

Shoreline Development and Sea-Level Rise in the Danish Wadden Sea

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ABSTRACT

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On a time scale of 5-6000 years the subsurface of the Wadden Sea is stable and the sedimentation due to a steadily rising sea level. The problems are discussed through dated profiles and the results are valid for the whole west coast of Jutland south of Bovbjerg, to the main stationary line of the Würm/Weichel glaciation. Regional differences related to isostasy are also considered.

The Tønder area was open to the sea since Eemian time. Here the shore-line displacement can be followed since early Atlanticum. The Ballum area was protected by a barrier system represented today by the isle of Rømø. East of Rømø, peaty, swampy areas and forests were transgressed later in the iron age transgression J (200-600 AD).

ADDITIONAL INDEX WORDS: *Sea-level rise, shoreline displacement, Wadden Sea, Tønder salt marsh, Ballum salt marsh, Jutland west coast.*

INTRODUCTION

The general rise of sea level, as indicated by the marine foreland, can be verified from borings and archeological excavations and dated by pollen and C¹⁴ analyses. North of the Elbe the coastal area is divided into 6 different types according to landscapes south and west of the main stationary line of the Weichsel (Würm) glaciation, a northern limit at Bovbjerg north of Nissum Fjord. The landscape types included are (1) fluvial salt marsh areas along the Elbe, (2) the Ditmarschen salt marsh, (3) Eiderstedt, (4) the Halligen area, (5) the Danish Wadden Sea area, and (6) the lagoon landscape north of Blåvandshuk. The tidal range is about 3 m at the Elbe, about 3 m at Husum, 2 m at Tønder, 1.5 m at Esbjerg and north of Blåvandshuk 1-0.5 m diminishing to the north (Figure 1).

The area south of Eiderstedt has a pleistocene surface at a level of about 20 m below NN (German Ordnance Datum) representing the Urstromtal of the Elbe and the Eider (DITTMER, 1960). At a late stage (Subboreal), an accumulation of sand in the area gave rise to (1) systems of beach ridges along the coast (for instance at Lunden), (2) for-

mation of tidal flats, and (3) formation of salt marshes. The southern coast of Eiderstedt, in continuation to the north via Amrum to Sild, formed a barrier beach fixed on nuclei of old moraines or even tertiary knots (central part of Sild). The pleistocene surface in this area, as well as further north, is a level plain sloping westward (outwash plains). The Danish Wadden Sea area comprises a "bay" between the tertiary knot at Sild and Blåvandshuk, the latter representing a cusped foreland caused by the presence of Horns Rev. Horns Rev is a terminal moraine of the Warthe interstage of Saale (F-stadium) (REINHARD, 1974). The height is 4-7 m below sea level. The moraine is covered with sand and slopes steeply to about 20 m. It stretches 40 km SSW of Blåvandshuk. For the Danish Wadden Sea, it represents a pronounced landscape element. In the interglacial Eemian period it was an isle, and it must have existed as such for some time during the Postglacial period.

The climate in the Eemian interglacial was at least as warm as today. Marine deposits from this period are found in southwestern Jutland (Tønder-Blåvandshuk) in borings at deeper locations due to erosion by Weichsel outwash streams. The topmost level is given by DITTMER (1960) as -7 m NN at Leck, 15 km south of Tønder.

