The High Sands of the Danish Wadden Sea—Especially the Ebb-Tide Delta, Søren Jessens Sande, and its Incorporation with the Island of Fanø

N. Kingo Jacobsen

Institute of Geography
University of Copenhagen
Østervoldgade 10
DK-1350 Copenhagen K, Denmark

ABSTRACT


This article attempts to account for the coastal morphology south of Blavandshuk, western Jutland, Denmark. This coastal section is dominated by a barrier beach development, behind which lies the Danish part of the Wadden Sea. There is a description of the results of borings that were made in order to understand the dynamics at work since the very first offshore bar development. The effect of the changing sea-level since the Weichsel Glaciation, which has been accompanied by different tidal conditions and stormfloods of varying magnitude during the past 3000–8000 years is also described. The origin and balance of sediments is dealt with; especially the high sands and shoals of the Danish Wadden Sea with particular reference to the evolution of the ebb-tide delta, Søren Jessens Sande, which is described in detail with the use of maps. How and when its incorporation with the island of Fanø took place is described.

ADDITIONAL INDEX WORDS:—Coastal morphology, sediment transport, sedimentary budget, barrier island, bar, shoal.

INTRODUCTION

If Denmark, within the Nordic context, is to be considered representative of a geomorphological landscape complex that contributes to the Scandinavian sub-continent as a whole, it is without doubt because of the coastline to the south of Blavandshuk in southwest Jutland with its estuaries, saltmarsh and tidal flats. The barrier islands of Skallingen and the north Frisian Islands are found here too. Figure 1.

Located in this unique natural area is the field station Skalling Laboratory, owned by Copenhagen University Geography Institute. It represents an important research centre studying the dunes, tidal flats and saltmarsh. The high sands represent one of the special landscape elements under study. An account of their genesis and dynamics necessitates an understanding of the entire set of coastal geomorphological processes. Figure 2.

The current picture of the coastal dynamics, involving the interaction of waves, tides and sediments, represents but a fleeting point in time in the overall development of the changing coastline of the North Sea. The coastal zone studied stretches southwards from Blavandshuk on the west coast of Denmark to Den Helder in Holland. From the mainland, it extends seawards (westwards) as far as the 10m deepwater mark.

THE COMPLEXITY OF THE WADDEN SEA COASTAL ZONE

(1) In the west, the coastal zone consists of a row of barrier islands called the Frisian Islands. They are separated by a series of deepwater channels that function as water exchangers between the North Sea and the Wadden Sea which lies between the barrier islands and the mainland. The Wadden Sea consists of several basins each with networks of dendritic channels (the Danish priel channel systems). In relation to the tide, the priel channel networks behave like pulsating bellows or the lungs of the sea. Figure 3.

(II) The sediment that has built the Wadden Sea tidal flats originates from further along the coast or the North Sea. Vast volumes of water are sucked into the Wadden Sea at high tide through the priel channel networks and sucked out again at low tide (Figure 3). The high sands are important landforms in this coastal zone. Their distribution relates to the continuous battle between the ingoing and outgoing water masses, and in particular to the position of the dendritic flood and ebb tidal channel networks. The high sands are thus determined by both flood and ebb tidal conditions. Nevertheless, it is essential to understand that the high sands are a product of both current coastal dynamics as well as much older processes; such as the origin and evolution of the Wadden Sea itself once the North Sea became post-glacially tidal—that is to say that the North Sea was re-established as a consequence of the post-glacial sea-level rise in the Atlantic Period.

(III) Borings taken from the barrier island complex have helped ascertain the genesis of the whole region (Figure 8). Useful datings have fixed the chronological development. Post-glacially, the Wadden Sea was initially a gigantic la-
Figure 1. The Danish Wadden Sea. The dashed line represents the littoral equilibrium line.

Figure 2. Statistics on the Danish Wadden Sea: (a) tidal area water balances (b) the tidal prisms.
Figure 3. Models of the Danish Wadden Sea showing: (a) the creation of barrier islands and the Wadden Sea caused by rising sea-level (b) the circular transport pattern of fine-grained sand. (redrawn from Carter, 1988).

Figure 4.

CREATION OF THE WADDEN SEA

The formation of the barrier island chain started with the creation of beach ridge systems in the Skallingen, Fane and Rømø area that now lie at a depth of 25–30 m as confirmed by borings (Figure 8). The continuous arrival of more material by the aforementioned processes has led to the barrier island chain and west coast dune landscape as we recognize them today. Several points along the west coast of Jutland have functioned as hooks to which the Wadden Sea barrier island chain from Skallingen to Sild has attached itself. These points are; Blåbjerg, Hjerting, Hornsrev, Emmerlev, Sild, Fehr, Amrum, Eiderstedt (Sct. Peter).

