coast of Denmark facing the North Sea is a highly dynamic environment with geomorphologic elements of varying origin and genesis. South of Blåvands Huk (Figure1) the Wadden Sea features large barrier islands intersected by deep inlets, protecting tidal flats and marsh areas. To the North the spit of Skagen is the dominant feature, and continues to build outward into the Skagerak. The central part of the West coast stretches from Blåvands Huk to Hanstholm in a nearly straight line, and the bays and fjords between the headlands are all closed by wave-dominated barriers. How these present barriers have evolved has not previously been studied using geophysical methods. However, some of the fossil barrier complexes have been subject to various research activities (e.g. Clemmensen, 2001a). This paper presents a variety of geological and geophysical observations from the Ringkøbing Fjord area and the Holmsland barrier. The data originates primarily from a ground-penetration radar study and shallow high-resolution marine seismic surveys. Evidence from the combined data sets has been used to reconstruct the development of the Holmsland Barrier.

Physical setting

The study area is located at the west coast of Denmark and exposed to the North Sea (Figure1). Due to a large fetch and strong westerly winds, the North Sea coast in this area is characterised by a high-energy wave-regime. The tidal range is up to 0.5 m, increasing southwards. Storm-induced setup, however, can raise the sea-level by several meters.

During the last glaciation (Weichsel) only the southwest of Denmark was ice-free, and large outwash plains covered this area, infilling and locally eroding the valleys of the existing landscape (e.g. Houmark-Nielsen, 1987). Large Weichselian outwash plains are today found in the southwest of Denmark, and the older Saalean landscape protrudes these plains (see Figure 2).

During the Holocene transgression, the outwash plains were gradually submerged below sea level. The upper part of glaciofluvial sediments was reworked and redistributed by coastal and marine processes. The early Atlantic Transgression was very rapid, as has been demonstrated for the northeast North Sea area (Leth, 1998). By approx. 4-5 ka BP the sea in the study area reached a level close to the present day level (e.g. Pirazzoli, 1991). However, relative

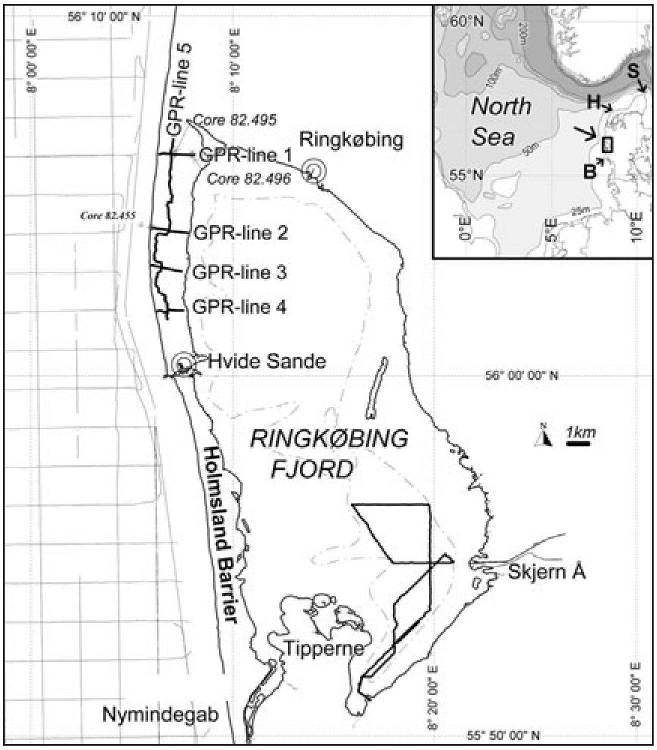

Figure 1: Location of study area. The Holmsland Barrier is located between the North Sea and Ringkøbing Fjord. Transects for both marine and land-based surveys referred in the text are indicated. Depth contour lines in the Ringkøbing fjord area represent 2 and 4 meter intervals. Labels in the insert: B=Blåvands Huk, H=Hanstholm, S=Skagen.

sea-level fluctuations have occurred since then, especially in the north of Denmark due to glacio-isostatic rebound (Mertz, 1924; Mörner, 1979; Clemmensen, 2001b), but according to Krogh (1979), the study area has not experienced significantly higher sea levels than the present level during the Holocene.

The Holmsland Barrier is approximately 35 km long and 1-2 km wide. High foredunes, up to 25 meters above sea-level, are situated along the North Sea coast. From these foredunes, dune fields extend east-southeast. Most of these are parabolic dunes, but some may also have formed at the rims of washover fans, as observed on the Skallingen barrier south of the study area (Aagaard et al., 1995). Marsh areas have developed at the easternmost part of the barrier, but the installation of sluice locks at the inlet at Hvide Sande in 1931, combined with coastal nourishment and dune stabilisation along the coast, have halted marsh flooding and further marsh growth.

The Holmsland Barrier is relatively narrow, and in historical times there have been only few inlets, no ebb-tidal deltas, and a large flood tidal delta, which is typical for a wave dominated barrier (e.g. Davis, 1994). After the closure of the southern inlet, Nymindegab, the former flood-delta complex, Tipperne, is no longer flooded, and due to coastal nourishment of the North Sea coast, washover of the barrier has practically stopped.

Data and general methods

Data from new surveys in the Ringkøbing Fjord region are presented in this study. Central in this context is a ground-penetrating radar study.