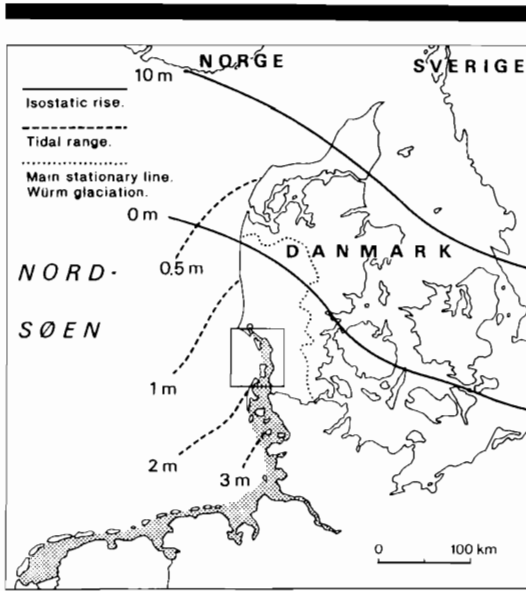


Figure 1. The west coast of Jutland showing tidal range and isostatic rise since *Litorina*. Main stationary line of the Weichel/Würm glaciation is shown as a dotted line.

Some Basic Concepts

In 1953 the ideas of the postglacial development in question was based on JESSEN (1916) and partly on NORDMANN (1935). Jessen was of the opinion that salt marsh formation had to follow the high tide level which at Ribe was +0.8 m DNN (Danish Ordnance Datum). Because salt marsh was found up to +2 m DNN, he assumed an uplift since the Bronze age of 1.2 m. Nordmann proposed, from his studies together with MATHIESEN (1935) in the Ballum area (Misthusum), a subsidence in this area of 2 m as the foot of an artificial mound (værft) dated from about 1200 was superposed by marine deposits of 2 m. Because the Ribe area was uplifted, he explained the Ballum results by salt dome structures. Later investigations showed the cause to be subsidence since the mound is situated in the old riverbed of the rivulet Brede Å. The studies in Tønder did not support either of these hypotheses but all evidence pointed to a stable subsurface and sedimentation in accordance with a steadily rising sea level.

The salt marsh of western Denmark contains deposits submerged by the rising sea level. The marsh represents processes that are at work today and with a vertical range partly due to the tidal range, and higher levels caused by storms and

floods. Acknowledgement of these higher levels becomes important when relating levels of former deposits found in borings to sea-level rise. It is also important to consider shrinkage (compaction) of the different layers. In the first case the present sea level indicates a formation of salt marsh deposits in the Tønder area from +0.9 m \pm 2.5 m DNN. In the Ballum area, even higher levels of +3.5 m DNN have been registered. The topmost layers of these high-lying salt marshes, due to extreme situations, are sandy and silty. Further, the level depends on exposure and time scale involved, as for instance, in the salt marsh at Skallingen with a minor tidal range (1.2 m) where the formation has taken place since 1930. Here, the highest salt marsh is found at the level of +0.60 m DNN. A large difference is noted today (Table 1):

In this respect it is necessary to discuss the results of detailed studies of the Tønder area (JACOBSEN, 1956, 1957, 1959, 1960, 1964, 1972).

Augering the topmost sediment layers in the innermost parts of the Tønder salt marsh (ended 1555) shows a sequence of sandy layers (20–25 cm) over heavy clays which lie on top of peaty layers (Figure 2). The heavy clay consists of 2 parts, a grey-colored layer (Y) on top of a brown clay (Z), separated by a black horizon at about 40 cm below the surface (Figure 3B). The formation of this organic (peaty) horizon may have been caused by barriers enclosing lagoons. Borings in the Ballum area, the Ribe area, the Ringkøbing area and further north in the Stadil Fjord and the Nissum Fjord areas showed the same depositional sequence with the same black horizon at about the same level. This was the first indication of a general result of sea-level rise. It was registered in 1953 and established in the literature following research at Stadil Fjord and the Skjern Å delta (JACOBSEN, 1961).