It is thus a very dynamic landscape which is under discussion. The Wadden Sea is an important element. Its creation is a result of tidal action behind the barrier island chain. The tidal waters have cut channels in the island barrier. Twice daily, 1 cubic kilometre of water passes backwards and forwards through the 4 deeps. The tidal range is about 2 m at Højer and 1.5 m at Esbjerg.
TIDAL DYNAMICS OF THE WADDEN SEA

In order to understand Grådyb and Søren Jessens Sande, it is necessary to account for the tidal dynamics at low tide during both ebb and flood dendritic channel systems known in Danish as priel systems. The regular ebb and flood currents are distinctly different in nature but they occupy the same channel system; firstly they flow in quite opposite directions, and furthermore they differ in speed, temperature, salinity and sediment content. The Danish Wadden Sea is therefore a vast accumulation flat separated from the North Sea by the broad offshore island barrier. Figure 5.

The topography of the Wadden Sea consists of the high sands, tidal flats and priel systems oriented towards the deeper channels. The progression of the tidal wave through the system creates local changes in the height of the sea level. VAN VEEEN (1950) distinguishes between the ebb-tide channels which are open to the ebb current in the direction of the ebb flow with bars at their lower end, whereas flood-tide channels are open to the flood current in the direction of the flood flow. In addition to ebb and flood tidal channels, there are the main deeps that are strongly influenced by the former because the ebb tide flows in from one end whereas the flood tide flows in from the other end. This might be due to differences in the physical parameters such as material transport. This gives rise to a helicoidal current in the deeps and widespread meandering. Van Veen believes that the meandering
ESTUARY TYPES AND SAND DEPOSITION IN THE WADDEN SEA

The morphology of sand deposition in estuaries is controlled by the interaction of a number of processes; (1) tidal causes division in the main channels; a tendency that is enhanced by the Coriolis force in relation to the ebb currents, which again relates to the emptying and filling of the Wadden Sea basin. Understanding the morphological phenomena in the Wadden Sea requires a knowledge of the forces at work in relation to the channels and barriers, as well as the flood and ebb tidal channels.

At the start of the flood tide, the current follows the route created by the ebb current, but the increasing water level eventually causes the flood current to flow over the banks and fill the basin. The orientation of the channels plays an important role with regard to filling and emptying. The channels between the barrier islands lie equally favourable for both ebb and flood tides. However, it is clear that the flood tide has difficulty in turning and runs up against banks in the Wadden Sea, such as Langli Sand, and thus loses its energy and deposits its load to build the banks at the mouth of the ebb-tide channel. The ebb-tide channel deviates from the main direction of the flood current. The swinging movement leads to the flood tide cutting its own channel in a right-angled direction, and in so doing the current weakens, depositing material in the form of crescent-shaped or horseshoe-shaped banks at the upper end of the flood-tide channel because some of the water overflows the banks. The North Sea bed is covered by a layer of unconsolidated sediment that is transported landwards by the flood current creating a very special pattern of submarine landforms near to the coast.

The tidal wave in the North Sea approaches from northeast of Scotland and circulates around an amphidromic centre some 150 km west of Blåvands Huk. The tidal current operates with great regularity both in terms of time and direction. During the flood, the current flows for approximately 6 hours in one direction, then reverses at the turn of the tide to flow in the opposite direction for another 6 hours as the ebb tide.

In the North Sea, the turn of the tide follows an elliptical route in which the ebb-tide current flows northwards. Current velocity decreases markedly at the incidence of high tide and low tide respectively. Current velocity also decreases as land is approached. Due to the strong flood current velocity, the duration of the flood tide in the Wadden Sea is a little shorter than that of the ebb tide.

As mentioned previously, the priel systems are created by both the ebb and flood tidal currents because the vector sum of the flood and ebb tidal current velocities varies within a particular channel and a residual current will flow in the opposite direction in every tidal period. The two types of channel seek to avoid each other and this results in a weight- ed complicated flow pattern. This is due to a delay in the tidal current pattern. The ebb current continues to flow outwards for at least 20–30 minutes after low tide has been attained despite the rise in water level as the flood tide begins to flow landwards. In its attempt to avoid the delayed, out-flowing, ebb-tide current, the flood-tide current cuts its own channel beside the ebb channel. Figure 6.

