The Backbarrier Sediments of the Skallingen Peninsula, Denmark

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Abstract

The Skallingen peninsula is formed by sand derived from the south-going littoral drift along the North Sea coast. The backbarrier has accumulated sand as a result of wash-over deposits. In the beginning of the 20th century, fine grained sediment started to cover the surface in form of salt marsh deposits.

The sand on the peninsula consists primarily of fine sand with a mean grain size of 2.5-2.25 phi (0.177-0.210 mm). Exposed to waves in the tidal flat environment and to tidal currents in the salt marsh creek environment, the finest sand fractions are removed and deposited on the salt marsh. The remaining sand is sorted in accordance with the dynamics in the sub-environments. The change in grain-size characteristics during this dispersal of sand in the back barrier is analyzed by means of decomposition of the grain-size distributions into overlapping log-normal distributions.

The import of fine grained sediment is demonstrated, based on measurements of tidal dynamics and concentration of suspended matter in the mouth of a salt marsh creek.

The salt marsh formation is analyzed on the basis of ^{210}Pb-datings and grain-size analysis of the surface layers in a line across the central part of the backbarrier environment. The deposition rate is observed to increase from south to north, when approaching the inner part of the tidal area. The grain-size distribution of the average material depositing on the backbarrier in the central part of the peninsula consists of 15% sand, 46 % silt and 39% clay with a corresponding deposition rate of 0.07 $g \cdot cm^{-2} y^{-1}$. The dry density of the salt marsh clay is primarily controlled by variations in the content of organic matter and by compaction. Two power functions are formulated to describe variations in the dry density: $D = 4.47 \cdot O^{-0.81}$; $10>O>50$; $r=0.98$ (surface samples) and $D = 0.58*X^{0.17}$; $0.5>X>32.5$; $r=0.70$, where D is the dry density (g/cm^3), O is loss in ignition (%) and X depth below the surface.

Keywords

Estuarine sediments, salt marsh, grain-size distributions, barrier islands.

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In the Wadden Sea, relations between hydrodynamics, morphology and sediment types are extremely sensitive. Small variations in one of these three sedimentological fundamentals are able to cause relatively large variations in the other. This depositional system is therefore well suited for investigations linking grain-size characteristics to environmental parameters (e.g. Reineck & Singh 1986; Bartholdy 1985; Flemming et al. 1992, Flemming & Ziegler 1995, Krögel & Flemming in press). Describing the sediments in the Danish Wadden Sea, Hansen (1951) distinguished between three main types, truncated at 0.063 mm and 0.250 mm. According to Hansen the two finest fractions are true Wadden Sea sediments, whereas the coarse one (when present) represents a "none Wadden Sea" source of some kind. In Hansen (1953) these considerations are used to explain the somewhat coarser sand in Grådyb Tidal Area as a result of local erosion in "foreign" deposits.

Kuhlman (1957) describes the sediments in the coastal zone of the peninsula Skallingen as 0.17-0.19 mm sand. He concludes that it is difficult to distinguish between marine and eolian sand in this environment.

Earlier work on the sedimentary environment of Skallingen has concentrated on the formation of salt marsh in the backbarrier environment (e.g. Nielsen 1935 and Jakobsen 1953, 1954). Aspects of the geomorphology of the peninsula are described by Jakobsen (1964), Møller (1964), Nielsen & Nielsen (1973), Jacobsen (1980), Bartholdy (1983) and Aagaard et al. (1995).

In spite of many attempts (e.g. by Friedman 1961;

Passega 1964; Doeglas 1968; Visher 1969; Buller & McManus 1974; Middleton 1976,) it is still not possible to make definitive interpretations of sedimentary environments based on grain sizes alone. In many cases even comparisons of one environment with another are problematic. Part of the reason for this is that the causal relationships between hydrodynamics and grain size compositions are far from being understood in any detail. Although in recent years significant progress has been made with respect to grain-size entrainment and bed-load transport (e.g. Komar & Li 1986; Komar 1987, Kirchner et al. 1990, Wilcock & Southard 1989; Wilcock 1992; Bridge & Bennett 1992; Bennett & Bridge 1995), there are still many unanswered questions.

Another significant reason is that available tools for the description of natural grain-size distributions are restricted to models which fail to give a complete characterization. At present, two approaches, the log-normal and the log-hyperbolic, are the most commonly used methods of grain size description (Bagnold 1937; Folk & Ward 1957; Barndorff-Nielsen 1977; Bagnold & Barndorff-Nielsen 1980; Barndorff-Nielsen et al. 1982; Wyrwoll & Smyth 1985; Christiansen & Hartmann 1988, Sutherland & Lee 1994).

It is not the intention here to make any direct comments concerning the dispute between these "schools". The primary objective of this paper is to give a comprehensive description of the depositional environment and sediment types in the backbarrier of the Skallingen peninsula and to point out the advantages which can be obtained from an analysis and comparison of the dominant parts of grain-size distributions, based on the decomposition of such distributions into overlapping log-normal sub-populations.

Methods

Samples of the surface sediments were collected by means of a 3 cm long cylinder with a volume of 25 cm^3. If bed forms were present, the samples were collected at the crests in order to avoid the often poorly sorted and less representative trough sediments. In the salt marsh, vertical sections were cut and sampled from the walls of 0.5-1.0 m deep holes. In the salt marsh creeks, small sediment cores were collected by means of a 0.7 m long tube sampler with a 52 mm diameter.

Grain-size analyses were performed after ultrasonic treatment of the samples in a solution of $Na_4P_2O_7$ in demineralized water. The separation between sand and finer particles was carried out by wet-sieving through a 0.063 mm sieve. The sand (typical sample size $\approx$ 15 g) was dry-sieved (20 minutes) at 1/4 phi intervals. The fine fractions were analyzed by means of the Andreassen pipette method.

In addition to the statistical parameters calculated after Folk & Ward (1957), the composite grain-size distributions were decomposed into overlapping log-normal distributions. The decomposition of the polymodal distributions was conducted in 1/4-phi steps following the method described by Sheridan et al. (1987).

The current velocity and direction were recorded with a Niskin winged current meter (model 6011 MKII) and the turbidity with a GMI model TU-150IR (transmission; infrared light) turbidity meter. Records were stored every 5 minutes. The velocity was averaged over 40 discrete measurements, spaced with 5 second intervals and the turbidity as a mean of 10 measurements with one second spacing. The turbidity signal was transformed into concentration of suspended sediment in accordance with Bartholdy & Anthony (in press). In a few incidents (5) where the maximum range of the turbidity meter was exceeded the concentration was extrapolated. The Water level in Hobo Dyb was estimated based on linear interpolation between tide gauge recordings in Esbjerg and on the ebb tidal delta just outside Grådyb. Levels are stated relative to DNN (Danish Ordnance Datum).

The accumulation rates on the salt marsh were determined using ^{210}Pb-datings of the surface layers (Madsen & Sørensen 1979). The dated cores are from Bartholdy & Madsen (1985). The accumulation rates related to the surface samples are based on the total ^{210}Pb activity in the uppermost 3 cm of the salt marsh. This procedure is only meaningful if all other necessary information are provided, by the analysis of adjacent cores. All ^{210}Pb-datings and associated analyses were conducted by the former Danish Isotope Centre.

Area of study

In numerous descriptions (e.g. Nielsen 1935; Jakobsen 1954; Nielsen & Nielsen 1973; Bartholdy 1983; Bartholdy & Pejrup 1994; Aagaard et. al 1995; Davis et al. 1997), the Skallingen has been characterized as a young barrier "island" or barrier spit (Aagaard et al. 1995). It was formed during the last 400 years under the influence of a relatively large south-going littoral drift along the west coast of Denmark.

Based on a 3-month winter/early spring measuring period, Aagaard et al. (1995) calculated mean significant wave height off the coast to be 0.5 m, with wave heights exceeding 2 m, present in 10 % of the time. The average tidal range in the area is approximately 1.5 m.

The geomorphological zonation across the peninsula from the ocean to the lagoon comprises the following depositional sequences: beach, dune, salt marsh, tidal flat. This sequence is a typical example of the zonation observed across a Wadden Sea island and is easy to recognize on the aerial photo of Figure 1.

The base of the peninsula is formed by sands, washed over during storms (Davis et al. 1997). In the rear of the barrier these are drained by salt marsh creeks developed synchronously with salt marsh formation. This process started around the beginning of the 20th Century (Nielsen 1935), with fines accumulating on the vegetated parts of the sand flat. In this period all "weak spots" in the foredune ridge were closed by dikes (Aagaard et al. 1995). The muddy salt marsh material is primarily derived from the North Sea (Bartholdy & Madsen 1985) where a weak residual current (the Jutland Current) carries fine-grained material up along the Wadden Sea coast (e.g. Eisma & Kalf 1987). The rate of deposition in the central part of the salt marsh area is relatively uniform and close to 1.5 mm/y, which is a little higher than the sea level rise, reported by Aagaard et al. (1995) to be 1.1 mm/y in the period 1890-1987.

The coarse-grained sediments

The sand on the Skallingen peninsula is derived from the south-going littoral drift along the North Sea coast and consists primarily of fine sand composed of subangular quarts grains (Figure 2) with a shape factor of 0.5-0.7. This was determined by plotting mean settling velocities against mean sieve diameters, as suggested in "Subcommittee on sedimentation (1958)". The fine sand is by far the most dominating grain size, but it should be mentioned that pebbles (up to approximately 2 cm with a median diametre of approximately 7 mm and virtually no particles between 2 mm and the fine beach sand) are often found in form of gravel-lags on the beach. These gravel lags are also, although rarely, found in the wash-over deposits (Davis et al, 1997).

In Figure 3, typical examples of grain-size distributions of sand from characteristic depositional environments on the peninsula give a good visual impression of the sediment types. The variations follow a logical trend from the relatively poorly sorted wash-over sand with a fine "shoulder" (the source material) to the three primary sandy depositional environments in the backbarrier, each displaying a characteristic grain-size distribution derived by a modification of the source material: The tidal flats, the creek bed and the point bars in the salt marsh creeks.

The wash-over sand (Figure 3) represents a mean of 4 samples from a transect across a "fresh" wash-over fan in the prominent wash-over channel (Figure 1). It reopened during winter storms early in 1990 (the samples are from May 1990, all having similar distributions). The Tidal flat sample represents a mean of 5 samples spread from north-west to south-east on the tidal flat adjacent to the salt marsh to the north-east of the peninsula, again all samples having similar distributions. The channel bed sample consists of a mix of 3 samples from the surface to a depth of 10 cm in the thalweg (under the surface sample marked "33" in Figure 6) and the point bar sand is a mix of 6 samples spread over the main part of the adjacent point bar in "Store Lo", marked with a bar in Figure 1. The statistical parameters of these samples are relatively irregular, but they are all composed of very similar log-normal sub-populations, albeit in different proportions.

From the wash-over to the tidal flat and creek bottom environments, the modal value of the sand changes from 2.5 phi (0.177 mm) to 2.75 phi (0.149 mm) with an increased share of the total sample in both the tidal flat and the creek bottom sand. The main part of the grain-size distributions of both the tidal flat sand and the creek bottom

Table 1: The statistical parameters based on Folk and Ward (1957) for the sand fraction in typical sandy depositional areas of Skallingen: Mean (Mz), sorting coefficient (Sd), skewness (Sk) & kurtosis (kg).