THE TØNDER AREA

Types of Sedimentation, Facies According to Sea-Level Position

Figure 2 shows a longitudinal section through the Tønder salt marsh. The Pleistocene subsurface consists of four elements: (1) The old moraine with the geest border. The salt marsh limit, placed at the high tide level +2 m DNN, represents the modern innermost coastline. The sea never extended further inland, although the Eemian sea level is supposed to have been 6 m higher than at present. Possible subsidence since then (140,000

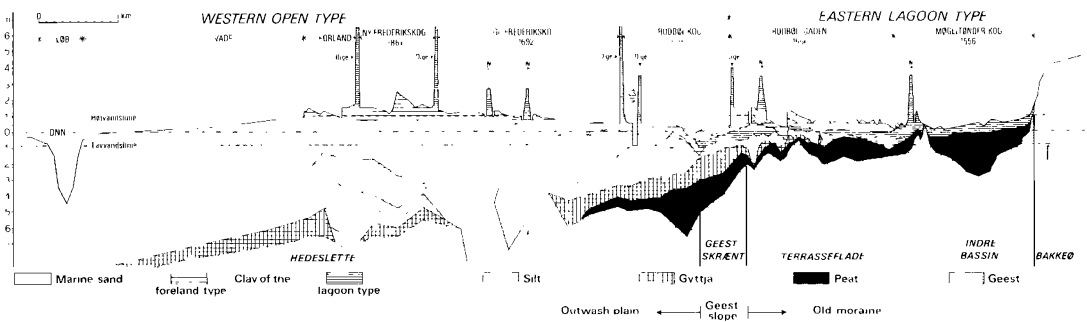


Figure 2. Longitudinal section of the Tønder salt marsh as a model of landscape along the Danish west coast south and west of the main stationary line of the Weichel/Würm glaciation.

The profile at the geest slope in Figure 3A demonstrates a basal peat 1 m thick inundated by salt and freshwater gytje at a level of -2.73 m DNN. MULLENDERS (1960), using pollen analysis, estimates the peat to be Debut Atlantique (VII) in age. It is superposed by 65 cm of clayey gytje which in turn is overlain by 5 cm of peat. The topmost layer, 2.20 m in total thickness, represents two transgressive stages, -1.07 m and -0.42 m DNN (C & S transgressions). An intermediate stationary phase, -0.42 m to -0.27 m DNN, and another transgression stage comprising the J-V-M transgressive phases. The topmost 60 cm is sand from dike bursts (1634?). The area was endiked in 1555 and the site lies just behind the dike.

Archaeological Excavations

In discussions concerning the rise of sea level along the southern North Sea basin archaeological excavations have played a dominant role, at least until more recently when C¹⁴ dates have become more generally relied upon. In the Tønder area, excavations at Fællesværre, an artificial mound placed at a levee along a channel (priel) in the southern Møgeltønder Kog. Three C¹⁴ dates were obtained from the sites SW and NE of the central part of the mound because a house is placed on top of it. Further, two profiles from the NE excavation (also shown as photos in Figures 5 and 6) will be discussed.

The SW excavation facing the priel (channel) shows the latest development of the area (Figure 4C). The geest is placed at -1.16 m DNN, transgressed by heavy clay 5 cm thick which is superposed by peat (T1) to -0.65 m DNN. The peat has been transgressed by clay with a sandy stripe

in the topmost level at -0.52 m DNN. On top of this, is found a heavy brown brackish clay from which Phragmites were washed out and dated by C¹⁴ analyses: 770 AD \pm 100 (K-797). The clay continues as black striped clay with a top level of -0.04 m DNN. The mound is built on this layer, the youngest parts of which represent the Frisian colonization period 800–1000 AD.

The NE excavation represents a sheltered position with a full sequence of layers to the geest on which the mound was built. In this marginal zone the geest (-0.70 m DNN) is superposed by a peat layer (T1) topped at -0.42 m DNN by a charcoal layer (2 cm) and a thin peat layer (T3) topped at -0.38 m DNN by a 2–3 cm black clay layer as transition to a grey clay to the level of -0.20 m DNN (Figure 4D). This again is transgressed by a 2 cm black clay horizon, a heavy brown clay topmost level of -0.13 m DNN and a black spotted clay to $+0.04$ m DNN, superposed by artificial deposits of the mound. The peat layer at -0.65 m to -0.50 m DNN was dated by C¹⁴ at 1450 BC \pm 120 yr (K-795). In the same site, about 30 m apart (Figure 4E), a piece of wood from the T3 just above the charcoal layer at level -0.48 m DNN was dated by C¹⁴ at 1700 BC \pm 120 (K-796).