ESTUARY TYPES AND SAND DEPOSITION IN THE WADDEN SEA

The morphology of sand deposition in estuaries is controlled by the interaction of a number of processes; (1) tidal
range, (2) tidal currents, (3) wave action, and (4) storm influence. Of these factors, the variation in tidal range has the widest large scale influence on the morphological differences in the sand accumulations.

Tidal ranges in this area have been classified by Davies

(1) Micro-tidal estuaries: Coarse-grained sediment accumulation in estuaries with semi-tidal range i.e. 0 m–2 m. Wave action and storm deposition are more important in this category than in the others.

(2) Meso-tidal estuaries: Coarse-grained sediment accumulation in estuaries with intermediate tidal range i.e. 1–2 m. Tidal deltas and tidal current formed sand bodies increase significantly in this category.

(3) Macro-tidal estuaries: Coarse-grained sediment accumulation in estuaries with a large tidal range i.e. over 4 m.

From a dynamic point of view, the bodies of material accumulation in this case are barriers islands, banks, flood-deltas etc. The tidal range is about 2 m (Esbjerg 1.5 m, Højå 2 m), making it a meso-microtidal area. Of decisive importance is of course the material constitution, budget and exposure etc. The material originates partly from the North Sea bed, partly from the Wadden Sea, and not least from the erosion of the west Jutland coastline (Figure 7). Accumulation is generally greater than loss (positive balance). The coast is under constant growth because of the strong influence of wind and waves, which operate mostly perpendicular to the coastline, and bring a continuous supply of material, mainly sand, in an attempt to establish a new littoral line of equilibrium (Figure 1). This process depends on changes in the sea-level, tidal ranges, and alterations in the climate such as an increase in storm floods. The Wadden Sea is by no means a mature landscape. In particular, the high sands must be considered as transitional features as they are continually being reformed and restructured. Their shapes have to be considered in the light of dynamics and materials. With respect to high sands, the material tends to be fine or medium-fine sand. The parts most affected by wave action contain the coarsest material whereas the less exposed parts contain a wider variety of material with regard to grain size, although finer material predominates. Figure 7.

SPECIAL “HIGH SANDS” OF THE WADDEN SEA

Recent studies in Denmark based on the high sand formation of Søren Jessens Sande, Fano, and Juvre Sand in north Rømø (Figure 1) have provided valuable material on:

(1) processes that cause the formation of ebb-tide high sands.
(2) the evolution of high sands (based on a recent 10-year period with storm floods, using aerial photograph digitalization and analysis). The 10-year period ended with the incorporation of Søren Jessens Sande with the barrier island of Fano (Figure 9).

The high sands naturally relate to the intervening channels which are regularly filled or emptied by the tides in the lagoon area known as the Wadden Sea. The high sands are

Figure 7. The material transport along the west coast of Jutland from Bovbjerg in the north to the island of Sild. The old moraine hills and intervening outwash plains constitute the landscape types of Jutland. The open arrows point to the localities of 1) Bovbjerg and 2) Blåbjerg that have provided material, during the Atlantic Period as the sea level rose and during storms, for the past formation of beach ridge systems and the continuous development of the coastal landscapes as we witness them today. The southward material transport from Bovbjerg is approximately 700,000 cubic metres per annum, from Blåbjerg approximately 400,000 cubic metres per annum; this means that the German Bight supplies at least 1,000,000 cubic metres per annum (Hofdahl, 1968). Climatic fluctuations account for changes in sea-level, changing cyclonic routes and alterations in the weather pattern through time. In the Atlantic Period, the sea-level rose rapidly (Jacobsen, 1993) and the substantial erosion of the west-facing cliffs of the old moraine hills provided ample material in the form of stones and gravels to form the barrier island system, spits and beach ridge systems. Thus the Wadden Sea was formed in the late Atlantic Period during which the tidal conditions as we know them today would have been established. The sub-Boreal regression temporarily transformed the Wadden Sea tidal flats into bog and marshland, and a peat layer is found beneath the current tidal flat sands across a large area. For example, off the coast at Hjerpestad, borings beneath the tidal flat sands prove the existence of an earlier mixed deciduous forest, where oak was the dominant species. Borings from Rømø (site A on map) illustrate the whole chronological process. Borings from Fano reveal a similar sequence of landscape-forming events.
not regarded as part of the Danish land area and have never been matriculated. The reason is their unusual position between land and sea. They are called high sands by the majority of researchers because they lie so high that they remain uncovered at normal high tides and form a bridge between the tidal flats and the islands proper.

