

Evidence for sediment recirculation on an ebb-tidal delta of the East Frisian barrier-island system, southern North Sea

Chang Soo Son · Burghard W. Flemming ·
Alexander Bartholomä

Received: 25 August 2009 / Accepted: 18 August 2010 / Published online: 14 September 2010
© Springer-Verlag 2010

Abstract The Otzum ebb-tidal delta, located between Langeoog and Spiekeroog islands along the East Frisian barrier-island coast, southern North Sea, was investigated with respect to its morphological evolution, sediment distribution patterns and internal sedimentary structures. Bathymetric charts reveal that, over the last 50 years, the size of the Otzum ebb-tidal delta has slightly shrunk, while sediment has accreted on the ebb-delta lobe to the east of the main inlet channel (west of Spiekeroog). Swash bars superimposed on the eastern ebb-tidal shoal (Robben Plate) have migrated south or south-eastwards, i.e. towards the inlet throat. The main ebb-delta body is composed of fine quartz sand, whereas the superimposed swash bars and the inlet channel bed consist of medium-grained quartz sand containing high proportions of coarser bioclastic material. Internal sedimentary structures in short box-cores (up to 30 cm long) are dominated by flood-oriented cross-beds. Longer vibro-cores (up to 1.5 m long) show that, at depth, the sediment is dominated by storm-generated parallel (upper plane bed) laminations with intercalated shell layers and dune cross-bedding. The cross-bedded sands in both box-cores and vibro-cores from the ebb-delta shoal predominantly dip towards the south or southeast, indicating transport towards the inlet throat by the flood current. The observations demonstrate that, contrary to previous

contentions, the sediments of the highly mobile swash bars do not bypass the inlet but are instead being continually recirculated by the combined action of tidal currents and waves. In this model, the cycle begins with both fine and medium sands, including shell hash, being transported seawards in the main ebb channel until they reach the shallow ebb-delta front. From here, the sediment is pushed onto the eastern ebb-delta shoal by the flood current assisted by waves, becoming strongly size-sorted in the process. The medium sands together with the shell hash are formed into swash bars which migrate along arcuate paths over a base of fine sand back to the main ebb channel located south of the ebb delta. By the same token, the fine sand between the swash bars is transported south-eastwards by the flood current in the form of small dunes until it cascades into the large flood channel located to the west of Spiekeroog. From here, the fine sand is fed back into the main ebb channel, thus completing the cycle. No evidence was found on the ebb delta for alongshore sediment bypassing.

Introduction

Tidal inlets along barrier coastlines throughout the world show a high diversity in morphology, hydraulic signature and sediment transport patterns (e.g. Barwis 1976; Weishar and Fields 1985; Buynevich and FitzGerald 2003). Ebb-tidal deltas are usually part of such inlet systems with sediment accumulating on the seaward side of the tidal inlets (Hayes 1980). In general, ebb-tidal deltas are best developed along mixed energy, tide-dominated (upper mesotidal) coasts ($2.0 < TR < 3.5$ m; TR, tidal range), whereas well-developed flood-tidal deltas occur preferentially along mixed energy, wave-dominated (micro- and

C. S. Son (✉)
Faculty of Earth System & Environmental Sciences,
Chonnam National University,
77 Yongbong-ro, Buk-gu,
Gwangju 500-757, South Korea
e-mail: senlab@hanmail.net

C. S. Son · B. W. Flemming · A. Bartholomä
Department of Marine Science, Senckenberg Institute,
Suedstrand 40,
26382 Wilhelmshaven, Germany