Model of Landscaping Along the Danish West Coast

Figure 2 is a model for the postglacial development south of Bovbjerg. To the north the coastline and topography of the land result from the changing boundary between isostatic and eustatic movements. In order to understand the progress of the North Sea transgression, it is necessary to

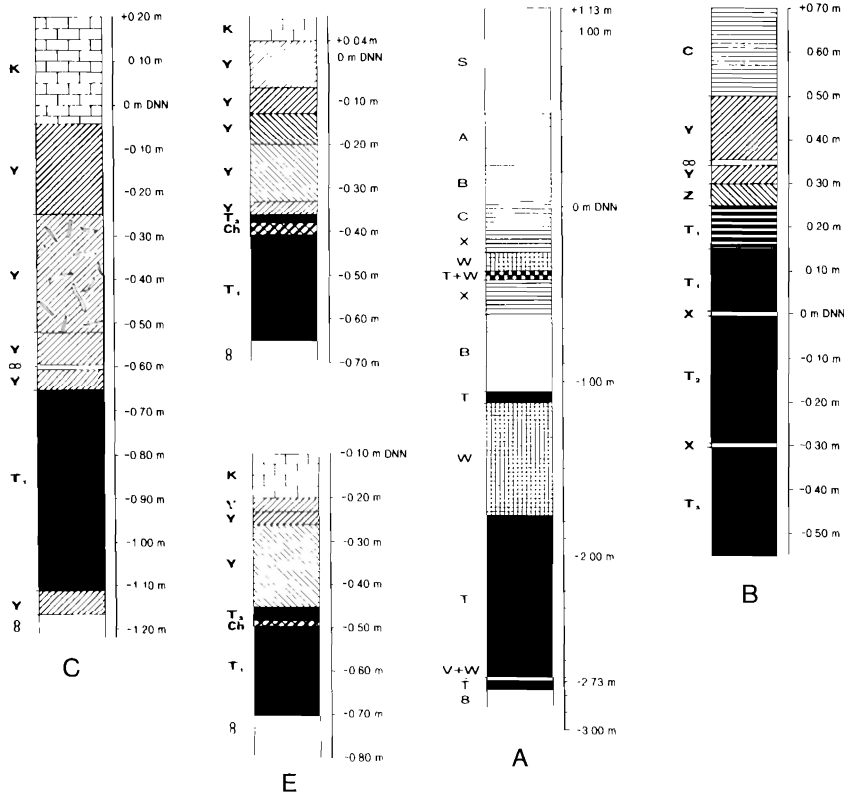


Figure 3. Postglacial sediments of (A) the open type (the slope). Note the transgression layer at level -2.73 m DNN. Postglacial sediments of (B) the lagoon type. Note the transgression at -0.30 m, ± 0 m, and $+0.35$ m DNN. The black horizon (stationary phase) is indicated at $+0.30$ m DNN at the change of type of clay from Z to Y. 8 = geest. T = peat. W = gyttje, brackish water. v = gyttje, salt water. X, Y, Z, C = clay. A, B, C, = foreland clay with increasing clay content. S = sand. = sand stripe. Ch = charcoal. K = artificial mound.