In recent years ground-penetrating radar (GPR) has proven to have great potential to the study of internal sediment structures, including features typically found in the coastal zone (e.g. Jol et al., 1996; Bristow et al, 2000). A GPR survey was carried out along four lines crossing the Northern part of the Holmsland barrier and one line parallel to the barrier axis. Profile data were collected with the Sensors & Software pulseEKKO 100 system, equipped with a 400 v transmitter and 100 MHz antennae, with an antenna

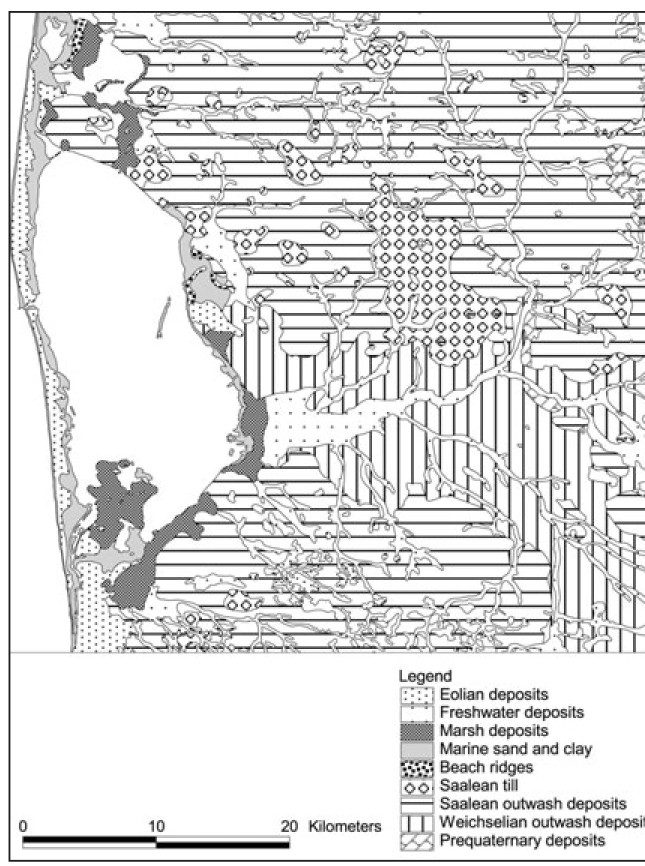

Figure 2: Surface geology of the Ringkøbing Fjord area (from GEUS, 1999).