The most important high sands are Koresand (7 km²), Kiil Sand (2 km²), Rømø Havsand (3 km²), Peter Meyers Sand (1.2 km²) and Søren Jessens Sande (10.6 km²). Some researchers regard high sands as tidal flats uncovered at high tide in places where embryonic dune formations are created during dry periods. The author defines high sands as high-lying areas between +0.5m and +3.0m DNN located along the outer exposed coastal stretches. The height +3.0m DNN is an important threshold as it represents the level only reached by storm floodtides. High sands are dominated by drifting sand and characterized by unstable dune and salt formations.

The risk of stormfloods is ever-present in the harsh environment to which high sand flora is exposed. The plants are intermittently flooded and buffeted by waves. During dry periods, the plants are pelted by the sharp grains of drifting sand and finally subjected to prolonged desication in the strongly saline environment. It is however important to emphasize that the creation of a dune area is dependent on the growth of very resistant plant species like sea lyme grass (Elymus), marram grass (Ammophila marraem) and sea couch grass (agropyrum).

The high sands may be classified into three main categories according to dynamics and location:

(1) The First High Sand Category

Includes Koresand and Peter Meyers Sand which lie exposed on the coast, affected by normal barrier formation processes such as wind, waves and a perpendicular supply of material (Figure 1). An ample supply of sand contributed by such right-angled, wind-wave processes have produced Koresand. Its location agrees with the current littoral line of equilibrium along the coastline. In contrast to normal barrier islands, it is inundated at times of stormflood causing continual redeposition of its material. Peter Meyers Sand is considered to be a product of identical processes. It has been built on the tidal flat that is presumed to be the relic barrier-island complex where the islands of Fanø and Mando once constituted a single narrow, elongated island. The relic barrier-island complex has been disintegrated by stormfloods and is now dissected by channels such as Knudedyb whose orientation would suggest formation by the Great Stormflood of 1825. Some of the disintegrated material has probably been redeposited to form part of Koresand and Peter Meyers Sand.

(2) The Second High Sand Category

Includes Rømø Havsande and Søren Jessens Sande on Fanø. This group lies exposed in the tidal channel area. Similar landforms are to be found in Holland and U.S.A. They are associated with tidal channel dynamics and the material transport of the ebb-delta zone. Much research on the local current and material conditions has been undertaken by Helge GRY (1950) and Asger LUNDBAK (1945). The study by Børge JAKOBSEN (1964) on the north Rømø channel of Juvrø Dyb is also valuable literature. The formation, development and migration of Søren Jessens Sande have been closely observed because of its closeness to Grådyb channel which serves as the shipping lane to the port of Esbjerg. Figure 8.

Søren Jessens Sande is relatively young. There is hardly any doubt that the high-lying sandbank called Smørsand is its predecessor. Søren Jessens Sande lies on the flats south of Grådyb channel and is separated from Fanø by the tidal channel Hamborg Dyb (Figure 5). Its material originates from the eroded west coast of Jutland and is deposited by the southeast-flowing coastal current. Helge GRY (1950) describes the initial development of Søren Jessens Sande as having started from complex currents and a circulation cell (Figure 5).

The currents included the southeast-flowing and northeast-flowing coastal currents through the channel of Hamborg Dyb and the west-flowing ebb current through Grådyb channel. The later development is probably caused by the flood-tide current as it loses its velocity on bending into the channel, thus depositing more sediment. The wind and waves shape the sand formation by simultaneously supplying new material, redepositing existing material, and transporting material eastwards. The prevailing westerly winds have gradually eroded the west side of the shoal and transported sand to the east side where it slowly fills Hamborg Dyb. Moreover, large quantities of sand have drifted across northern Fanø, producing a dune landscape.

According to LUNDBAK, (1945) the west side of the high sands shifted 200m eastwards in the decade 1950-60 while the east side grew eastwards by 400 m. After 1960, Søren Jessens Sande became incorporated with the island of Fanø at the end of Hamborg Dyb (Figure 8). Similar seascape dynamics are known from the east coast of U.S.A. Today the channel of Hamborg Dyb has literally disappeared. In just one storm in February 1990, when a large part of the spit Skalling Ende disappeared, enormous quantities of sand were transported across Søren Jessens Sande, reducing the breadth of Hamborg Dyb by another 50m, while a new, long sandbank on the south side of Grådyb channel almost closed off the north end of Hamborg Dyb. Figure 9.