Figure 4. (C) Profile from the artificial mound Fællesværre SW. K is signature for the mound. The dated *Phragmites* is washed out of the clay Y (-0.40 m DNN). Age 770 AD. (D) Profile from Fællesværre NE. The dated peat T3 (-0.38 m DNN). Age 1700 BC. (E) Profile from Fællesværre NE. The dated peat T1 (-0.50 to -0.65 m DNN). Age 1450 BC. 8 = geest. T = peat. W = gyttje, brackish water. v = gyttje, salt water. X, Y, Z, C = clay. A, B, C, = foreland clay with increasing clay content. S = sand. = sand stripe. Ch = charcoal. K = artificial mound.

determine the zero point of the Fennoscandian isostasy and to find the area further south where the relative lowering of the land is of the same magnitude as sea-level rise. As a primary assumption, the zero point is Bovbjerg (MERTZ, 1924). Mertz drew the isobases for the maximum level of the Litorina sea with a zero line from Nissum Fjord towards the south east via Lillebælt to the northern Falster (Figure 1). The area to the south is experiencing a relative lowering of the land. The line of stability today will, according to this observation, follow a line from Esbjerg SE via Als.

According to PELTIER (1987), changes in the geoid caused rhythmic climatic changes; this means seven glaciations with interglacial periods, which on a global scale caused six different patterns of relative sea-level changes. This study area is not considered in detail. It does, however, belong to stage II (rising sea level). In discussing the reaction of the 200 km upper mantle of the earth to the latest ice pressure (Weichel, Würm), Peltier refers to LOWE and WALKER's (1984) model. This model suggests that a forebulge is formed in front of the ice margin with depressions on both sides. Peltier's Figure 18 shows a theoretical displace-

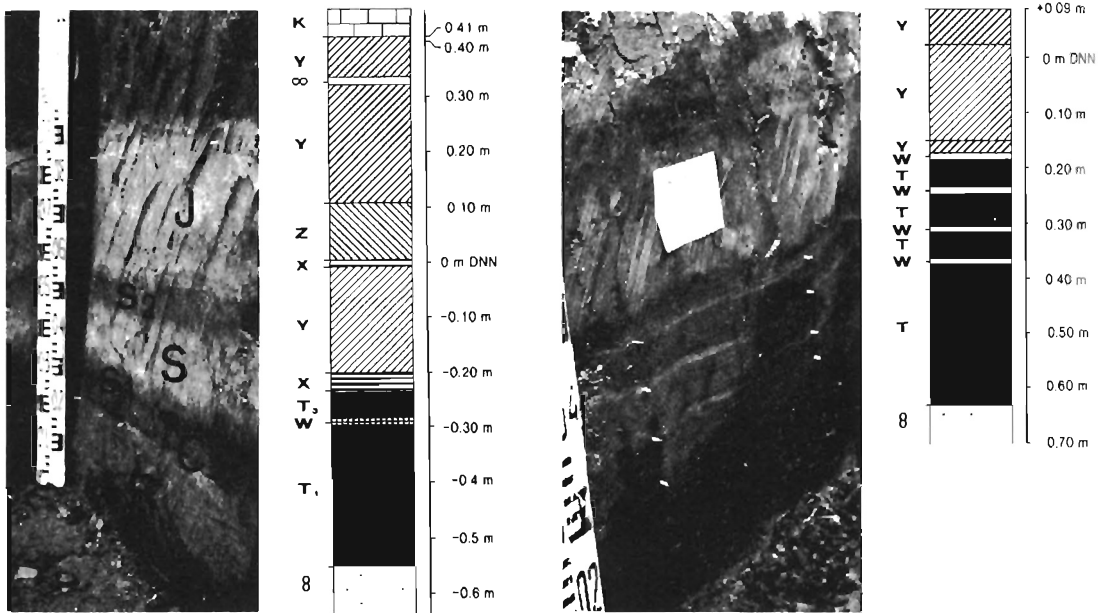


Figure 5. Profile from Fællesværre northeast toward the south. The geest at bottom is superposed by peat (R) and transgressed by C2, S & J with black horizons (stationary phases) s1 and s2 in between. Topmost is clay of the mound. 8 = geest. T = peat. W = gytje, brackish water. v = gytje, salt water. X, Y, Z, C = clay. A, B, C, = foreland clay with increasing clay content. S = sand. = sand stripe. Ch = charcoal. K = artificial mound.