lower mesotidal) coasts ($TR < 2.0$ m; Nummedal et al. 1977; Nummedal and Fischer 1978; Davis and Hayes 1984; FitzGerald et al. 1984). Moreover, a close relationship exists between inlets and ebb-tidal deltas regarding evolution, morphodynamics and sediment transport. The morphodynamic behaviour of inlet systems and ebb-tidal deltas has been studied by, amongst others, Hayes (1975), Luck (1975), FitzGerald et al. (1984), Eitner (1996), Hicks and Hume (1997), Balouin and Howa (2002), Burningham and French (2006), Elias and van der Spek (2006) and van Heteren et al. (2006), and sediment transport patterns along the periphery of inlets have been assessed by, for example, Oertel (1972), Hanisch (1981), Nummedal and Penland (1981), Sha (1989a, 1989b), Vinther et al. (2004) and Cheung et al. (2007). It has furthermore been demonstrated that ebb-tidal delta sand volume is dependent on the volume of the tidal prism (e.g. Walton and Adams 1976; Kana and Mason 1988; Sha and Van den Berg 1993; Hughes 2002; Powell et al. 2006), whereas sediment movement on ebb-tidal deltas and along their periphery is driven by tidal currents and waves (Powell et al. 2006). In addition, sediment transport rates on ebb-tidal deltas and in associated inlet systems have been calculated by means of numerical models (e.g. Özsoy 1986; Kana et al. 1999; van de Kreeke 2006). Many of these studies have suggested that sediment bypassing is the most characteristic feature of inlet systems, whereby sediment supplied by alongshore transport is delivered to the up-drift side of an inlet, from where it is transported across the ebb delta towards the down-drift side and onwards along the coast (e.g. FitzGerald 1984, 1988, 1996). Indeed, sediment bypassing appears to be the most widely accepted model, only a few studies challenging this concept—e.g. Tanner (1987) for the Gulf coast of Florida; Hanisch (1981) for the Harle ebb delta and Flemming and Davis (1994) for the Otzum ebb delta, both located along the southern North Sea coast of Germany; Smith and FitzGerald (1994) for the Essex River inlet along the coast of Massachusetts, USA; and Sha (1990) and Elias et al. (2006) for the Texel inlet along the coast of The Netherlands.

Based on aerial photographs of the upper mesotidal East Frisian barrier islands along the southern North Sea coast of Germany, inlet sediment bypassing had initially been postulated to proceed in the form of swash bars fed by sediment from the up-drift shore, migrating along the periphery of the ebb-delta terminal lobes towards the down-drift shore (Homeier and Kramer 1957; Lüders et al. 1972). Using the same data, this interpretation was subsequently propagated by Nummedal and Penland (1981) and FitzGerald et al. (1984). Alternative viewpoints challenging the bypassing model in this region were offered by Hanisch (1981), Ehlers (1984) and Flemming and Davis (1994). These mutually exclusive interpretations warranted

a closer in-situ examination of sediment transport directions on the ebb deltas of the East Frisian barrier-island system. The objectives of the present study thus were to document the sedimentary and morphodynamic characteristics of an inlet of this system and to reconstruct sediment transport pathways on the basis of historical maps, modern nautical charts, sediment distribution patterns and internal sedimentary structures.

Study area

The Otzum inlet (Fig. 1) is located between the East Frisian islands of Langeoog and Spiekeroog. The study area has a semidiurnal mesotidal regime with a mean tidal range of 2.8 m and a tidal prism of about 114×10^6 m³ (Walther 1972; Postma 1982). The tidal wave approaches from the west and rotates counter-clockwise around an amphidrome located in the central North Sea (Huntley 1980). Seaward of the inlet is an ebb delta covering an area of over 20 km², dissected by a large ebb channel in the centre, two marginal flood channels, and numerous smaller tidal channels located between the swash bars superimposed on the ebb delta (Fig. 1, upper panel). Maximum current velocities in the inlet during calm weather reach 0.7–1.3 m s⁻¹ (Davis and Flemming 1995). In general, the ebb phase is of shorter duration and the current hence slightly stronger than during the flood phase. An analysis of local wind data reveals that a twofold increase in the frequency and a fourfold increase in the duration of winds exceeding 6 Bft have occurred in the German Bight since 1989, a situation which has persisted to the present day. Strong winds of 6–7 Bft are not restricted to the stormy winter months, but can occur throughout the year (Tilch 2003). In addition, the frequency of winter storms has increased significantly in the second half of the last century. The more severe storms generally approach from the west or northwest. In the year 2005, storms were associated with elevated water levels reaching 3 m above mean high tide at the gauge station on the island of Norderney (Fig. 2, upper panel; NLWKN 2006), but storm surge simulations (Bork et al. 2005) predict potential water levels of up to 4 m above mean high tide at Norderney (Fig. 2, lower panel).