Observations following two further great storms in March 1990 and May 1991 refer to several new surface formations. The first observation was the appearance of an almost regular pattern of circle-like rises with a diameter of 1.0–1.5 m which had gently sloped edges. These formations were located in the northwest area of the high sands at regular distances from each other, 70–90 m, in all directions. These formations were distinguishable from the surrounding flats as they were lighter in colour, meaning that they were drier. They were embryonic dunes of the barchan type. The second observation was the existence of the same formations, but this time in a regular pattern, more linear than before.

(3) The Third High Sand Category

Is dominated by Kiil Sand (Fig 1). This group lies on the leeward side of island barrier on the edge of the channels and
is seldom affected by the waves of the sea. The formation of Kii Sand is a product of tidal action and there is little doubt that it is a flood-tide delta. A simple representation of this category is the recently formed high sand on the tidal flats of Langli Sand inside Gradyb Channel. There is no doubt that the origin of this formation may correlate with the floods of 1976 and 1981 caused in connection with the dredging of Gradyb Bar to enlarge the shipping lane into Esbjerg to a depth of 9.3 msl.

OTHER IMPORTANT COASTAL LANDFORMS OF WESTERN JUTLAND

At the end of the late glacial period, about 7000 BC, the landscape of western Jutland was still dominated by the old moraine hills of an earlier glaciation; such as those of Skovbjerg, Varde, Esbjerg and Hjerpested, but in between these hills stretched the new outwash plains of Karup, Grindsted and Tinglev; a product of the last glaciation (Figure 1). The level of the North Sea rose from 15m below the present level to +/− 0 by the year 1000 AD. Tides were established and the Wadden Sea began to form (Figure 3). The rise in sea-level meant an increase in tidal range.

As the ice melted at the end of the last glaciation, enormous quantities of sand and clay were transported into the North Sea basin where it formed the sea-bed, apart from intermediate end moraine ridges from the penultimate glaciation as at Hornsrev which formed the basis of Blavandshuk, an impressive sand buffer built out into the sea as a tombolo. Bla-
Coastal Morphology in Jutland

Figure 9. Results of an attempt to digitalize watermark boundaries from Geodaetic Institute (Kort & Matrikelstyrelsen) aerial photographs following storms. The drawings show the watermark boundaries for the following periods: a) 1964-68 b) 1968-71 c) 1971-76 d) 1976-88 e) 1988-90. It is apparent that Søren Jessens Sande became attached to the island of Fanø in 1976 and it is also evident that continuous redeposition of sand is in progress, expressed here as the ebb-tide delta of Søren Jessens Sande.

vandshuk is a buffer of sand 25-50 m high that stretches for 15-20 km in an east-west orientation. This landform is the product of the current along the west coast of Jutland influenced by the NW wind, wave action and the creation of large beach ridge systems. One of these large ridge systems provides the basis for the heathland Karlsmeersk Hede which lies between Grærup and Blåvandshuk. The material has derived from the dunes of the old moraine hills north of Blåbjerg and the bed of the North Sea. The North Sea is actually shallow, being only 20-40 m deep, which means that gigantic storm waves are able to erode its bed, stirring material into the seawater before transporting it coastwards. Figure 10.

Wave-induced currents play a major role. The south-flowing coastal material transport measures 1 million cubic metres per annum. Thus the creation of the landscape along the west coast has been controlled by the post-glacial sea-rise in the North Sea basin, the existing topography, and finally the presence of substantial sands and gravels (Figure 7).

All in all, the Wadden Sea functions as an enormous sieve. It acts as the background for the masses of fine-grained material that are washed out through the deep at low tide. The flood brings in material from the North Sea. The fine-grained material is deposited all over the Wadden Sea until the tide changes and the reverse movement of sediments dominates the picture. Figure 11.

CONCLUSION

The explanation of the genesis of the barrier island complex and the Wadden Sea may be regarded as a development model for the whole of the west coast of Jutland from Vendsyssel if one merely pays attention to the isostatic movements. Here, special attention must be paid to the ridge and swale systems; the outstanding character of which is a product of these isostatic movements, and which are particularly conspicuous in Vendsyssel. The tidal factor is however vital, or rather structural, with regard to the chronological development, when the whole picture is to be considered. The dynamics around and on the high sands are of the utmost importance to the establishment of the coastal dune landscape,
given that the necessary material transport to the area occurs. Storms and climatic fluctuations appear to have been very influential as coast-forming processes as they have provided much of this material (Figure 7).

![Figure 10. Seasonal changes in the coast profile are partly shown in the definition transect. The Per Bruun Rule of Erosion (1988) explains the material movements that are responsible for the development of beaches and sea-bed profiles along the west coast of Jutland.](image)

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LITERATURE CITED