ment at Esbjerg of about -0.4 mm/year with a zero point at Hamburg and a rising coast of $+0.8$ mm/year in Belgium. DIETRICH (1954), analysing tide-gauge records from the Esbjerg harbour since 1890, indicates a sea-level rise of 1.1 mm/year. This role should be compared with GUTENBERG's (1941) results who, from a world-wide study of tide-gauges, has suggested a eustatic rise for the period 1860–1936 of 11–12 cm. This seems to suggest, also during a period of 76 years, a corresponding rate of 1.5–1.6 mm/year, or a rise of sea level from -0.4 to -0.5 mm/year for Esbjerg. GORNITZ and LEBEDEFF (1987) indicate for the past century a “corrected” average eustatic sea-level rise of 1.1 mm/year. The magnitude in the Tøndermarsken area is difficult to estimate, but if it is assumed that the figure is -0.2 mm/year this will, in a period of 5,000 years, correspond to a lowering of the dated transgression surface in Figure 3A (-2.73 m DNN) by 1 m.

Salt marsh deposits are found along the west coast to Bovbjerg. The slope on the model in Figure 2, dividing an open sea area from coastal lagoons, can be found south of the Danish/German

border in the Gudskog area. From here it runs north to Højer where it turns west towards Jord-sand which it encircles continuing to the north just east of Rømø. It is found again between Fanø and Esbjerg and continues to the north just west of Hjerting/Grærup coastal cliffs, north of Kærgaard it disappears in the sea. It seems reasonable to suggest that this slope may be a possible coastline of the Eemian sea; at least it constitutes a prominent feature along the coast that is broken only by deep river valleys. These river valleys belong to the very low base level in late glacial and early postglacial times.

Recapitulation

In the Tønder area the early Atlantic transgression is the earliest evidence of the rising sea at -2.73 m DNN. In the lagoon of Møgel-tønder Kog, two thin clay layers at -0.30 m and ± 0 m DNN were found, below which the subboreal basal peat is situated (Figure 3B). During the archaeological excavation of Fællesværre, the Litorina transgression was shown in the peat layers below the mound (Figure 5). The peat itself, dat-