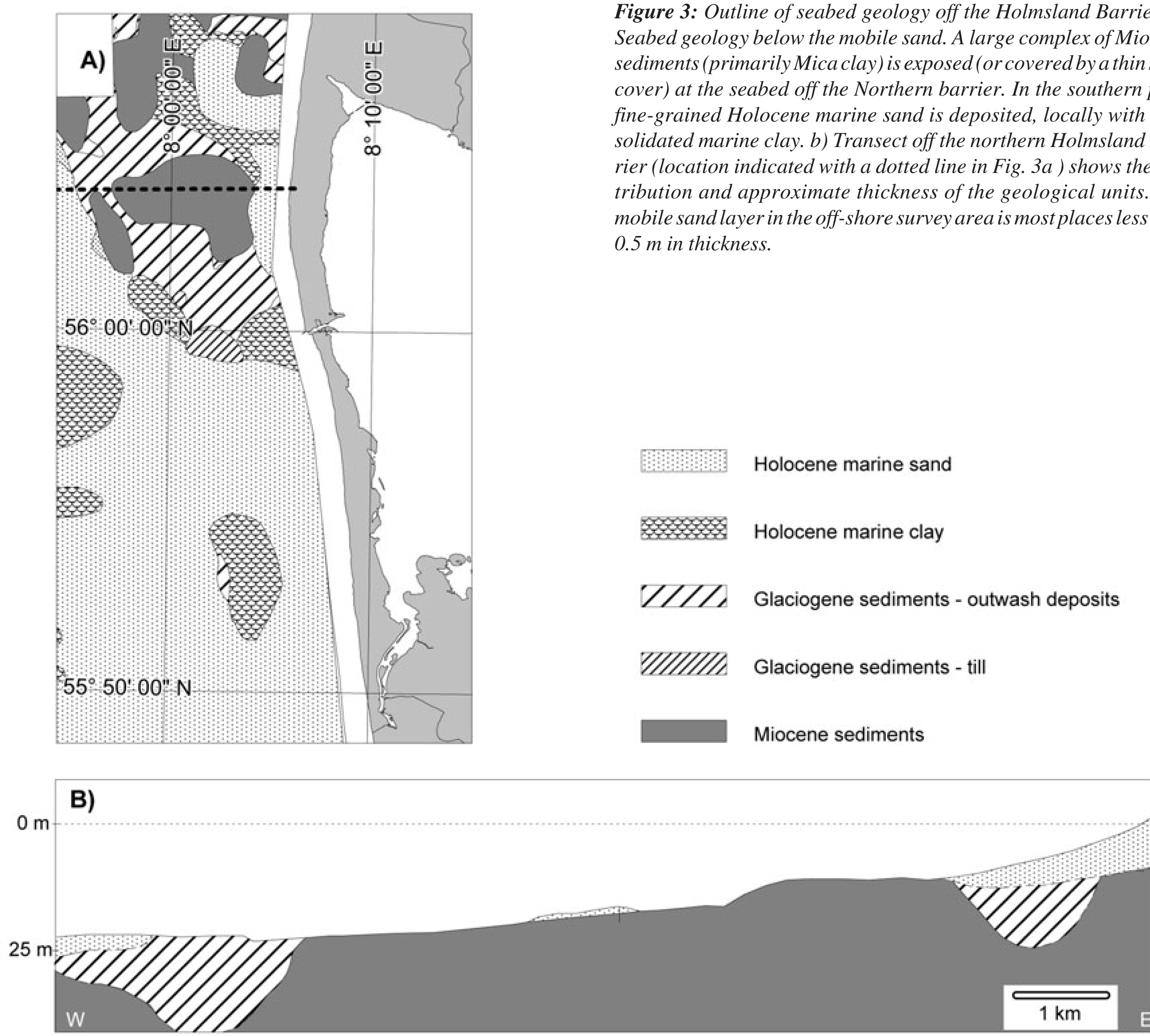

Figure 3: *Outline of seabed geology off the Holmsland Barrier. a) Seabed geology below the mobile sand. A large complex of Miocene sediments (primarily Mica clay) is exposed (or covered by a thin sand cover) at the seabed off the Northern barrier. In the southern part, fine-grained Holocene marine sand is deposited, locally with consolidated marine clay. b) Transect off the northern Holmsland Barrier (location indicated with a dotted line in Fig. 3a) shows the distribution and approximate thickness of the geological units. The mobile sand layer in the off-shore survey area is most places less than 0.5 m in thickness.*

separation of 1.0 m. Correlation between drill logs and the reflectors in the radiograms yields a radar wave velocity for saturated sand of 0.06 m/ns. This wave velocity was used for depth conversion. Interpretations of large-scale architecture and small-scale internal structures of the northern part of the Holmsland barrier based upon these GPR profiles.

In addition, a marine survey with high-resolution marine seismics and vibrocores was carried out off the Holmsland Barrier between 10 and 25 meters of water depth, and a limited high-resolution seismic survey was made in the Ringkøbing Fjord. The offshore survey is documented in Leth et al. (1999) and Anthony (2001). The seismic equipment used are the Edgetech X-star system, EG&G Boomer and EG&G Side-Scan Sonar. The vibrocore was equipped with a 6 m drill pipe.

Vibrocores were also collected onshore along the central part the Danish West Coast at 2-4 km intervals. At the GPR-lines two additional boreholes were made. Vibrocore and borehole data were used to map the depth of the pre-Holocene surface and interpret the depositional environment. Grain-size parameters were calculated using Folk & Ward (1957).

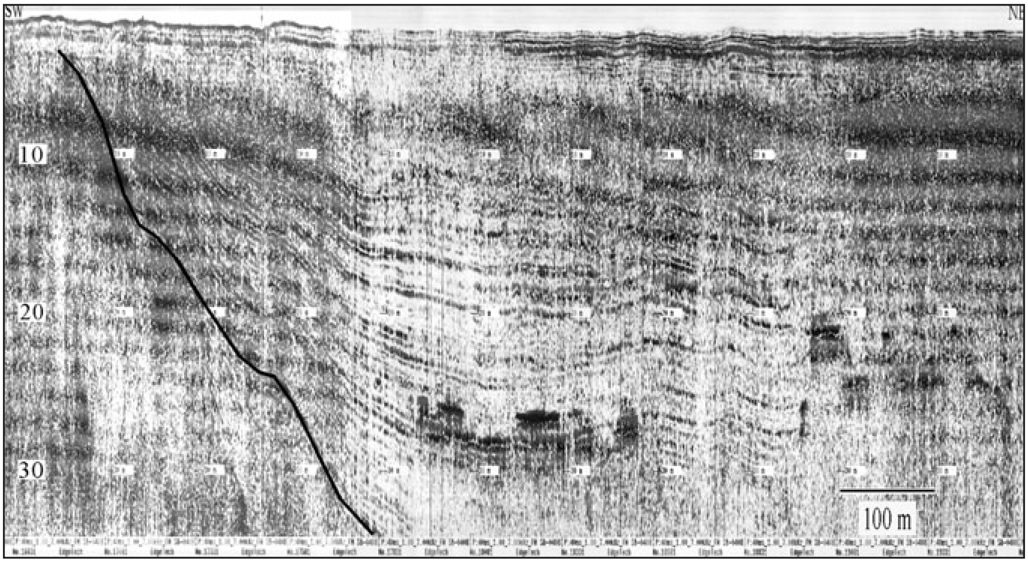

Figure 4: *Seismic profile (X-STAR) from the southern part of Ringkøbing Fjord, at approx. 2 meters of water depth. Depth scale in meters. The flank of a large valley is outlined, and the valley is filled with acoustically laminated sediments near the flank, but in the northeastern part gas-rich near-surface sediments block the deeper signals.*

Results

Marine high-resolution seismics and vibrocores off the Holmsland Barrier

The marine geological study off the Holmsland Barrier (see Figure 1 for survey lines) was part of a programme covering the offshore coastal zone from Nymindegab to Lodbjerg (Leth et al., 1999; Anthony, 2001). The primary sediment types found are 1) mobile Holocene sand, 2) immobile Holocene sand, 3) Holocene marine clay 4) glaciogene outwash deposits (sand / clay), 5) diamictons and 6) Miocene deposits. The textural composition of the mobile Holocene sand (i.e. unconsolidated coarse to fine) resembles the equilibrium composition arising from modern hydrodynamic conditions. The immobile sand, however, is finer and has laminaes of silt and clay. The distinction between the mobile and the immobile Holocene sand is supported by AMS C-14 datings.