Environment	*Mz*		*Sd*	*Sk*	*Kg*
	phi	*mm*	*phi*		
Wash-over	2.52	0.174	0.38	0.00	1.03
Tidal flat	2.44	0.184	0.35	-0.15	1.16
Creek bed	2.40	0.189	0.43	-0.29	1.18
Point bar	2.25	0.210	0.44	-0.35	1.35

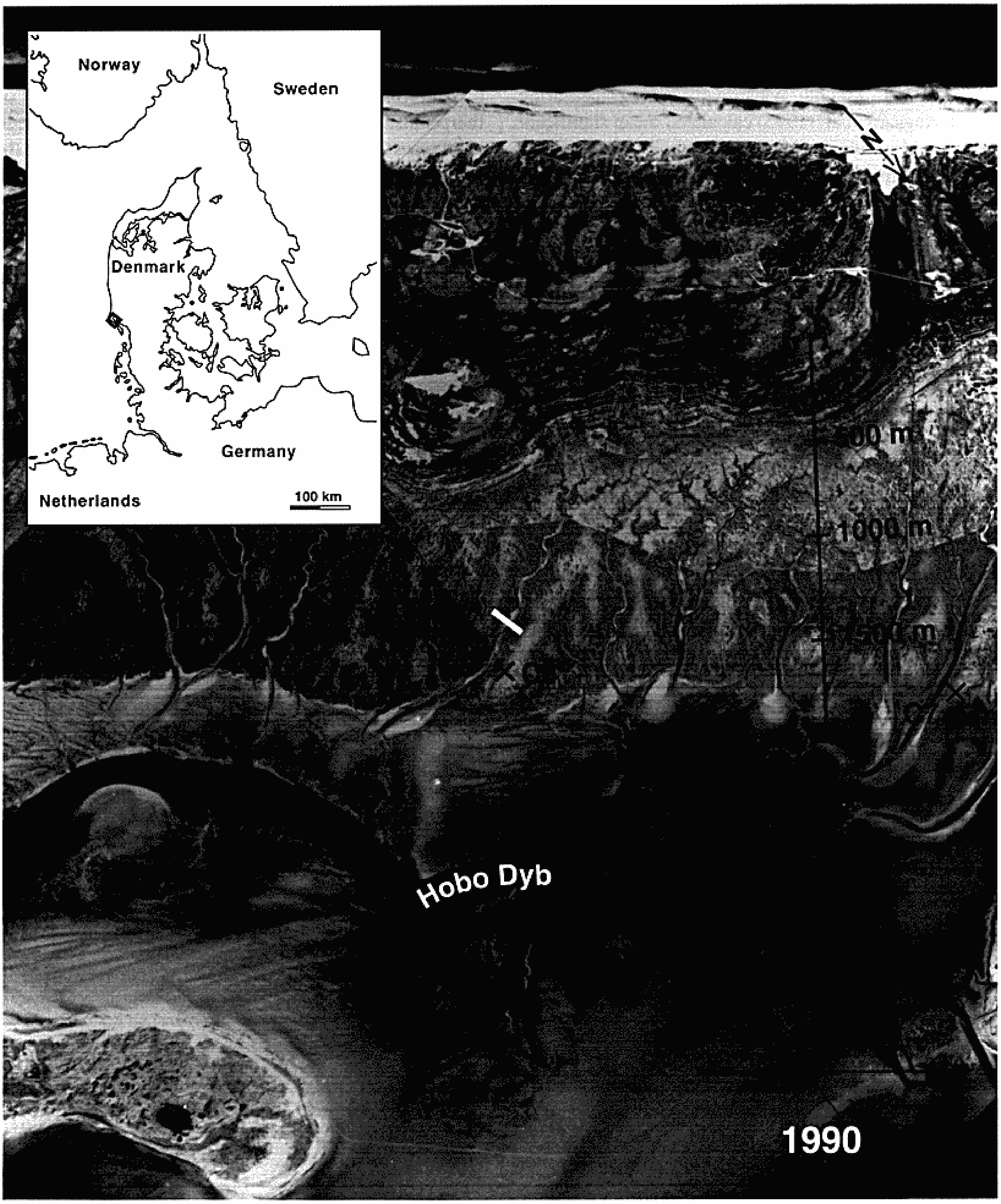

Figure 1: Location map and aerial photo of the central part of the Skallingen peninsula. The line across the backbarrier area marks the location of the section shown in Figure 10. In the salt marsh creek "Store Lo", the profile shown in Figure 5 is marked with a white bar.

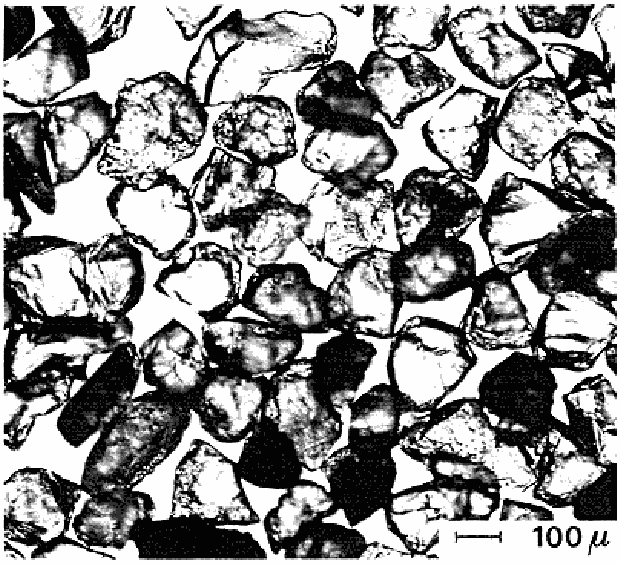

Figure 2: Microscopic enlargement of sand (2.5-2.25 phi; 0.177-0.210 mm) from the salt marsh creek "Store Lo".

sand are slightly shifted towards the coarser side. In the Point bar, the modal value is back to 2.5 phi (0.177 mm).

The textural parameters of the mean samples (Table 1) show variations which, to a considerable extent, diverge from the visual interpretations given above. This reflects the tendency of the statistical procedure to condens a large part of the grain-size information into a few parameters, rather than to describe the main characteristics of the central part of the distributions.

Based on the statistical parameters, the wash-over sand exhibits an almost perfect symmetrical distribution. The fine shoulder and the clearly less well-sorted main distribution (compared to the main distribution of the other samples) are not revealed here. On the contrary, the clearly better sorted main populations of the other three sediment types are not reflected in their sorting coefficients, these being almost similar or even larger. These results thus indicate that an unambiguous interpretation of modifications to the source distribution from one depositional environment to another cannot be achieved on the basis of the statistical parameters.

These drawbacks can be avoided if, instead of using the statistical parameters of the whole distribution, it is separated into log-normal components. This procedure permits identification of any modifications experienced by the distribution in the course of its transport to different depositional environments. For example, Figure 4 shows the same four distributions of Figure 3, now decomposed into log-normal components (numerically described in Table 2) where the main populations are named A,B,C,D and E in decreasing grain size order. From this decomposition it is very clear that the two main populations, C and D, in the wash-over sand (representing 94 % of the material) change into a slightly finer and better sorted C-population (87% & 82%) in the tidal flat and creek bottom sand. In both cases, the main distributions are "garnished" with more pronounced coarser populations than found in the wash-over sand. This might, at least as far as the coarsest particles are concerned, be an effect of biased sampling favoring the smaller fractions because of a tendency of coarse material to concentrate in specific sub-environments during the wash-over incident. However, even if this "missing" coarse tail in the wash-over sand has been produced by a sampling bias, no doubt also the sorting of the sand, produced by the specific dynamic characteristics of the different sedimentary environments, plays an important role. Thus, the finest fractions are resuspended and removed by the tidal currents in the salt marsh creeks, whereas at the same time channel lag deposits displaying an extremely pronounced coarse tail are formed. Like wise, sand is re-

Table 2: Deconvolution of the grain-size distributions shown in Figure 3 & 4 into log-normal sub-populations described by their mean grain size (Mz) and standard deviation (Sd) the fraction (%) indicate the single populations share of the total distribution.

Environment	*Fraction*	*Pop. A*			*Pop. B*			*Pop. C*			*Pop. D*			*Pop. E*		
	coarser than Pop. A	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*
Wash-over	0			0	1.80	0.18	4	2.44	0.28	75	2.90	0.18	19	3.40	0.15	2
Tidal flat	0	1.30	0.25	2	1.87	0.17	9	2.51	0.26	87			0	3.30	0.25	2
Creek bed	3	1.32	0.25	5	1.88	0.17	8	2.50	0.25	82			0	3.30	0.25	1
Point bar	3	1.30	0.25	6	1.87	0.15	11	2.40	0.23	76			0			0

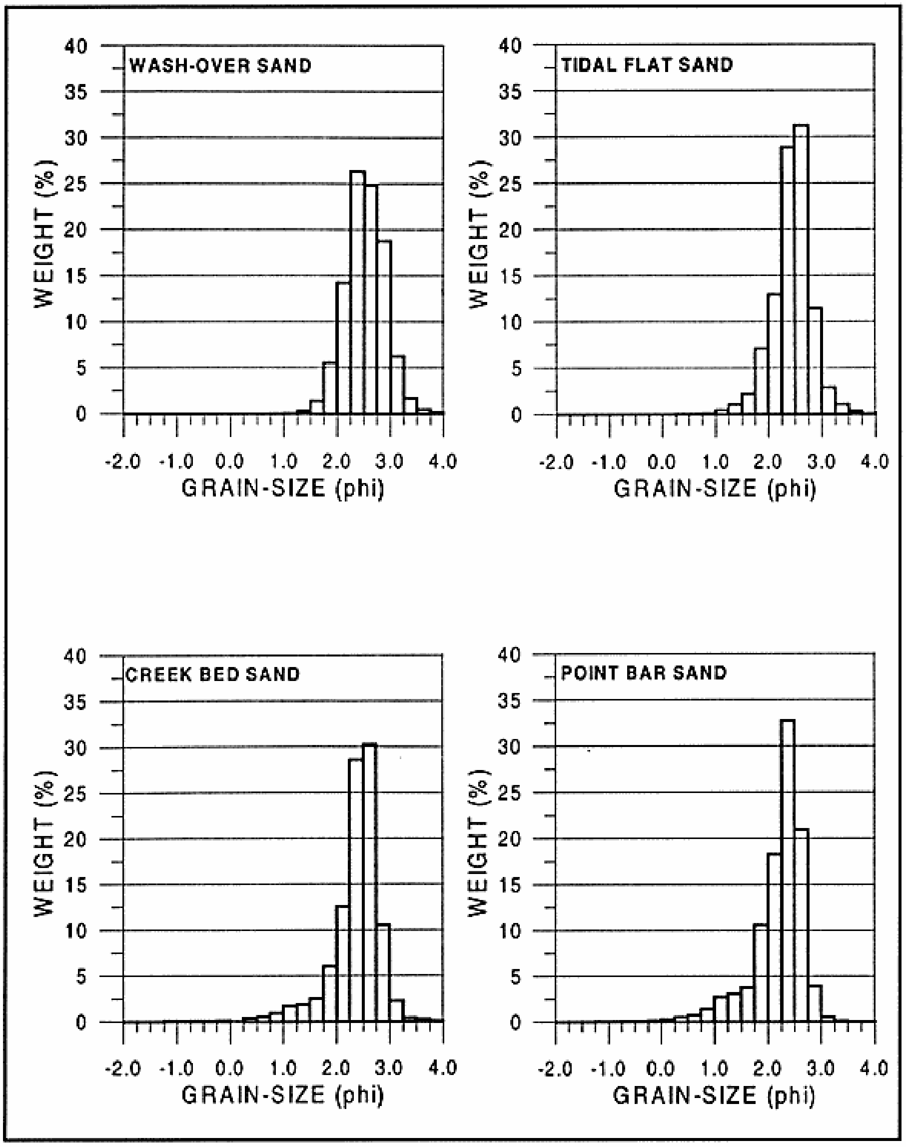

Figure 3: *Grain-size distributions of sand from typical sandy depositional environments in the back-barrier environments of Skallingen.*

worked by waves on the tidal flats and, during storms, the fine fractions are removed to be subsequently trapped on the salt marsh surface. In the following two sections, the sand fractions of these depositional environments are analyzed in more detail.