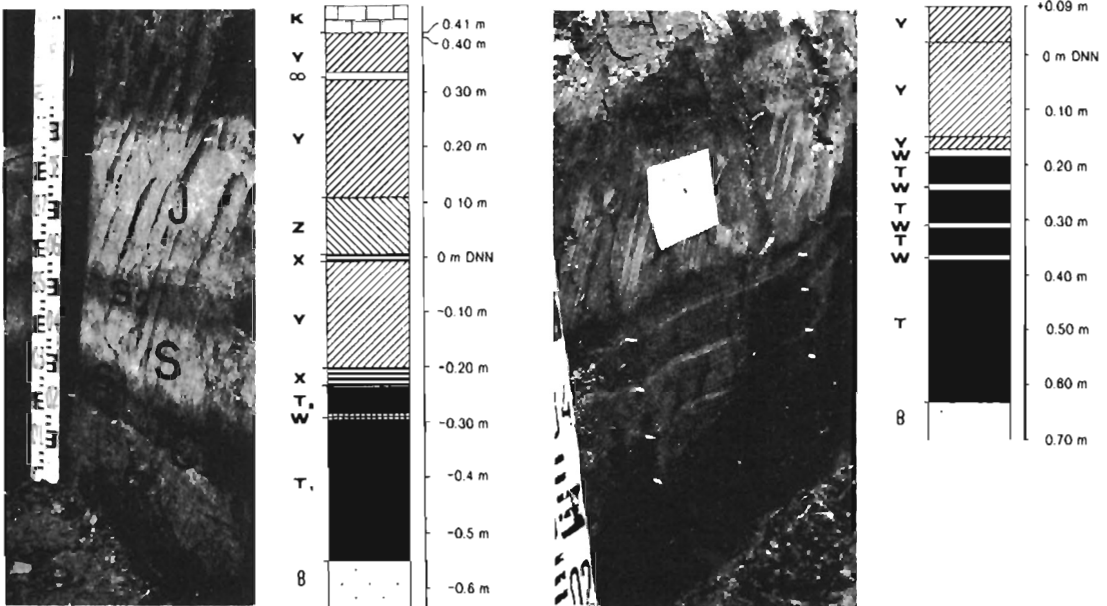


Figure 6. Profile from Fællesværre NE, wall of a ditch to the south. The Litorina transgression is given in the 4 clay intrusions in the peat. On top is the S-transgression. 8 = geest. T = peat. W = gytje, brackish water. v = gytje, salt water. X, Y, Z, C = clay. A, B, C, = foreland clay with increasing clay content. S = sand. = sand stripe. Ch = charcoal. K = artificial mound.

ing to about 1700 BC and 1450 BC is separated by the C-2 transgression. On top of this peat, both the subatlantic transgression S (700–100 BC) as well as the iron age transgression J (200–600 AD) were found (Figure 6). In the lagoon, the transgression (change from peat into clay) was found at +25 cm DNN (V transgression, 800–1000 AD) and within the heavy clay a stationary phase (black horizon) was registered at +30 cm DNN broken by a transgression at +35 cm DNN (M, 1362). The topmost layer (+50 to +70 cm DNN) represents dike burst sediments since endikement in 1555.

THE BALLUM AREA

How do these dates fit the sporadic studies made along the coast. In the Ballum salt marsh, three excavations have taken place: (a) At Misthusum (NORDMANN, 1935) a salt marsh at the level of about +0.5 m DNN was inhabited about 1200 AD by Frisians. Immediately afterwards a mound was built, the topmost level of which is found at +3.88 m DNN. Of the several floods that have occurred, as recognized in the mound sediments, the most significant took place in 1362 and in 1634 (Figure

7, site 1). (b) At Forballum, the Brede Å valley has narrowed with a large lagoon to the east (Figure 7, site 2). The mound has a top level of +3.75 m DNN. On the ground (geest) at a level of +1.55 m DNN habitation was found in two separate layers at a level of +2.10 m DNN. Eleven centimeters of heavy clay was found on top followed downward by four cultural layers divided by 2 layers of rubbish, each 0.5 m thick (+2.25 to –2.75 m DNN and +3.0 to –3.55 m DNN). The initial settlement on the ground was dated by C^{14} at 950 AD (K-1753) which, as a reasonable suggestion, places the 1362 flood at +2.10–2.21 m DNN and the 1634 flood at +3.0 m DNN. (c) At Abterp, Stenholm in the eastern part of the salt marsh of Ballum (Figure 7, site 3) a neolithic stone age cairn was excavated in 1962. The topmost level was +1.85 m, 15 cm below ground surface. When the neolithic cairn was built, the water level in the rivulet Brede Å must have been at least 5 m lower than at present, this means about –3 to –3.5 m DNN. The whole landscape, the geest, is without any stones so they must have been brought in by boat from Emmerlev, which is the nearest locality available. The topmost meter shows de-

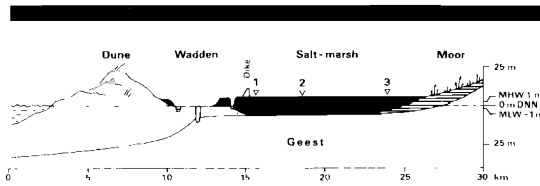


Figure 7. Ballum salt marsh. Cross section through the Wadden Sea, the salt marsh and the moor to the geest. Note the slope of the geest just east of Rømø and the imposing beach bar with dunes. (1) Misthusum, (2) Forballum, (3) Abterp (Stenholm).

posits of the historic floods: 1909–1911 (+2 to +1.85 m DNN), 1825 (+1.85 to -1.80 m DNN), 1634 (+1.60 m DNN), 1436 (+1.35 m DNN), 1362 (+1.20 m DNN).