Figure 3a shows the main shallow geological sedimentary units beneath the mobile sand layer. The thickness of the mobile sand layer in the offshore area is generally less than 0.5 m, but increases towards the shore. Off the northern part of the barrier the seabed is relatively complex. Seismic data and vibrocore samples reveal a dominant area of Miocene deposits, surrounded by glaciogenic sediments. To the south most of the area is covered by immobile Holocene marine sand. The depressions in the glacial / Miocene landscape have a infill of marine clay. Figure 3b shows a east-west transect of the geology off the northern part of the barrier. The Miocene deposits, which mostly consist of Mica clay, form a relatively resistant seabed. These cover a large part of the profile, and continue beneath the barrier. Glaciogenic sediments in the profile are probably of Saalean age or older.

Marine high-resolution seismics in Ringkøbing Fjord

Ringkøbing Fjord is very shallow, mostly less than 2 m deep, while the deepest part is 4.5 m. The seismic equipment (Edgetechs X-STAR system) requires a minimum of 1 m water depth to operate, and an additional 1 m for safe operation. Consequently only a limited area of Ringkøbing Fjord is suited to this kind of seismic survey. A pilot survey was carried out in the southern part to test whether it is possible to operate with this type of marine geological seismic equipment in such shallow waters, and if so, to locate the main geological structures.

In water depths less than 2.5 m, the seismics revealed acoustic facies that can be interpreted as sandy, marine / coastal sediments, while in the southern part a reflector representing the flank of a more than 30 m deep valley system was observed (Figure 4). Based on observations from the off-shore study area in the North Sea as well as information on the large-scale distribution of Quaternary valleys in the North Sea (Huuse and Lykke-Andersen, 2000) this valley is assumed to have an infill of mainly Quaternary deposits. Gas-rich sediments in the deepest part of Ringkøbing Fjord prevent penetration of the seismic signal. The presence of the gas, however, is a clear indication of accumulation of organic-rich sediments, as also found by Villumsen (1977).

The sediments of the barrier

Figure 5 illustrates grain-size distribution across the north-

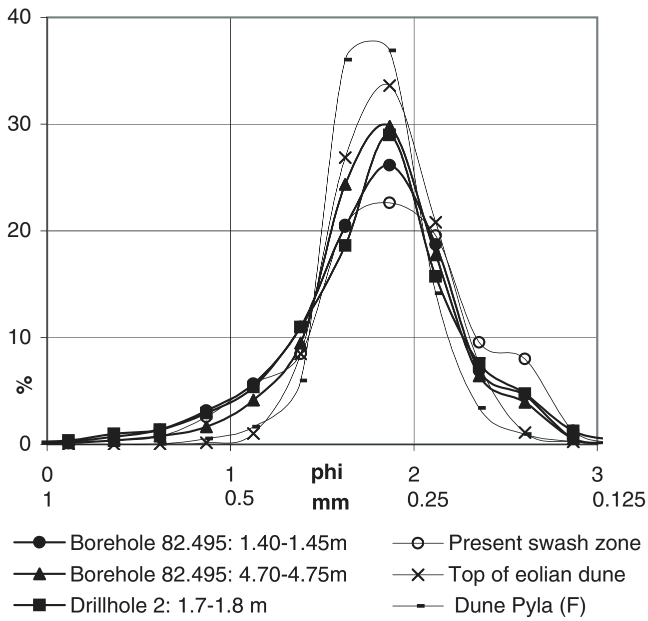

Figure 5: *Grain-size distribution across the Northern Holmsland Barrier.*

ern part of the Holmsland barrier. Samples were sieved at ¼ - phi intervals; the results show the percentage in each sieve interval. The samples shown are from two depth intervals in borehole 82.495 (1.40-1.45 m and 4.70-4.75 m below the surface), and from a single depth interval in borehole 82.496 (1.7-1.8 m below the surface). Borehole 82.495 is situated at the intersection of GPR lines 1 and 5, and borehole 82.496 is close to the lagoon on GPR line 1 (see Figure 1). Core logs are shown in Figure 6. These samples are representative of the marine sand sequences found in the boreholes. Grain-size distribution curves for sand from the modern swash zone as well as from the top of the active eolian dunes are also shown.

The grain-size distributions are remarkably uniform – only the sorting varies. The Holmsland Barrier samples all have a peak value very close to 1.9 phi (0.27 mm). All the samples are very well sorted with sorting coefficients in the range 0.11 to 0.06, using the method outlined by Folk and Ward (1967). From the poorest to the best sorting, the ranking is as follows: the present swash zone; the upper part of the central core (no. 82.495, 1.4-1.45 m); the lagoon coast core (no. 82.496, 1.7-1.8 m); the lower part of the central core (no. 82.495, 4.70-4.75 m); and finally the active eolian dune. The swash zone has a fine-grained shoulder, a tendency mirrored in the core samples. This is not seen in the eolian sediments, presumably because the fine fraction is blown away during eolian transport.

The sorting shows that even though marine processes sort the sediment well, windblown action is even more efficient. The sediment samples from the cores are more or less hybrids between the present swash sediment and the eolian sediment, both in terms of degree of sorting as well as presence of a fine-sand shoulder. The sand from the cores is thus presumed to have a marine origin, comparable to the swash-environment, but with some eolian reworking or eolian components. Overwash sediments are assumed to encompass these criteria.