The salt marsh creek environment

The salt marsh creeks are represented by samples from a transect across the most prominent meander bend in "Store Lo" (Figure 5, for location see Figure 1). To the left (ebb-direction), the erosion in the undercut bank is just about to cause the collapse of a minor tributary creek. On both sides of the creek a 10-20 cm thick layer of salt marsh clay covers the sand. To the right, the top of the point bar is separated from the salt marsh by a chute channel. The point bar top is covered by vegetation and interbedded sand/clay salt marsh deposits. In Figure 6 and Table 3, six typical grain-size distributions illustrate the characteristics of the creek sands.

The sand lag in the two finest fractions of the channel and point bar sands is obvious and corresponds to the fact that almost all of the sand (97%) in the salt marsh on the point bar is made up by material from these two sources. The finest fractions are winnowed from the channel sand,

Table 3: Deconvolution of the grain-size distributions shown in Figure 3 & 4 into log-normal sub-populations described by their mean grain size (Mz) and standard deviation (Sd), the fraction (%) indicates the single populations share of the total distribution.

Environment	*Fraction coarser than Pop. A %*	*Pop. A*			*Pop. B*			*Pop. C*			*Pop. D*			*Pop. E*		
		Mz phi	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*
Bed of creek	3	1.32	0.25	5	1.88	0.17	8	2.50	0.25	82			0	3.30	0.15	0
Channel lag	26	1.21	0.32	12	1.84	0.15	7	2.51	0.25	55			0			0
S.aq. dune top	4	1.30	0.25	10	1.87	0.15	16	2.33	0.23	70			0			0
S. aq. dune front	4	1.30	0.25	11	1.85	0.15	15	2.32	0.23	69			0			0
S. aq. ripple	1	1.30	0.25	2	1.85	0.15	8	2.39	0.23	90			0			0
Point bar salt marsh	1			0	1.85	0.15	1			0	2.70	0.22	84	3.24	0.23	13

being brought into suspension and occasionally deposited on the banks. The channel bed sample is the same as the one shown in Figure 3 & 4. This material is much finer than the channel lag sand, however, the main C-populations of these two distributions are identical, as they are indistinguishable from the main C-population of the tidal flat sand (Table 2 & 3). This main population is somewhat finer than the corresponding population in the average point bar sand (2.51 phi or 0.176 mm vs. 2.40 phi or 0.189 mm), a deviation which becomes even more pronounced when looking at recently transported sand on the point bar platform. Figure 7a, b & c, show the point bar surface at low water after a relatively high spring tide. The surface is dominated by 10-15 cm high ebb-oriented subaqueous dunes spaced of approximately 2-3 m. The dunes have ripples in their troughs. The orientation of the 2-3 cm high and 10-15 cm long ripples is evidently influenced by currents in the late stage of the ebb period, the dune troughs now acting as small channels leading the water in an oblique, ebb-oriented angle towards the center of the channel. It is a characteristic phenomenon that poorly sorted, relatively coarse material (shell fragments) is caught by the back flow immediately downstream of the dune crests, forming sub-horizontal layers in the point bar deposit (Figure 7c).

In Figure 7b the location of three sand samples (dune crest, lee slope and trough) is shown by their sample marks. As evident from Figure 6 and Table 3, these samples are characterized by a slightly coarser main C-population. In the active dune sand this finest population comprise approx. 70 % of the total sample and has a mean

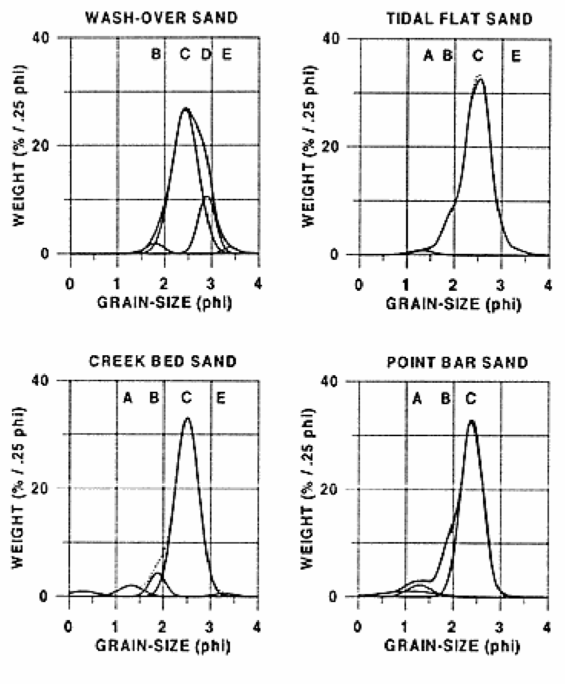

Figure 4: Decomposition of the grain-size distributions shown in Figure 3 into overlapping log-normal distributions. The dotted line represents the composite (constructed) curve. It is almost invisible in most of the sequence as a result of perfect match.

grain size of 2.33 phi (0.199 mm). In the ripple sand the main C-population comprises 90 % of the sample and is practically identical with the main population of the average point bar sand (Table 2). The tendency for a coarser main population in the point bar sand, may be related to the sorting mechanisms found in fluvial meander bends, as described by Bartholdy & Kisling-Møller (1996).

In summary, sorting of sand in the salt marsh creeks is characterized by: 1) The finest sand populations are winnowed from the channel environment. 2) Coarse material is "concentrated", giving the distributions a pronounced coarse tail and contributing to the development of channel lags. 3) In the main channel environment, the C-population (the most dominant and virtually the finest population present) is identical to that of the tidal flat sand (Md: 2.5 phi or 0.177 mm; Sd: 0.26 phi). 4) On the point bar, the C-population (still the dominant and finest population present) is coarser and slightly better sorted (Md: 2.4 phi or 0.189 mm; Sd: 0.23 phi) than in the main channel.

The salt marsh environment

Examples of grain-size distributions of sand in the salt marsh environment are illustrated in Figure 8 and the corresponding decomposition into log-normal populations is listed in Table 4. The first three distributions represent "proper" salt marsh examples, whereas the last three exemplify other environments present in the salt marsh. In general, the sand in the salt marsh is made up of the two fine populations D & E. The sand from the exposed salt marsh is from the outer part of the profile shown in Figure 10 (#5). Here the salt marsh surface may be expected to receive a small amount of wave-suspended tidal flat sand every time the salt marsh is inundated under wave action. It is therefore not surprising that this sand has its dominant grain-size component in the finest E-population (80%) and a smaller amount in the coarser D-population (18%). This is in contrast to the sand layer sample, also from the exposed part of the salt marsh (C7, Figure 1 & Figure 13; 34-35 cm), which probably represens a storm event. The proportions are here 90% in the D-population and only 6% in the E-population. Apart from this difference, the distributions are dominated by the two populations and, as the sand can only originate from the adjacent tidal flats (0 % in the D-population and only 2 % in the E-population; Tab. 2), it can be assumed that, during the reworking of the sand on the tidal flats, the main populations are sorted in such a way that the finest sand fractions are extracted from the flats to be delivered to the surrounding salt marshes.

During extreme events such as storm surges, which leave a thin layer of sandy mud on the salt marsh surface, even parts of the C-population can find their way up to the marsh. The storm surge material (18% sand, 50 % silt &

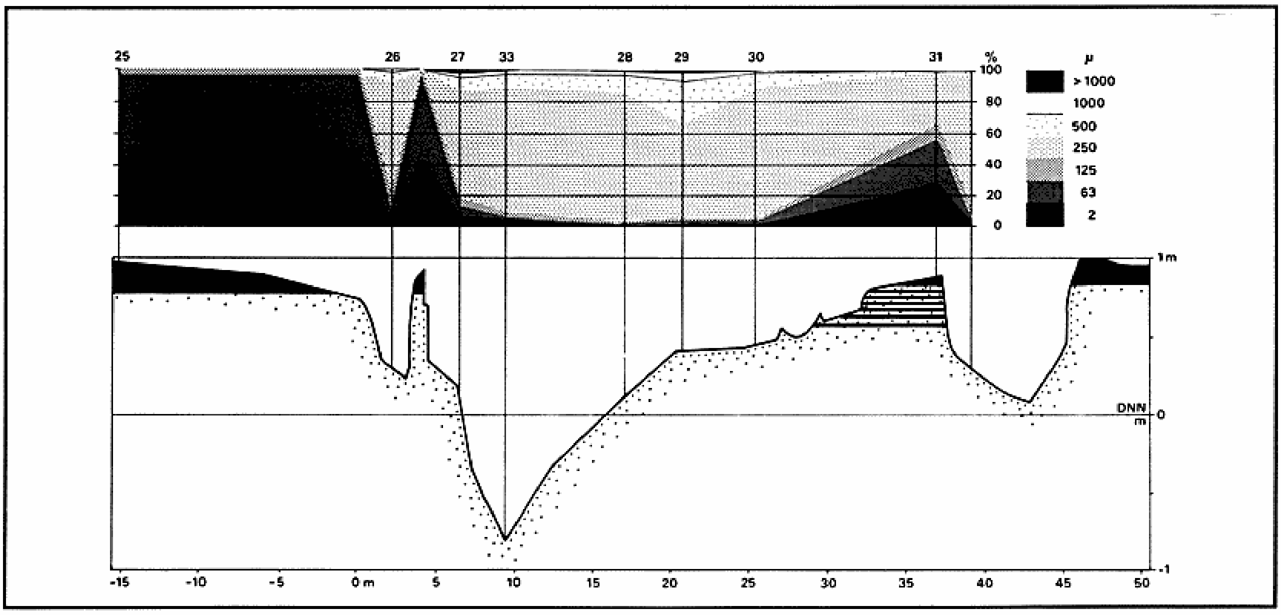

Figure 5: Cross-section of the salt marsh creek "Store Lo" with indication of grain-size composition and sample numbers. For location see Figure 1. From Bartholdy (1983).