Land reclamation along the East Frisian mainland coast has partly resulted in dramatic reductions of the tidal prisms of individual tidal basins over past centuries. The only exception is the tidal catchment draining through the Otzum tidal inlet. The reason for this opposing trend is the geometry of the mainland coast to the east of the Otzum catchment produced in the wake of the severe storm surge of 1362, in the course of which the so-called Harle embayment was excavated (Flemming and Davis 1994). This embayment, which once extended >10 km into the

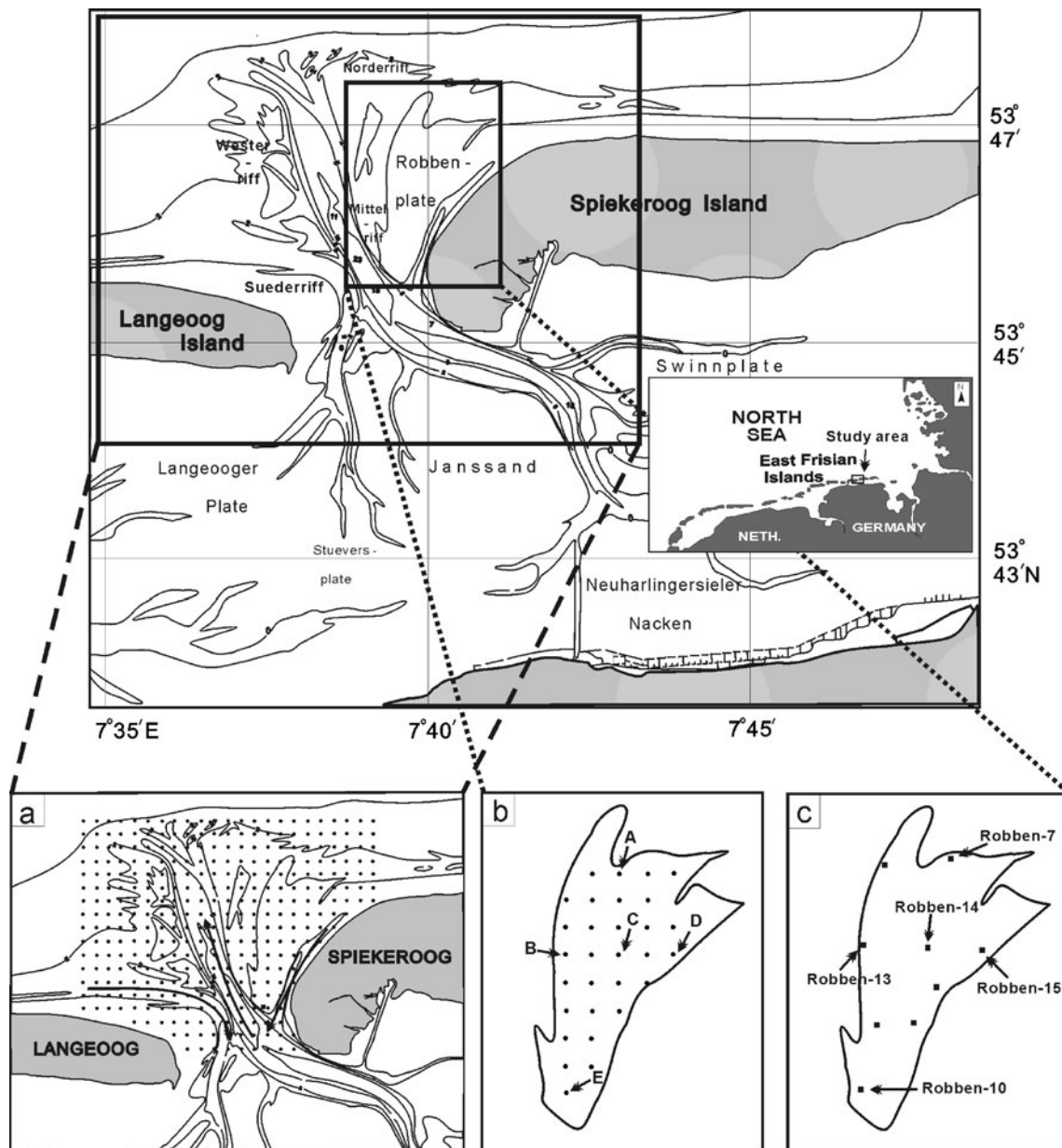


Fig. 1 Location map of the study area (0 m water depth=mean spring-tide low water level; depth contours in meters), showing **a** surface sediment sampling stations, **b** box-coring stations and **c** vibro-coring stations