Grain-size distributions from dune blowouts and gravely layers in the present foredunes deviate from the pattern mentioned above. These deviations were locally restricted, but should be mentioned as a part of the record.

In Figure 6, an example of lithological variation at a larger scale is illustrated by core 82.455. This core consists of marine sand in the upper 9.2 m, below which a thin unit of marine clay overlays another thin layer of marine gravel. All are interpreted to be of Holocene ages. Below the gravel bed and extending down to the bottom of the core, however, is almost 4 m of mica clay, interpreted to be of Miocene age.

GPR survey of the northern Holmsland Barrier

The GPR survey was carried out on the northern Holmsland barrier to study the coastal evolution of this part of the barrier. The GPR lines are shown on Figure 1.

Both the high-amplitude continuous reflectors, indicating the general large-scale architecture, as well as medium to low amplitude reflectors from the internal structures have been identified and mapped for all GPR lines. The main units of the east-west profiles are cross-correlated with the north-south-oriented GPR profile, and sub-units are identified from radar facies and radar characteristics. Internal structures across the barrier identified from the GPR profiles are shown in Figure 7, and an example of the radargrams is shown in Figure 8.

In the western part of the profiles the foreshore and the dune topography are seen, as well as it is seen that the penetration is limited due to saline water. The lowermost strong, continuous reflector has a general seaward slope. Core samples show that in the northern part the reflector represents a surface of glaciogenic sediments (presumably Saalean Till), draped with up to 0.5 m of gyttja / marine clay.

This fits with data from other drillholes in the northernmost part of the barrier, where glaciogenic deposits are found at only few meters depth, and corresponds with the Saalean glacial landscape just north of the Ringkøbing Fjord (Figure 2). The marine clay represents back-barrier deposits. At Line 2, Mica clay is observed at the beach at 10.3 m below sea-level, which corresponds well with the

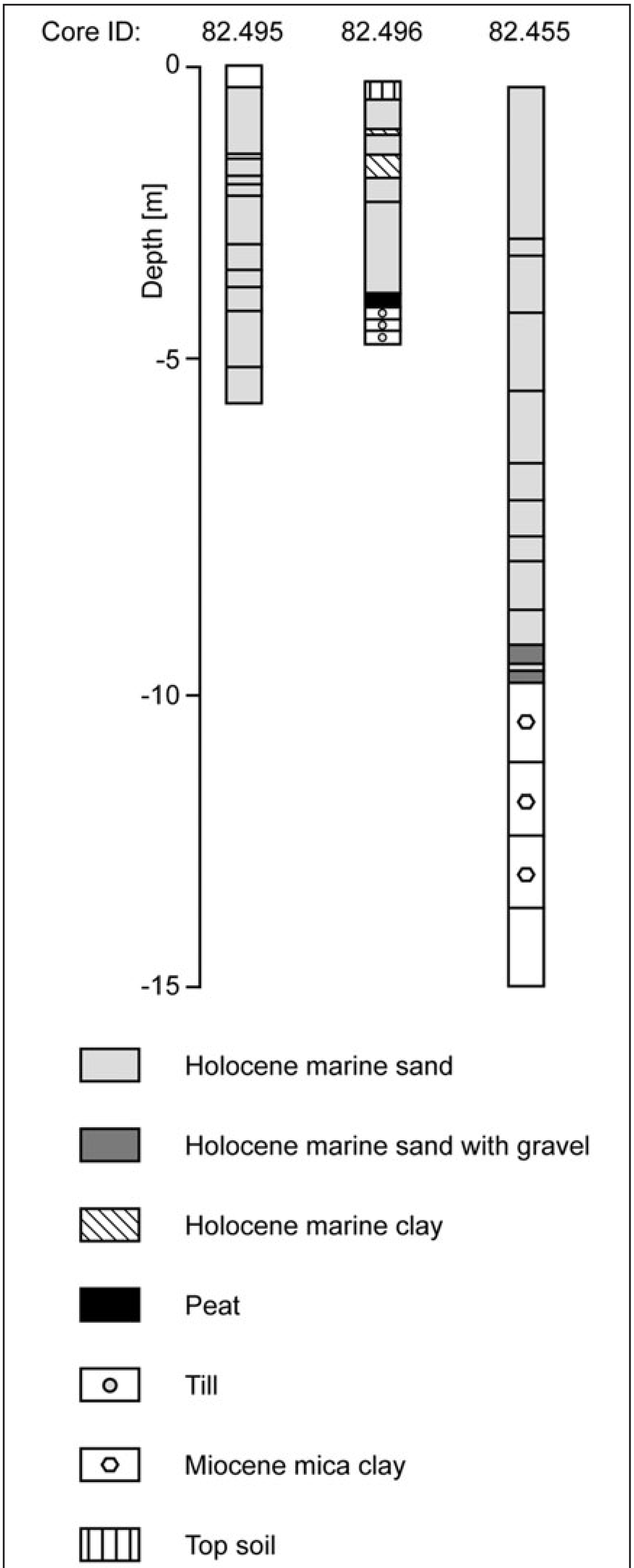

Figure 6: *Core logs from the Holmsland barrier. No. 82.495 and 82.496 sampled with hand-held drilling equipment (lined auger) in connection with the GPR-profiles. Core no. 82.455 is a vibrocore from the seaward end of GPR-line 2.*

Mica clay found in vibrocores from the seabed offshore.