32% clay), sampled close to C8 (Figure 1) after a very severe storm surge in November 1981, has 24% of its sand belonging to this population, whereas 50% and 19% belong to the D- and E-populations, respectively. The sand ridge parallel to the salt marsh front, visible on the profile of Figure 10 (#6), consists of relatively coarse sand, 71 % belonging to a coarse version of the C-population (Md: 2.36 phi or 0.195 mm; Sd: 0.28 phi) and 24 % to yet coarser populations. These sands presumably originate from a beach ridge on the former tidal/wash-over flat where waves have winnowed the fine material from the matrix during its formation. The two last distributions in Figure 8 are primarily from beneath the salt marsh on the right part of the profile across the salt marsh creek (Figure 5).The upper example consists of a mixture of 5 samples down to 12 cm beneath the clay (one of these subsamples is from under the clay at pos. C7, see Figure 1 & Figure 13; 40-41 cm), and the lower example consists of a mixture of 4 samples from 20-26 cm beneath the clay. Between 12 and 20 cm beneath the clay some kind of transition takes place between the two "clean" types discussed here. The upper sand is very similar to the tidal flat sand. Its main distribution, comprising 83 % of the sample, is practically identical to that of the tidal flat sand (Md: 2.55 phi or 0.171 mm; Sd: 0.27 v. Md: 2.51 phi or 0.176 mm; Sd: 0.26).

From a geomorphological point of view, it seems obvious that this sand formed the top layer of the former tidal flat before salt marsh formation began. It therefore supports the contention, that the tidal flat character is clearly reflected in the grain-size distribution of the sand. This interpretation is extended to the lower sample which bears the characteristics of the wash-over sand. It is clearly bimodal with two main distributions, a large (60 %) C-

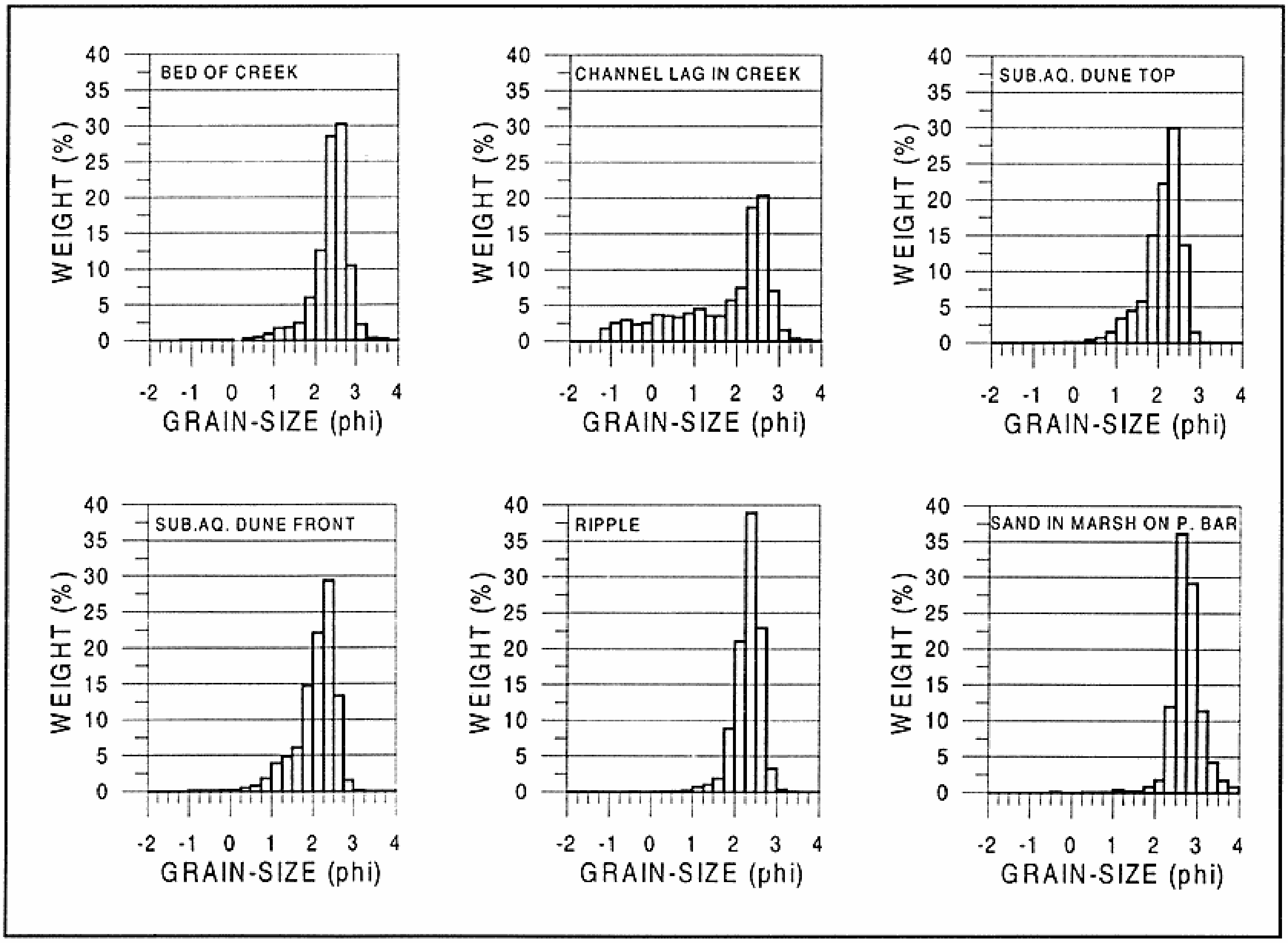

Figure 6: Grain-size distributions of typical sand types from the salt marsh creek environment.

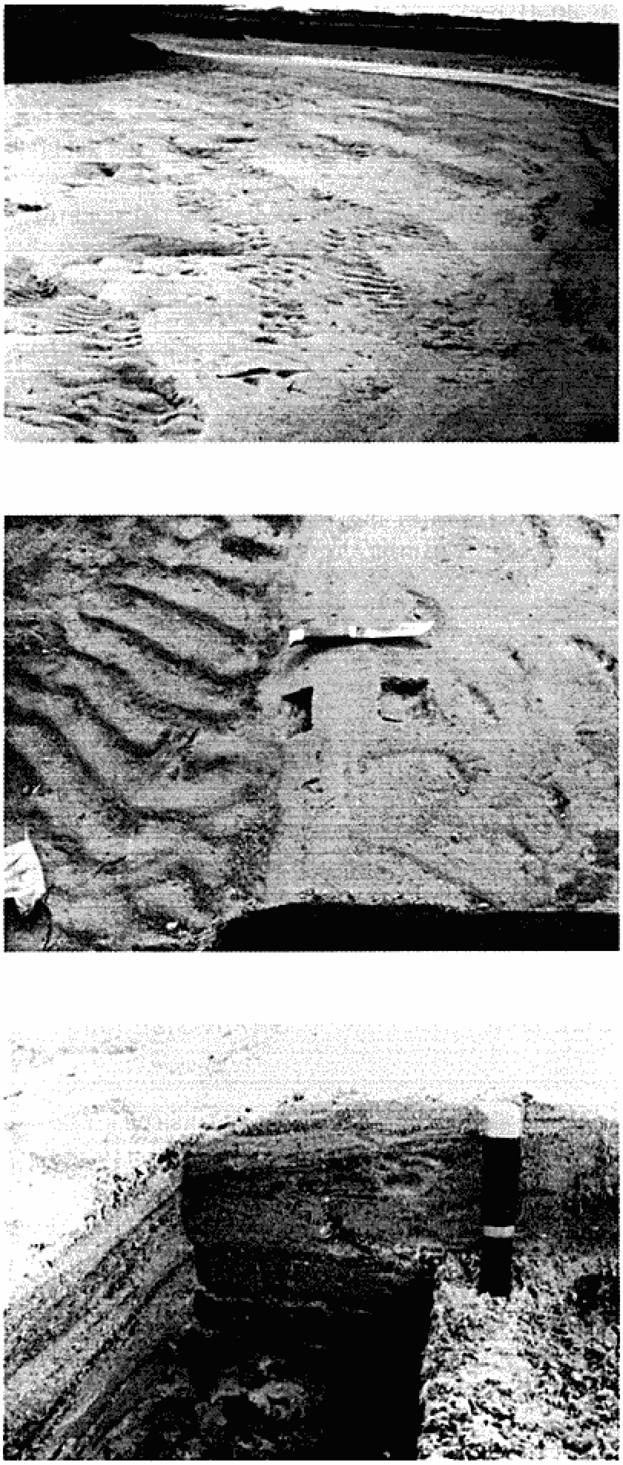

Figure 7: Photos of the investigated point bar in "Store Lo". The knife for scale is 20 cm long. The ebb current direction is from upper right (A) and from right to left (B& C):

population (Md: 2.44 phi or 0.184 mm; Sd: 0.20 phi) and a smaller (36%) D-population (Md: 2.76 phi or 0.148 mm; Sd: 36 phi). The C-population is somewhat better sorted and the D-population a little coarser than the previously described wash-over sand, indicating the existence of natural variations within this sand type. The mean grain size of the C+D population is 2.54 phi (0.172 mm) and 2.51 phi (0.175 mm) in the previously described sand of this type. These results therefore suggest that, in general, the major part of the sand body under the salt marsh consists of wash-over sand with a "fine shouldered" bimodal main distribution on which a 12-20 cm thick top layer has lost the finest sand fractions as a result of wave reworking during its former existence as an exposed tidal flat.

In summary, sorting of sand from the tidal/wash-over flats to the salt marsh is characterized by: 1) The finest sand populations are winnowed from the former surface and deposited on the salt marsh. 2) During this process the original bimodal C- and D-populations of the wash-over sand change in the salt marsh almost exclusively to consist of D- and E-populations. 3) The remaining sands on the tidal flats lose the finest sand fractions and develop a prominent C-population with a coarse tail.

The fine-grained sediments

The vegetation constitutes an effective trapping mechanism for fine-grained sediment on the salt marsh surface. When the tidal flats approximately reach the mean high water level (0.7-0.8 m DNN), salt marsh plants become abundant and begin to generate a sufficiently sheltered environment to favour the formation of a salt marsh. This raises the level of the former bare sand flat, turning it into a densely vegetated area. The first two plants to colonize the tidal flats are *Salicornia europaéa* and *Spartina townsendi* followed by *Suaéda maritima* and the dominating *Puccinellia maritima.* When the level of the flat is raised further, the primary plant in the newly formed salt marsh is *Halimione*, this was formerly named *Obione portulacoides* and has developed its dominance since 1931 where, according to Iversen (1954), only a few plants were present on the peninsula. Now *Halimione* is dominating the young low laying salt marsh areas and form, with a few other plants of which *Limonium vulgaris* and *Artemisia maritima* are representative, a very efficient sedimentation promoting vegetation carpet.