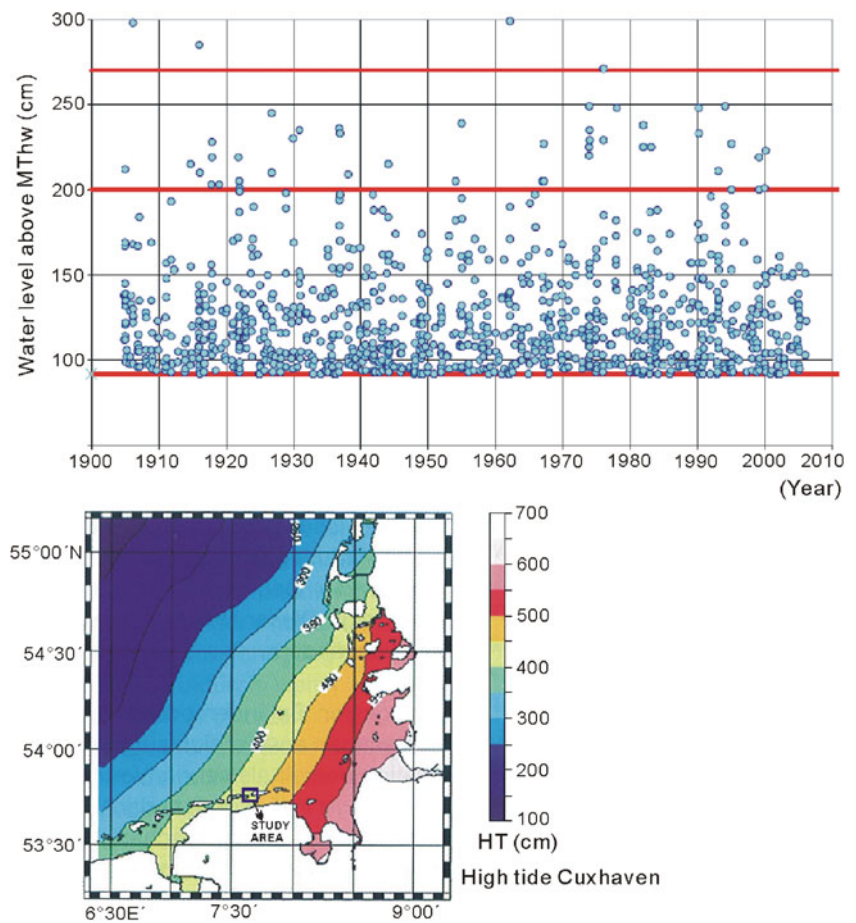
hinterland, was progressively reclaimed in later centuries, the modern dike line having been completed in 1960. After the AD 1362 storm surge, the eastern tidal divide of the Otzum tidal basin was attached to the western margin of the Harle embayment, which itself drained through the Harle inlet located to the east of Spiekeroog. During reclamation, the island of Spiekeroog doubled in length towards the east, as a result of which the eastern tidal divide of the Otzum catchment also migrated eastwards, thereby progressively increasing its catchment area and, hence, the tidal prism. The largest step was evidently accomplished between 1841 and 1860, as reflected by the massive growth of the ebb

delta (Fig. 3) in response to the sudden increase in tidal prism (Flemming and Davis 1994). Since then, the area of the Otzum catchment has remained essentially unchanged.

Materials and methods

Altogether, 333 sediment samples were collected on the ebb-tidal delta on a regular grid defined by constant geographic intervals (0.15' latitude and 0.25' longitude) in the course of three field campaigns between August and October 2005 (Fig. 1a). In the deeper subtidal areas, the

Fig. 2 Storm surge information for the southern North Sea. *Upper panel* Storm surge heights (in cm) measured at the Norderney water-level gauge since 1900 (NLWKN 2006); *lower panel* predicted maximum water levels associated with a north-westerly storm surge (after Bork et al. 2005)