The present-day back-barrier has a very gently sloping surface, and the internal structure of the top layers has a correspondingly low angle. The internal structures of the middle and lower units (MU and LU on Figure 7) suggest that the barrier formerly developed due to washover processes (cf. Schwartz, 1975).

The east-west GPR sections are characterized by the following units, as outlined in Figure7:

1) The Lower Unit LU (GPR profiles 1 and 4) is wedge-shaped and located at the seaward ½ km of the sections, pinching out toward the central part of the sections. Radar facies are characterised by sub-parallel internal reflectors, horizontal to slightly eastward-dipping.
2) The Middle Unit MU (GPR profiles 1, 2, 3 and 4) pinches out in easterly direction at 1000-1200 m from the west coast. On profile 1, and partly on profiles 2 and 3, the Middle Units radar facies shifts from sub-parallel, slightly eastward-dipping reflectors in the western part (MU-1), locally with eastward-dipping foresets, to a more chaotic appearance in the eastern part (MU-2). This shift is associated with a change in character of the top reflector of this unit, from smooth in the western part to hummocky towards the east.
3) The Upper Unit UU (GPR profile 1, 2, 3 and 4) is draped on top of MU. The radar facies are characterized by sub-parallel continuous internal reflectors in the western part, horizontal to slightly eastward dipping (UU-1). Towards the east, where MU terminates, the radar facies shifts to display a steeper angle of the larger sets, and delta-foresets become common (UU-2, Figure 8). The unit UU-3 is a local unit with a chaotic appearance.
4) The Top Unit (TU): The lower boundary of this top unit is set by the groundwater table, which generally is less than a meter below the backbarrier surface, as no other strong internal boundary can be seen on the radargrams. The radar facies of this unit are characterised by chaotic internal structures.

From the north-south striking GPR profile, the upper and middle unit can be correlated for profiles 1, 2 and 3. Profile 4 is not directly correlated by the north-south-profile.

Interpretations of the radiograms

The TU represents the foredune. From field observations of dune profiles at Holmsland, washover sequences were re-