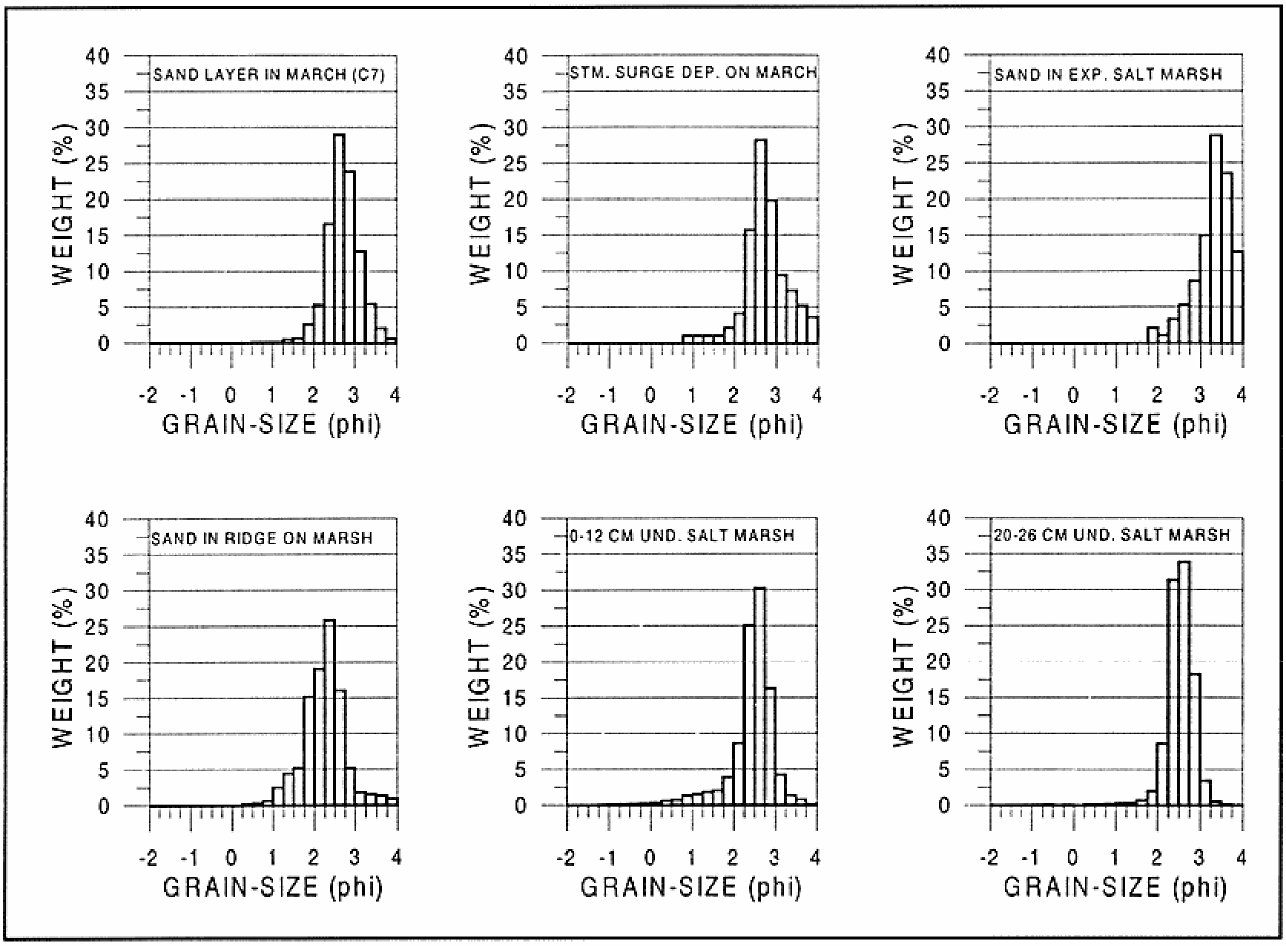

Figure 8: Grain-size distributions of typical sand types from the salt marsh environment. The first three including the one labeled "Sand in exposed salt marsh" represent "proper" salt marsh examples. The last three exemplify other environments present in the salt marsh.

After the contribution of wash-over sand from the North Sea ceased at the beginning of this century, the creeks became the only source of sand for the east-facing tidal flats. As a result of this, the mouths of the salt marsh creeks are the only areas where the supply of sand is large enough to form sufficiently high elevations for the plants to grow on. These zones, often dominated by natural levees, are therefore potential new areas for the eastward growth of the salt marsh. The import of fine-grained sediments to this part of the Wadden Sea is primarily derived from the North Sea, as described in Bartholdy & Madsen (1985). Approximately 85% of a total deposition of $0.14 \cdot 10^6$ t/y, (66% silt and 34% clay) enters the Grådyb tidal area from the ocean. As the Skallingen peninsula is closest to the sea, this percentage is probably even higher here. Recent results (Bartholdy & Anthony, in press) show that this import of fine-grained material is episodic and to a large extent associated with windy periods following relatively long periods of calm weather conditions. This episodic nature is also preserved in the fine-grained sediment deposits on the salt marsh surface, although for different reasons, as illustrated beneath.

In Figure 9 the hydrodynamic conditions in Store Lo (at the mouth, Figure 1) associated with a storm in February 1997, illustrate the transport conditions for fine grained sediment in this area. During calm weather (26 & 27/2), concentrations are low (5-50 mg/l) with small variations in a relatively clear temporal variation pattern: Concentrations are low until late in the flood period when concentrations increase concurrently with velocity, when the salt marsh is inundated (the salt marsh level is ≈0.9 m DNN); the concentration drops during high water slack

***Table 4:** Deconvolution of the grain-size distributions shown in Figure 8 into log-normal sub-populations described by their mean grain size (Mz) and standard deviation (Sd) the fraction (%) indicate the single populations share of the total distribution.*

Environment	*Fraction coarser than Pop. A %*	*Pop. A*			*Pop. B*			*Pop. C*			*Pop. D*			*Pop. E*		
		Mz phi	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*
Sand layer (C7)	0	1.30	0.25	1	1.85	0.15	3			0	2.70	0.31	90	3.48	0 24	6
Storm surge dep.	0	1.30	0.25	5	1.94	0.15	2	2.55	0.22	24	2.72	0.27	50	3.49	0.30	19
Exposed salt marsh	0			0	1.85	0.15	3			0	2.75	0.30	18	3.48	0.28	80
Sand ridge on marsh	1	1.33	0.21	9	1.85	0.15	14	2.36	0.28	71			0	3.50	0.30	5
0-12 cm und. marsh	6			0	1.70	0.18	4	2.55	0.27	83	2.87	0.18	3	3.40	0.20	2
20-26 cm und. marsh	1	1.50	0.20	1	1.84	0.14	2	2.44	0.20	60	2.76	0.20	36			0

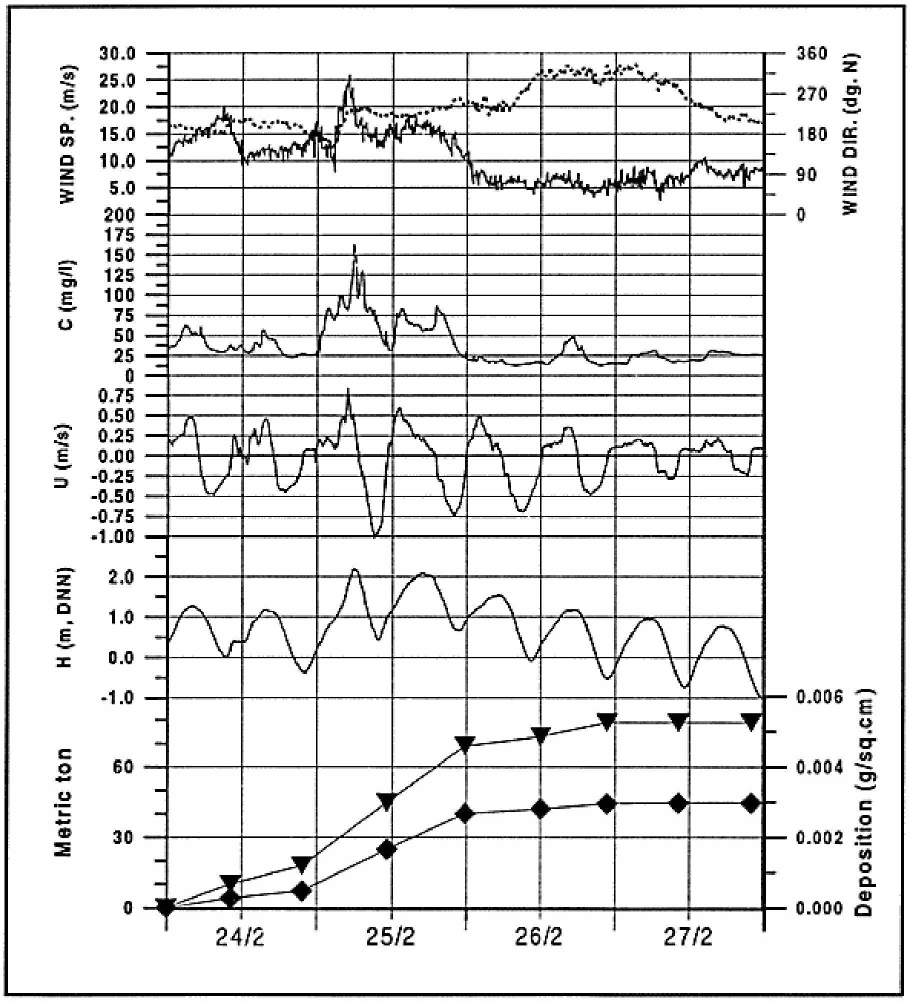

***Figure 9:** The dynamic conditions at the mouth of the salt marsh creek "Store Lo" 24.-27. February 1997 (for location see Figure 1). Wind speed and direction (dashed line) shown above, was measured at the harbour in Esbjerg. **C:** Concentration of fine-grained material, **U:** Current speed (0.5 m above the bottom in the middle of the creek) and **H:** Water level in Hobo Dyb estimated based on linear interpolation between tide gauge recordings in Esbjerg and on the ebb tidal delta just outside Grådyb. **Beneath:** Diamonds: Accumulated net-import of fine-grained material in metric ton. Triangles: Average deposition of fine-grained material associated with the net-import to the tidal area of the creek.*