The result of this information from the Ballum area is a rise of water level since Neolithicum of 5 m. At the same time the housing on the ground at Forballum (2 cultural layers) at 950 AD bears witness to a quiet period with a water level in Brede Å of at least 2 m below present, *i.e.* about ± 0 m DNN. Because the isle of Rømø is without any archeological findings, it is reasonable to think of Rømø as a barrier protecting the hinterland which was all lowlying, forested or with swamp and peat areas. At the transgressions J (200–600) and V (800–1000) the tidal flats E of Rømø and the first salt marshes were formed. At Misthusum, the Frisians settled about 1200, but then the stormy periods of the M transgression (1300–1650) started and continued through the little Ice Age (for instance 1717–1720). The Misthusum habitation tells a sad story. After 1362, the farms are described in the church register as desolated (1394). In the following years it was again settled but most of the inhabitants were lost in the flood of 1634. The habitation was finally abandoned in 1813.

RECAPITULATION

The Misthusum, the Forballum and the Abterp excavations tell about the recent rise of sea level and the history of the lagoonal part of the Wadden Sea and salt marshes. At Abterp, a rise in sea level means a significant rise in ground water, which in turn means that the 5–6 m rise of water level must be corrected for a rise of ground water level by at least half. This indicates a sea-level rise of 2.5–3 m since the beginning of the Subboreal, which corresponds to a rate of about 1 mm/year.

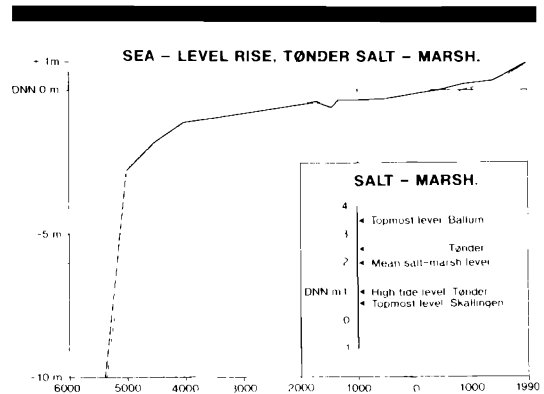


Figure 8. Time and depth diagram of the sea-level rise in Tøndermarsken partly relative and partly calibrated in accordance with PELTIER (1987:Figure 3.18).

SUMMARY

This study briefly summarises the postglacial development of the west coast of Jutland outside the Weichel (Würm) glaciation. Initial phases of Holocene sedimentation are indicated by transgressions into the deep valleys cut in the geest landscape by rivers when sea level was much lower than today. This study could have compared the marine sediments in these rivers, a characteristic sequence of marine clay and gyttje superposed by brackish and fresh water sediments.

The study also could have described old beach ridge systems which exist between +2.5 m and +4.5 m DNN. Instead of collecting data along the whole coast, this report focused on the two southernmost salt marshes inside the deep Lister Dyb (Tønder salt marsh, an open system) and the deep Lister Dyb/Juvre Dyb (Ballum salt marsh, sheltered by barriers to iron age transgression).

The study describes the shoreline displacement as a result of sea-level rise. Borings and excavations showing ingressions of the sea within peaty, lagoonal environments (facies) were dated and compared. Figure 8 attempts to illustrate sea-level rise in relation to time. Dates are from the Tønder salt marsh and calibrated in the relation to an isostatic rate of -0.2 mm/year. It is important to look at rates of sea-level rise in stages for comparison. In early Atlanticum, the rise is 1.2 cm/year decreasing to 1.7 mm/year until 4000 BC and to 0.28 mm/year until 2000 BC (Subboreal). Further on to the time of Christ, ± 0 , the rate decreases to 0.02 mm/year, a figure that was valid to 1000 AD. After this time, the rate of rise ac-

celerates again for the last 1,000 years at 1 mm/year.

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