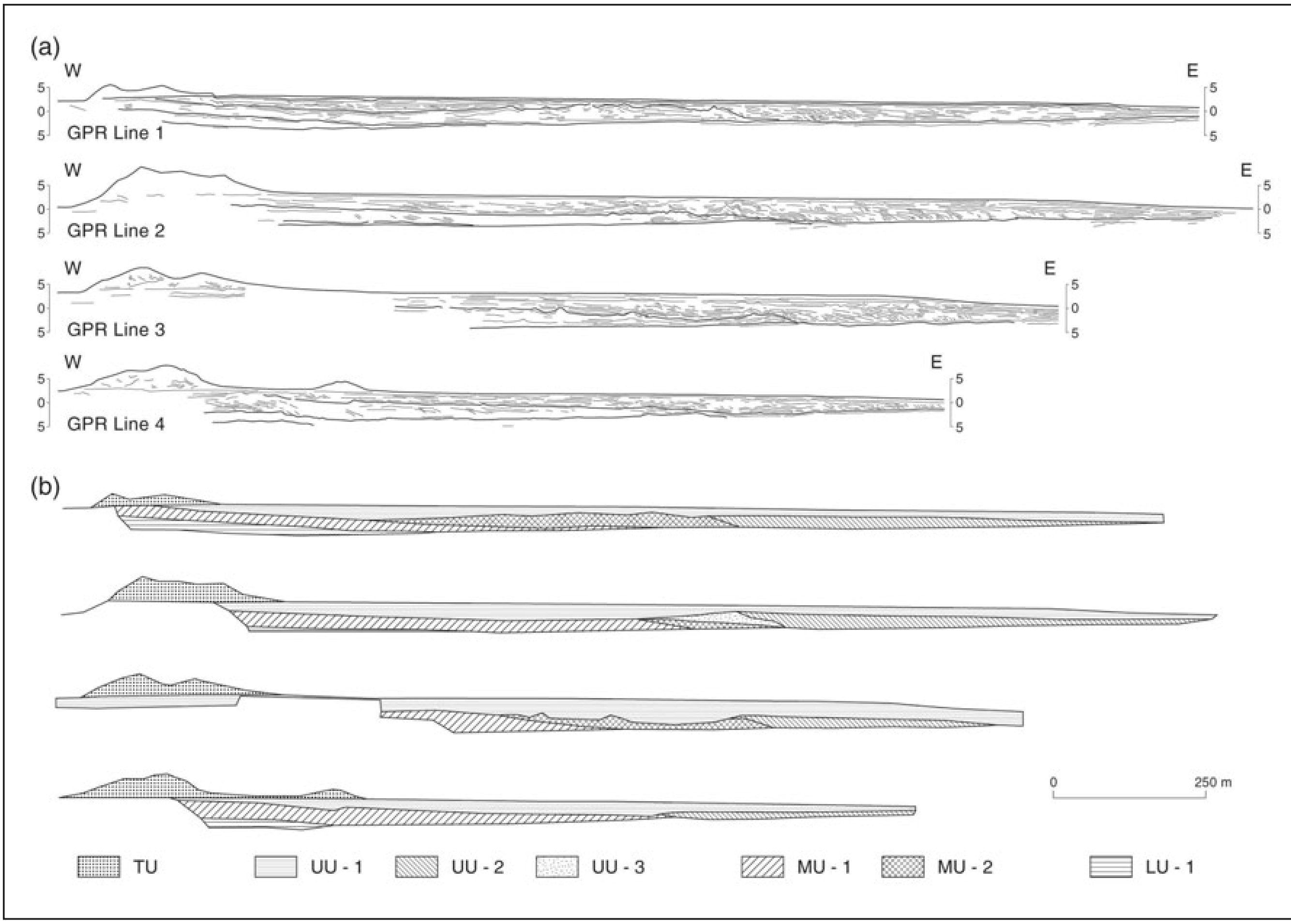

Figure 7: *a) Internal structures across the Northern Holmsland Barrier interpretted from four GPR-lines (see Fig. 1 for location). Thick lines indicate high-amplitude reflectors, representing regional surfaces. Thin lines are low-amplitude reflectors, indicating small-scale internal sedimentary structures. b) Main sedimentary units, interpreted from radar-facie. TU, UU, MU and LU represent Top Unit, Upper Unit, Middle Unit and Lower Unit, respectively. TU indicates the present eolian dunes, and MU-2 and UU-3 are older eolian deposits, presumably remnants of parabolic dunes. UU-1, MU-1 and LU-1 are horizontal to low-angle overwash deposits, and UU-2 is interpreted as high-angle washover deposits.*

cognized in the upper part of the TU unit, and there is no well-defined lithological lower boundary of the TU.

The UU is interpreted to be washover deposits. Low-angle deposits (UU-1) are deposited above sea-level, whereas the delta-foresets of UU-2 indicate deposition in standing water, according to Schwartz (1975). UU-3 is assumed to be eolian deposits, presumably fossil parabolic dunes, if we assume that the fossil dune configuration resembles modern configurations.

The MU-1 represents an older generation of washover deposits, merging locally into eolian dunes, MU-2.

The LU is interpreted as the oldest preserved generation of washover deposits that can be identified.

Discussion

The base of the Holocene in the Ringkøbing Fjord area

The coastline along the central Danish West Coast runs generally north-south, but at the Northern Holmsland Barrier, the coastline has a seaward convexcity. Marine vibrocores and high-resolution seismic data from the area off the Northern Holmsland Barrier have revealed that Mica clay as well as till are present at the seafloor, locally covered by an only thin layer of mobile sand. In onshore boreholes in the Northern part of the Holmsland Barrier, till and Mica-clay have been found at shallow depths below Holocene marine sand. The Mica clay and till sediments identified are thus likely to be remnants of a Saalean glacial hill with a

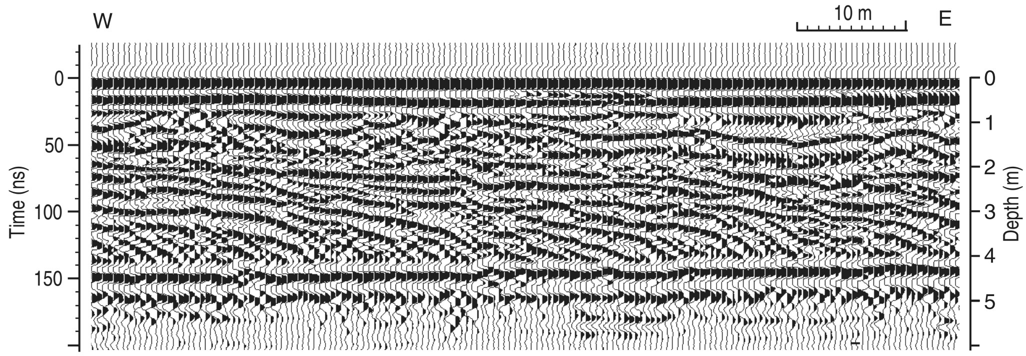

Figure 8: Example of a GPR-section from GPR-line 2, showing overwash sequences with high-angle, prograding delta-foresets in the lower part, and low-angle overwash deposits in the upper part.

Miocene core / base. This suggests the existence of a coherent submarine pre-Holocene shoal, extending from the North Sea offshore area to below the barrier, and probably connected to the Saalean glacial landscape North of Ringkøbing Fjord. This feature is suggested to explain the coastline curvature at the Northern part of the Holmsland Barrier.

The offshore marine surveys indicate that the outwash plain of Skjern Å (Figure 1, 2) has a westward extension to the North Sea. The Quaternary valley identified in the southern part of the lagoon is supposed to have a connection with the offshore extension of the outwash plain.

Model for the Northern Holmsland Barrier

The GPR profiles show a rather consistent structural pattern along the east-west profiles. Grain-size distributions, together with the interpretations of the GPR lines, suggest that the northern part of the barrier consists of overwash sequences, locally with eolian dune deposits. The main reflectors on the east-west GPR profiles, which can be correlated with the north-south GPR profile, indicate more stable sediment surfaces, where vegetation to some extent possibly evolved. During these stages, the grain-size distributions have not altered significantly. It is noteworthy, however, that even a slight increase in organic content will generally have a strong effect on the GPR signal.