and a very weak and significantly lower resuspension top occurs in the subsequent ebb current; the lowest concentrations are measured around low water slack. The water level in the creek has a minimum of -0.1 m DNN. When the level in Hobo Dyb gets lower than this, the salt marsh creek is disconnected from the tidal channel. The described variation pattern remains the same, although accentuated during the storm (25/2). In this situation, water with relatively high concentrations (up to ≈ 150 mg/l), caused by the raised dynamic impact, enters the creek with the flood current (measured flood $Umax_{0.5m\ a.b.} = 0.84$ m/s). During high water slack a large part of this sediment settles out. Some, although a significantly smaller part, is resuspended at the beginning of the following ebb period. After this the concentration drops relatively quickly towards the minimum values at low water slack. A couple of hours before low water the current velocity reaches its tidal period maximum (measured ebb $Umax_{0.5m\ a.b.} = 1.01$ m/s). These temporal variations illustrate very well how turbid water through the creek inundates the salt marsh area, and is efficiently "cleaned" by deposition on its surface. For each of the analyzed tidal periods the transport weighted mean concentration Cm was calculated for the flood and the ebb period as: $Cm = U \cdot C / U$, where U and C are the corresponding discrete measurements of current velocity and concentration of suspended matter during the period in question. The transport values were estimated as $Cm \cdot P$, where P is the tidal prism estimated from the water levels and the hypsometric curve from Bartholdy (1983). The estimated net transport values (flood - ebb) shown in the lower part of Figure 9 indicate a total import of fine grained material over the monitored 4 days of 45 metric tons which corresponds to an estimated deposition in the tidal area of the creek of $5.3 \cdot 10^{-3}$ g/cm^2 or about 8% of the average yearly deposition in this part of the peninsula (see below). It is obvious that the major part of this deposition takes place during the two highest high tides associated with the storm, and that deposition is insignificantly small during calm weather periods. It is interesting, however, that the deposition associated with the two tidal periods just before the storm is not negligible compared with the storm deposition. Considering the much higher frequency of tidal periods associated with wind speeds of 10-15 m/s and a small set up, this type of tidal periods most likely plays an important role in relation to the deposition of fine grained material on the backbarrier salt marsh. The wind-induced increase in concentration is mainly considered to result from wave action on the mussel banks fringing the tidal channel, but could also be associated with episodes where import takes place from the North Sea. However, over-marsh tides that are not necessarily associated with these particular episodes could change the link between salt marsh deposition and the net import from the North Sea.Some episodes, therefore, may cause an import from the North Sea, while others may be capable of moving stored fine-grained material higher up onto the salt marsh surface. These processes are currently being investigated. The deposition of fine-grained material on the peninsula is illustrated in Figure 10 in form of a transect across the backbarrier (for location see Figure 1). The elevation of the transect was surveyed and its morphological components discussed by Nielsen & Nielsen (1973). Along the line, samples numbered 1-17, were collected and analyzed by Bartholdy (1983). Based on the topography, the transect can be divided into six parts. The inner part (0-450 m) is characterized by small eolian dunes and ridges which probably result from a combination of eolian activity and breaking waves. From here (450-650 m) the lowest parts of the outer (eastern-most) ridges are covered with salt marsh clay. In this region, and in the relatively high outer part around the sand ridge (1400 m) mentioned previously, the salt marsh formation started around the turn of the last century (Nielsen 1935). This left the central part of the peninsula (650-1400 m) as a poorly drained, algae covered saline sand flat. Its transformation into the present day fertile salt marsh was caused by improved drainage conditions produced by the rapidly back-eroding virgin salt marsh creeks. Beyond the sand ridge (1400-1550 m) the exposed part of the salt marsh is open to frequent wave erosion and deposition, amongst others also incorporating ice-rafted material, giving the surface an uneven appearance. East of the salt marsh the tidal flat (1550-1700 m) borders on the area governed by the tidal channel "Hobo Dyb" (>1700 m).

The typical median diameter of the salt marsh material in the central part of the peninsula is 4 µ. It consists of 40-45 % clay (< 2 µ), 40-55 % silt (2 µ - 63 µ), and 5-15 % sand (> 63 µ) and has a typical loss on ignition (550°C) of 10-20 %. According to Deyu (1987), the clay minerals consist of 57 % illite, 20 % kaolinite, 16 % chlorite and 7 % smectite. The accumulation of this fine-grained material is concentrated in a relatively narrow belt between 0.7 and 1.5 m DNN. Sand mingles with the fine-grained sediment at both margins and towards the boundaries the fines rapidly becomes less than 10 % of the total sample.

The rate of deposition is surprisingly uniform in the central part of the salt marsh area, amounting to 0.07 $\text{g}\cdot\text{cm}^{-2}\cdot\text{y}^{-1}$ or between 1.4 and 1.7 $\text{mm}\cdot\text{y}^{-1}$. This coincides with relatively low values of the environmental index shown above in Figure 10. This index was suggested in Bartholdy (1985) and relates the coarse siltfraction between 5phi and 7phi to the (in phi-units) twice as large fraction between 5phi and 9phi. This index is generally less than 0.6 in this area, indicating a calm depositional environment. In the inner and outer part, this index increases reaching over 0.7 in the innermost part which corresponds to the fact that deposi-tion here is exclusively associated with stormy periods and very high wind set-up. The relatively high deposition rate (1.6-3.2 mm/y), and corresponding low index-values (0.50-0.53) on the border between the inner and central part (#14 & #13) are partly associated with peat formation (the loss on ignition for sample 14 is 35 %), but partly remains problematical. It could be the result of some kind of "border effect", as it corresponds to the zone in which frequent smaller storms deposit long lines of debris ("havskarn"), revealing the location of the high water line. The present data, however, provide no evidence for such an effect.

The high deposition rate (4.0 $\text{mm}\cdot\text{y}^{-1}$) and index value (0.64) in the outer part of the salt marsh area reflect its location close to the tidal flat and indicate that the growth of this part of the salt marsh would, in time, seal off the inner part of the peninsula, unless the salt marsh creeks maintained the water exchange between the salt marsh and the rest of the tidal area.

A combined grain-size distribution of the backbarrier

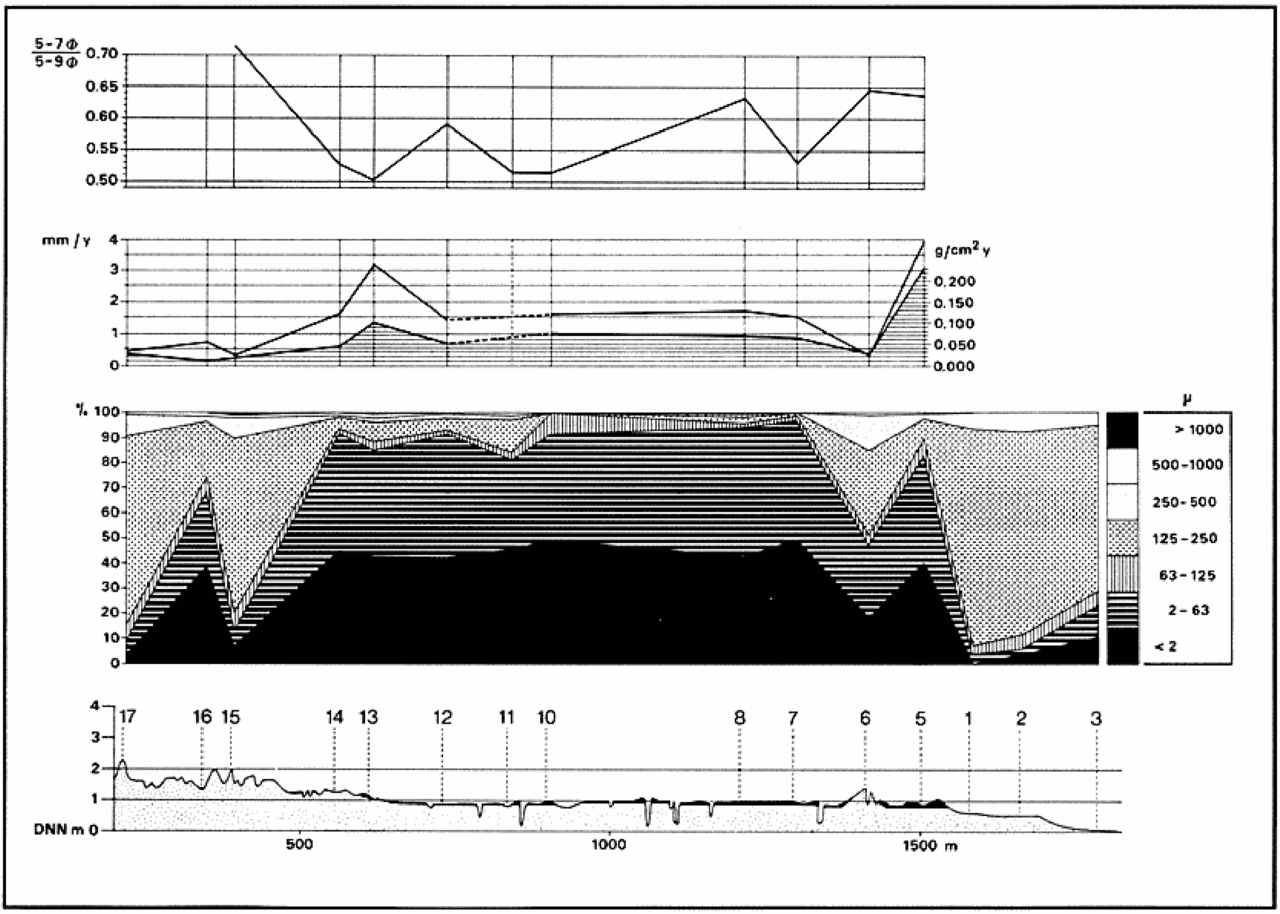

Figure 10: Topography, textural composition, deposition rates and environmental indices (5-7 phi/ 5-9 phi) in a transect across the backbarrier area of Skallingen. The topography is from Nielsen & Nielsen (1973). The numbers refer to sample numbers. For location see Figure 1. Modified after Bartholdy (1983).

deposits is constructed, based on the individual grain-size distributions, the deposition rates (in $g \cdot cm^{-2} \cdot y^{-1}$) and an estimated "representative" length of each sample in the transect. This procedure is considered to give a fairly accurate approximation of the average material depositing on the backbarrier. It consists of 15% sand, 46 % silt and 39% clay with a combined deposition rate of 0.07 $g \cdot cm^{-2} \cdot y^{-1}$. The distribution is shown in Figure 11. The relatively high sand content is due to the sandy samples from the inner most section. The sand deposited here is most likely reworked from the small eolian dunes and ridges present in this area. The silt fraction of this distribution, truncated at 4 phi and 9 phi, is shown in a spline approximation in Figure 12 where also 5 decomposed log-normal distributions and the combined result of the decomposition are shown. The statistical parameters and the size of the subdistributions are shown in Table 5.They reveal two significant coarse silt populations G and H constituting 70 % of the distribution. The coarse F population and the two fine I and J populations, are most likely artifacts owing their existence to the truncated distributions and the dispersion of the finest material. The distribution of the dispersed finest part is most likely of no sedimentological significance. Material finer than 7 phi (0.008 mm) will settle less than 20 cm during one our in motionless water of a temperature of 20°. Particles of this size are therefore not likely to settle out as single particles, but only as part of flocks. The size of the two fine distributions, however, indicates the content of fine silt smaller than ≈ 7 phi. Thus, this analysis, much better founded than the relatively crude analysis of the same kind conducted in Bartholdy (1985), confirms that a distinguishing between the silt content finer and coarser than 7 phi is justified in the grain-size distributions. In addition to this, a reanalysis of the two principal mud samples used as examples in Bartholdy (1985), confirms the results. A log-normal decomposition of these two samples: clay from C8 (Fig.1) and a sample of mud from the shell banks along the tidal channel "Hobo Dyb" (Table 5), shows that apart from adjustments of the sorting coefficient (a better sorted H-population in both samples and a less sorted G-population of the mud from the shell banks) the G and H-populations have the same mean grain-size as they have in the "mean sample". Thus, the fine grained material on the backbarrier of the Skallingen peninsula, is, in its dispersed form, found to consist of two log-normal distributions, G (Md: 5.4 phi or 0.024 mm; Sd: 0.60-0.74 phi) and H (Md: 6.8 phi or 0.009 mm; Sd: 0.45-0.61) plus a finer grained fraction constituting 1/3-1/2 of the fine-grained material.