Most probably the barrier evolved stepwise, with periods of overwash / barrier transgression and development alternating with periods of sediment stabilisation. A conceptual model for the evolution of the northern part of the Holmsland barrier is shown in Figure 9. Figure 9a shows the barrier at a slightly lower sea-level than the present, where

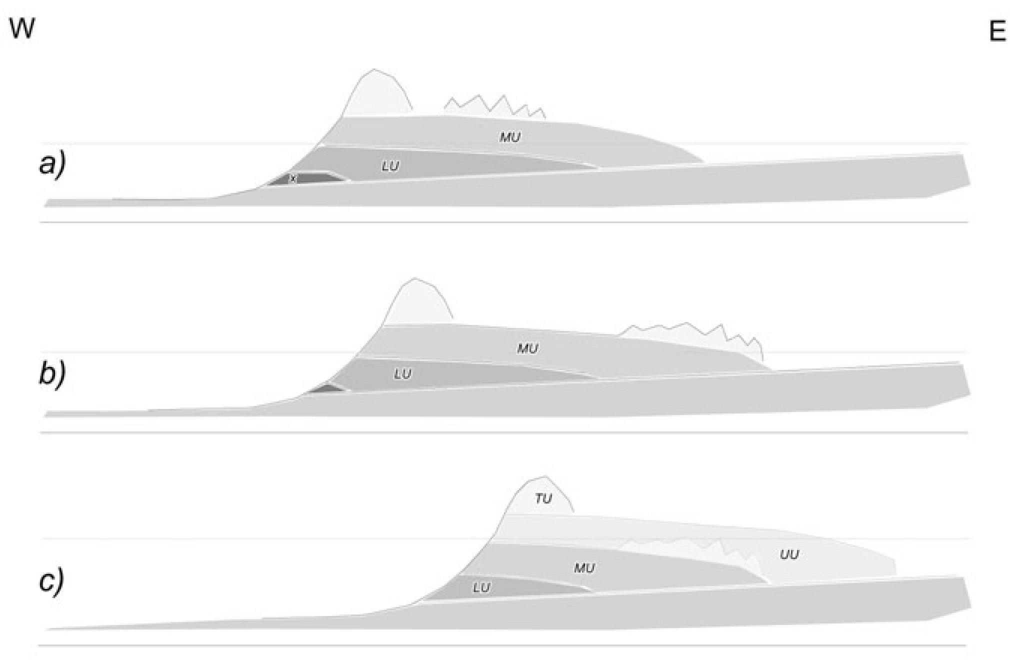

Figure 9: Schematic reconstruction of Northern Holmsland Barrier evolution. a) The barrier at a slightly lower sea-level than the present, where the unit MU is under development, and a foredune and a local (parabolic?) dune on the back-barrier have developed. b) The shoreface is eroded and the reworked sand deposited as overwash sequences on the back-barrier, and the local dune has migrated eastward prior to a stabilization of the surface. c) The present barrier, illustrating the formation of the Upper Unit, which is assumed to have been formed through breaching of the foredunes.

the unit MU is under development. A foredune and a local (parabolic?) dune on the backbarrier have developed. It is assumed that a washover sequence existed prior to the lower unit LU, which is shown as the lowermost unit x. In Figure 9b, the shoreface is eroded due to coastal erosion processes, and the reworked sand is deposited in a series of overwash sequences on the backbarrier, building up the middle unit MU. Furthermore, the local dune has migrated eastward, and the surface is assumed to have stabilized and possibly become overgrown due to decreased overwash activity. In Figure 9c, the present barrier is shown, illustrating the formation of the Upper Unit, and a foreshore which has moved eastward. The Upper Unit is assumed to have formed through breaching of the foredunes. Unit x has been totally reworked. Backbarrier deposits must have been transgressed, but this is not displayed in the figure.

Each washover unit is formed by a number of independent washover lobes, which are not necessarily deposited uniformly along the coast during a single storm event. The overwash mechanism has obviously maintained the barrier morphology during its transgression, but it cannot be directly verified whether the initial development is due to a spit formation or shoaling bars. The initiation is probably caused by landward transport and upward accretion of sand, a process by which most barriers are formed (e.g. Schwartz 1971, Davis 1994).

We do not have evidence to explain the mechanism or the frequency of the overwash / stabilisation cycles, but it is likely that the mechanism is connected to sea-level variations and / or changes in the wind-climate. Several studies in the North Atlantic region have found that there are a cyclicity in both wind-climate and sea-level on the order of one to two thousand years (e.g. Mörner, 1976; Bond et al., 1997; Clemmesen et al., 2001b). For example, evidence of increased (westerly) wind activity during the Little Ice Age has been documented (Jelgersma et al. 1995; Hass, 1996). The alternation between stabilisation surfaces and washover sequences may thus follow centennial to millennial scale cycles, but this has yet to be verified by datings.

Summary and conclusions

- Glacial till and Miocene mica clay, which is relatively resistant to erosion, prevail at the seabed off the northern part of the Holmsland Barrier. A landward extension of these deposits has been found below this part of the barrier.
- The northern part of the Holmsland Barrier has migrated in an easterly direction, and the presence of relatively high-lying pre-Holocene sediments has resulted in the present convex curvature of the North Sea coastline.
- The northern part of the Holmsland Barrier consists primarily of washover deposits with occasional eolian deposits. Washover deposits can be subdivided into sequences, separated by stabilization surfaces, with some eolian reworking. These stabilization surfaces are interpreted to have a regional extend.
- The large-scale internal structures of the barrier strongly indicate that the barrier has evolved step-wise. This means that periods of frequent overwash have alternated with periods of little or no overwash. The event frequency is possibly coupled to a cycle at a centennial to millennial scale.

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