Based on two ^{210}Pb-dated sediment cores from Bartholdy & Madsen (1985) the deposition rate is observed to increase at approximately the same distance from the tidal flat when approaching the inner part of the tidal area: C8: 2.5 $mm \cdot y^{-1}$ C7: 4 $mm \cdot y^{-1}$; for location see Figure 1. This is a natural phenomenon. Even though the turbidity maximum in this tidal area is relatively small, mudflat areas are present in the innermost part (Bartholdy & Folving 1986), reflecting a common pattern in environments of this type, which consistently show raised concentrations of fine-grained sediment in the inner parts of tidal areas.

The core "C7" is illustrated in Figure 13. The X-ray negative (light colours = high density) and the measured variation in dry density (based on cubes cut from the sediment core, with measurable side lengths) correspond fairly well with each other and correlate, to some extent, with the storm surge activity shown to the right in Figure 13. This is based on statistics placed at disposal by the

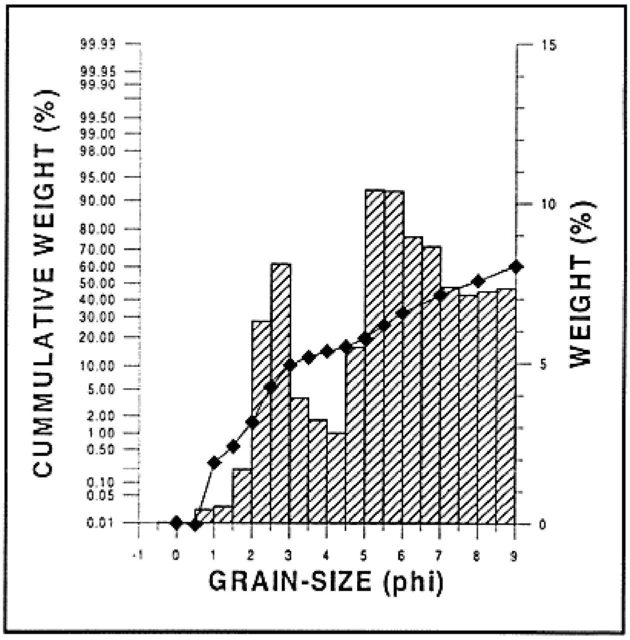

Figure 11: Average grain-size distribution of the material depositing on the backbarrier of Skallingen. The cumulative distribution curve is marked with diamonds, the bars show the distribution based on ½-phi fractions. Material finer than 6 phi is analyzed with 1-phi steps. The ½-phi fractions are here constructed based on interpolation of the cumulative curve on probability plot.

Table 5: Deconvolution of the grain-size distributions of three typical fine-grained sediments into log-normal sub-populations. Only the silt fraction is considred. The sub-populations are described by their mean grain size (Mz) and standard deviation (Sd) the fraction (%) indicate the single populations share of the silt fraction.

Environment	*Pop. F*			*Pop. G*			*Pop. H*			*Pop. I*			*Pop. E*		
	Mz phi	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz phi*	*Sd phi*	*Frac. %*	*Mz Phi*	*Sd Phi*	*Frac. %*
Average backbarrier deposition	4.25	0.20	2	5.40	0.60	40	6.77	0.61	30	8.00	0.50	19	8.71	0.29	10
Salt marsh C8			0	5.40	0.60	39	6.77	0.45	25	8.00	0.50	24	8.71	0.29	13
Mud from shell banks			0	5.40	0.74	30	6.77	0.45	27	8.00	0.50	35	8.71	0.29	11

harbour authorities in Esbjerg. The correlation improves a little, when the dates are corrected for sediment compaction (circles; see below). However, the exactness of the dates should be improved in order to go into further details with respect to an interpretation of relations between the hydrodynamic conditions and the sediment type. The variations in dry density seem to be well correlated with the the organic content, as indicated by the loss in ignition curve. No doubt, some of the light layers owe their existence to sand in the sediment column (note the visible light sand layer 16.5 cm from the top). In general, however, variations in the sand content do not seem to have any pronounced effect on the density of the salt marsh clay, this being primarily controled by the content of organic matter (Figure 14). The surface samples from the transect across the backbarrier have been fitted to a power function with the following result:

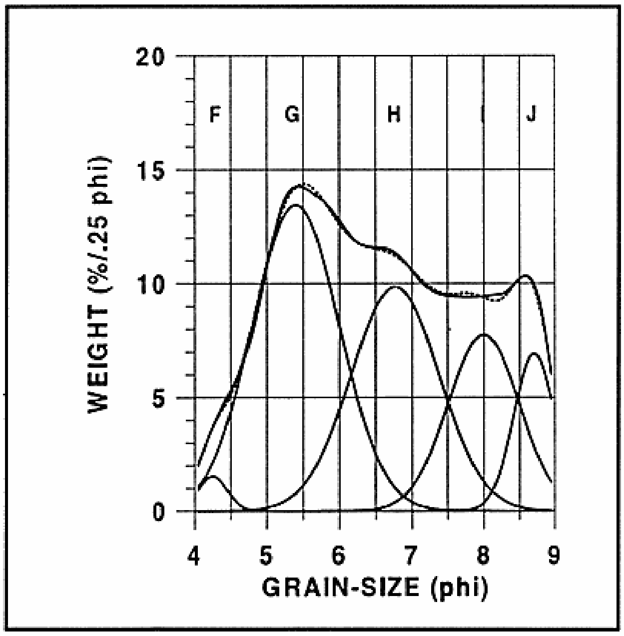

Figure 12: Decomposition of the silt fraction of the grain-size distribution shown in Figure 11 into overlapping log-normal distributions. The dotted line represents the composite (constructed) curve.

$$D = 4.47 \cdot O^{-0.81};\ 10>O>50\ ;\ r=0.98$$

where D is the dry density in g/cm^3 and O is the loss on ignition in %. The data from the sediment core (crosses) show the same type of relation but with a somewhat higher density level, presumably as a result of compaction.

The compaction is illustrated by the thin dotted line in Figure 13. It represents a log/log transformed linear regression between depth and dry density, based on the depth interval 0.5-32.5 cm:

$$D = 0.58 * X^{0.17}\ ;\ r=0.70$$

where D is the dry density in g/cm^3 and X is depth in cm.

Integrating this equation from X_1 to X_2 below the sediment surface and dividing the integral with the length between X_1 and X_2, gives the following expression of the mean density between X_1 and X_2:

$$\overline{D_{X_1-X_2}} = (X_2-X_1)^{-1} \cdot \int_{X_1-X_2} 0.58 \cdot X^{0.17}\, dX = 0.50 \cdot [X_2^{1.17} - X_1^{1.17}] \cdot (X_2-X_1)^{-1}$$

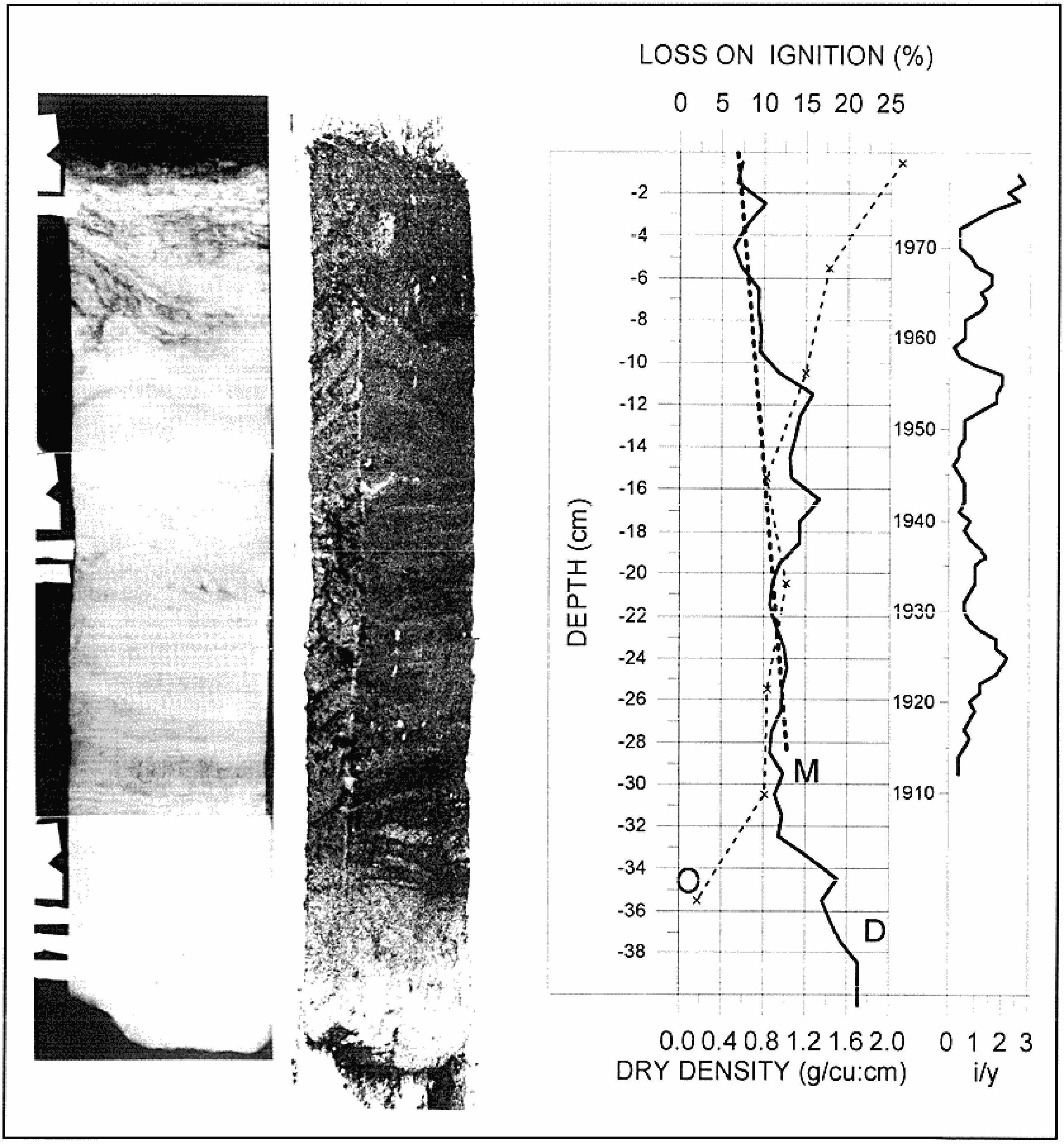

Figure 13: *X-ray photo (left) of core C7 (for location see Figure 1) from the northern part of the backbarrier. In the meddle a traditional photo of the same core was fitted to the correct length. To the right: B) Loss on ignition (0), dry density (D) and years of deposition, based on a constant deposition rate of 4.0 mm/y (Bartholdy & Madsen 1985). To the right a 5 years running mean of the number of incidents per year with high water levels above 2.4 m DNN (Danish Ordnance Datum) at the harbour of Esbjerg. The thin dotted line, represents a power function between depth (X in cm) and the dry density, D (g/cm^3), based on the depth interval 0.5-32.5 cm: $D = 0.58 X^{0.17}$. Years corrected for compaction are illustrated with circles, and corresponds to the nearest indicated year on the arithmetic scale to the right.*

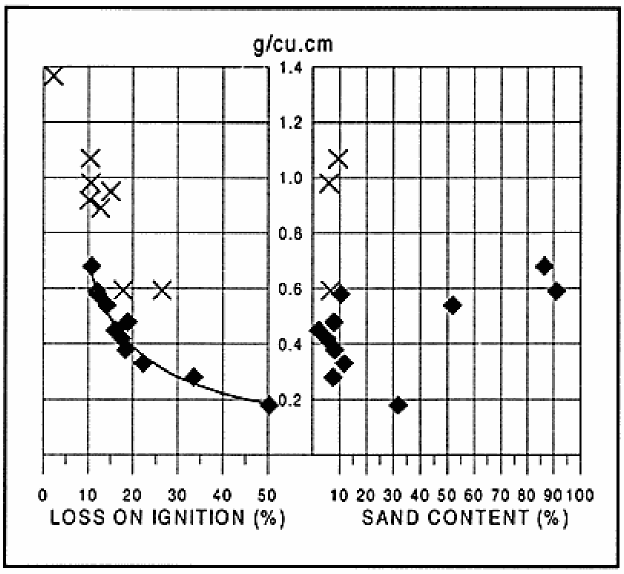

Figure 14: Dry density as a function of loss on ignition (left) and sand content (right) for salt marsh clay from the backbarrier of Skallingen. The diamonds show the results of surface samples from the transect across the backbarrier (Figure 10). They are fitted to a power function between loss on ignition (O in %) and the dry density, D (g/cm^3): $D = 4.47.O^{-0.81}$ shown to the left. The crosses are from samples of the sediment core shown in Figure 13.

From observations of the clay accumulating on top of the coloured sand flats established by Nielsen (1935), the compaction of the salt marsh clay was described by Jakobsen (1948-50). He found that, on the average the compaction (shrinking) of the clay, over 16 years changed a yearly sedimentation of 3.6 mm (5.8 cm) into an increase in the elevation of 2.6 mm/y (4.2 cm). This is eqvivalent to a density increase from an assumed surface density of approximately 0.5 g/cm^3 in the top layer into an average density of 0.69 g/cm^3 in the deposited 4.2 cm. Using the equation stated above, the coresponding dry density is 0.64 g/cm^3 and thus in reasonable good agreement with Jakobsen's results. Integrating this equation from 0.5 to 30.5 cm (the lover dating limit of Core C7), gives a mean density of 0.90 g/cm^3. With an average deposition rate of 4.0 mm/y this is equivalent to an average deposition of 0.36 g/cm^2/y. Holding this rate constant and using the above stated equation as a measure of the compaction from 0.5 cm and downward, the 10-year spacing changes from the arithmetic scale into the scale indicated by the circles on the depth/density curve (Figure 13).

Summary and Conclusions

The Skallingen peninsula is made up of sand derived from the south-going littoral drift along the North Sea coast. The backbarrier has accumulated sand as a result of wash-over deposits. Fine-grained sediment started to cover the surface in form of salt marsh deposits at the beginning of the 20th century.

The sand on the peninsula consists primarily of fine sand comprising mean grain sizes of 2.5-2.25 phi (0.177-0.210 mm), subangular quarts grains, and fall velocities corresponding to a shape factor of 0.5-0.7. The grain-size distributions can be described by means of overlapping log-normal distributions with an almost perfect match. The statistical parameters of the most common five distributions A, B, C, D & E (decreasing grain-size order), are shown in Table 6. Changes in the main distributions of the sand from the wash-over deposits, over the tidal flat and salt marsh creek environments, to the sand deposited on the salt marsh follows a logical pattern, as illustrated in Figure 15.

The typical wash-over sand is made up of a dominating C-population (Md: 2.44 phi or 0.184 mm; Sd: 0.28 phi) and a relatively large secondary D-population (Md: 2.90

Population	***Mean Grain Size***						***Standard Dev.***		
	phi			***mm***			***phi***		
A	1.30	-	1.50	0.406	-	0.354	0.20	-	0.40
B	1.70	-	1.94	0.308	-	0.261	0.14	-	0.18
C	2.32	-	2.55	0.200	-	0.171	0.20	-	0.28
D	2.70	-	2.90	0.154	-	0.134	0.18	-	0.31
E	3.24	-	3.49	0.106	-	0.089	0.15	-	0.30

Table 6: *Typical grain-aize distribution parameters of separated log-normal populations from grain-size distributions of sand from the Skallingen peninsula.*

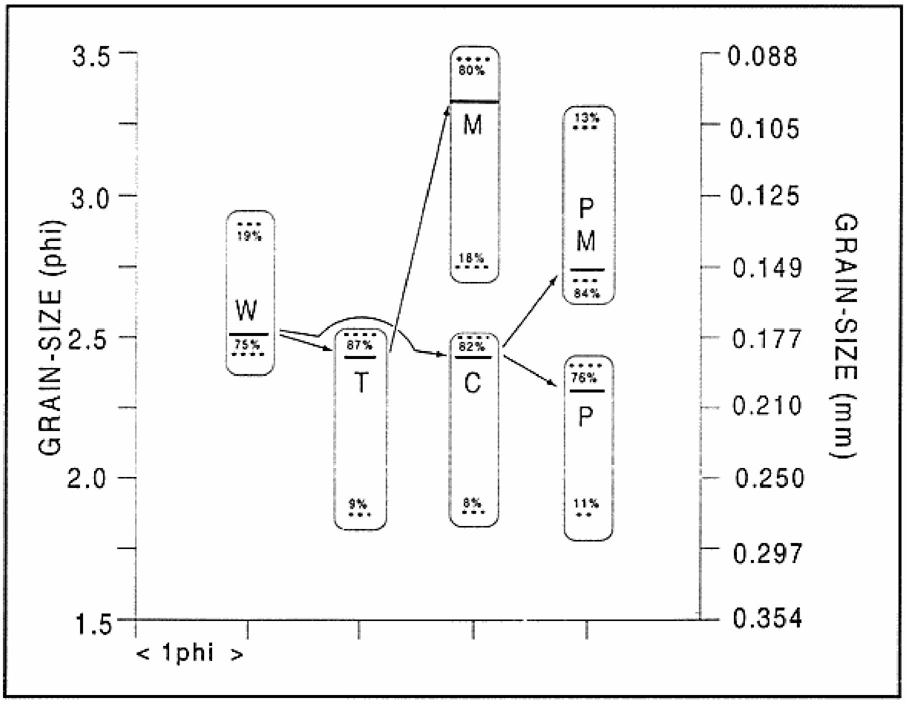

Figure 15: *Grain size (level of bars) and sorting (width of bars) of the two principal log-normal distributions (dotted line) and their combination (solid line) in typical sand types from the depositional environments of Skallingen. The percentages indicate the content of the sub-population relative to the whole sample. W: wash-over sand; T: tidal flat sand; C: creek bottom sand; M: sand in the exposed part of the salt marsh; P: point bar sand; PM: sand in the salt marsh on point bar.*

phi or 0.134 mm; Sd: 0.18 phi), with a combined mean grain size close to or slightly over 2.5 phi (0.177 mm).

Exposed to waves in the tidal flat environment and to tidal currents in the salt marsh creek environment, the finest fractions are winnowed from the sand which loses the D-population and develops a dominating C-population with a coarse tail. The C-populations in these two environments are practically identical (Md: 2.50-2.51 or 0.177-0.176 mm; Sd: 0.25-0.26 phi), as are the coarse tail B-populations (Md: 1.87-1.88 phi or 0.272-0.274 mm; Sd: 0.17). Together they make up more than 90% of the sand in these environments with a combined mean grain size of 2.43 phi (0.185 mm). The most prominent sandy depositional units in the salt marsh creek environment are represented by the point bars. Here the C-population is sorted and changed into a relatively coarse version (Md: 2.40 phi or 0.189 mm; Sd: 0.23 phi) with a very pronounced coarse tail represented by the same B-population as described above, plus an equal amount of coarser material. Thus, apart from the channel lag deposits, the basal parts of the point bars represent the coarsest sands deposited in the backbarrier environment. On the point bars, new salt marsh deposits with a relatively large sand content are formed in the highest parts. This sand is made up of a dominating D-population (Md: 2.70 phi or 0.154 mm; Sd: 0.22) and a subordinate E-population (Md: 3.24 phi or 0.106 mm; Sd: 0.23), opposite to the sand in the wave exposed parts of the salt marsh with a dominating E-population (Md: 3.48 phi or 0.090 mm; Sd: 0.28 phi) and a subordinate D-population (Md: 2.75 phi or 0.149 mm; Sd: 0.30 phi).Both these sand types, however, represent the winnowed sand from the two sandy backbarrier environments (the salt marsh creeks and the tidal flats) and, with their relatively fine-grained character, complete in this way the sedimentological story of sand dispersal in the backbarrier environment.

When the backbarrier sand reaches the approximate mean high water level (0.7-0.8 m DNN), salt marsh plants become abundant and generate the necessary conditions for the deposition of fine-grained sediments which are primarily derived from the North Sea. The typical median diameter of the salt marsh material in the central part of the peninsula is 4 μ. It consists of 40-45 % clay (< 2 μ), 40-55 % silt (2 μ - 63 μ), and 5-15 % sand (> 63 μ), and has a typical loss on ignition (550°C) of 10-20 %. The clay minerals consist of 57 % illite, 20 % kaolinite, 16 % chlorite and 7 % smectite.

The concentration of fine-grained material in the water entering the salt marsh creeks, depends on the weather conditions. In calm weather, the concentrations in the

central large creek are low (typical values between 5 and 50 mg/l). In rough weather, the wind set-up causes the salt marsh surface to be inundated and relatively turbid water to enter from the adjacent tidal areas (100-≈150 mg/l). This material is deposited on the salt marsh surface during high water slack and only a minor part is resuspended in the subsequent ebb-period. The accumulation of the fine-grained material is concentrated in a relatively narrow belt between 0.7 and 1.5 m DNN. The deposition rate is observed to increase from south to north, when approaching the inner part of the tidal area. In a cross-section of the central part of the Peninsula, the rate of deposition is found to be surprisingly uniform between 1.4 and 1.7 $mm \cdot y^{-1}$. This coincides with relatively low values (in general less than 0.6) of the environmental index (Bartholdy 1985). In the outer part of the central salt marsh area the deposition rate is relatively high (4.0 $mm \cdot y^{-1}$).

The grain-size distribution of the average material depositing on the backbarrier in the central part of the peninsula consists of 15% sand, 46 % silt and 39% clay with a corresponding deposition rate of 0.07 $g \cdot cm^{-2} \cdot y^{-1}$. The relatively high sand content is most likely due to reworked sand from aeolian dunes in the central part of the peninsula. The fine-grained material (< 4 phi) is found to consist of two log-normal distributions G (Md: 5.4 phi or 0.024 mm; Sd: 0.60-0.74 phi) and H (Md: 6.8 phi or 0.009 mm; Sd: 0.45-0.61) plus a finer grained fraction constituting 1/3-1/2 of the sediment.

The density of surface samples of the salt marsh was fitted to a power function:

$$D = 4.47 \cdot O^{-0.81};\ 10>O>50\ ;\ r=0.98$$

where D is the dry density in g/cm^3 and O is the loss on ignition in %.

An example of the compaction in the innermost relatively fast growing salt marsh (4 mm/y) was fittet to a power function:

$$D = 0.58 * X^{0.17};\ 0.5>X>32.5\ ;\ r=0.70$$

where D is the dry density in g/cm^3 and X is depth in cm.

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