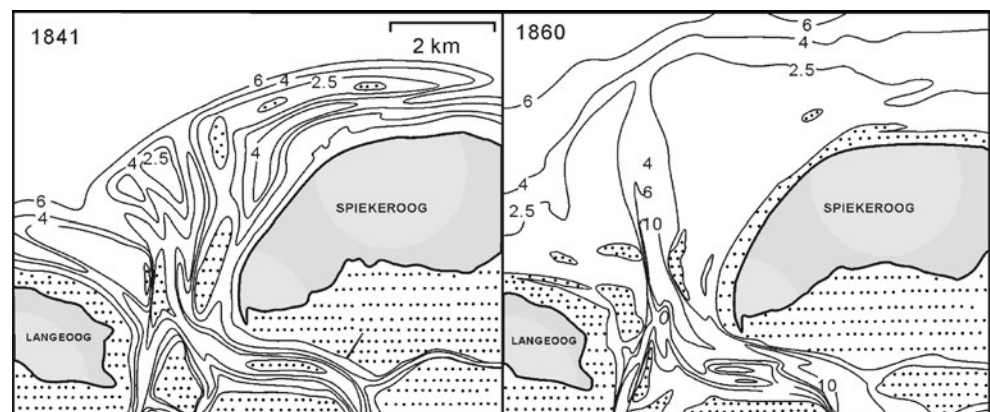


material was collected by means of a Shipek grab sampler deployed from the RV *Senckenberg*, positions being fixed by a Thales Aquarius 5,000 LRK (Long Range Kinematic) DGPS (accuracy <1 m). The intertidal and shallow subtidal areas were sampled at about high tide from a shallow-draught motorboat using a small, hand-operated van Veen grab, the positions being fixed by means of a handheld GPS in this case (accuracy ca. 3 m). Equivalent grain-size distributions of the sediment samples were determined by a high-resolution settling tube (Brezina 1986; Flemming and

Ziegler 1995), after having been processed according to standard laboratory procedures (Carver 1971). Textural parameters were calculated on the basis of percentile statistics defined in Folk and Ward (1957).

In addition, 60 short box-cores (up to 28 cm long) and nine vibro-cores (up to 1.72 m long) were recovered on the ebb-tidal shoal at low tide. In each case, five cores are described in the present study (for locations, see Fig. 1b, c). The boxes (5-l metal canisters) had a rectangular plan shape of 15×8 cm and a height of 30 cm. After draining excess

Fig. 3 Ebb-tidal delta growth and deepening of the Otzum inlet between 1841 (*left*) and 1860 (*right*), due to a substantial increase in the tidal catchment area (modified after Flemming and Davis 1994)



pore water, the boxes were laid flat and cut open lengthwise on both sides (30×15 cm). A ca. 5-cm-thick sand layer was then removed to avoid potentially disturbed sediments near the box walls. The exposed section was planed off and dried overnight in an oven at 80°C. After drying, epoxy peels were made by pouring a resin-hardener mixture on the planed sediment until the entire surface was soaked. The boxes were then placed in an oven and left to cure at 100°C. The sectioned vibro-cores were cut in half lengthwise and left overnight to partially dry in air. Epoxy peels were then made by applying the pouring method of Reineck (1970), using a resin-hardener mixture able to cure in partly wet sediment, and exposed to the air. Once cured, the epoxy peels of both the box-cores and the vibro-cores were photographically documented and then described in detail, giving particular attention to physical and biogenic sedimentary structures. Dip directions of the larger-scale cross-beds were determined on the basis of core orientations in the field, the compass readings having been marked on the boxes and core pipes before extraction. The measurement of dip directions of sedimentary structures or bedforms for the purpose of reconstructing flow and sediment transport directions is a common procedure in sedimentary research (e.g. Hanisch 1981; Sha 1990; Smith and FitzGerald 1994; Eitner 1996).

The evolution of the Otzum tidal basin was reconstructed on the basis of historical charts dating back almost

400 years. The shorter-term morphodynamics of the Otzum ebb-tidal delta was determined by comparing nautical charts from 1955 to 2005. Four of these were digitized with MapViewer 7 (Golden Software™) before being analysed for erosion/accretion tendencies using the software program Surfer (Golden Software™), and applying the ‘triangulation with linear interpolation gridding method’ (Lee and Schachter 1980). In addition, very short-term local topographic changes were monitored by three levelling surveys along an east–west transect on the eastern ebb-delta lobe (Robben Plate) in June 2006, January 2007 and April 2007, using a theodolite in combination with a portable GPS.

Results

Morphological changes

An interesting phenomenon of the inlet systems of the East Frisian Wadden Sea is the oscillating rotational motion performed by the large ebb channels feeding the ebb deltas. This is illustrated for the period 1955–2005 by the four bathymetric charts in Fig. 4 (note that the 0 m depth contour corresponds to the mean spring low-tide level). From 1955 to 1988, the direction of rotation was counter-

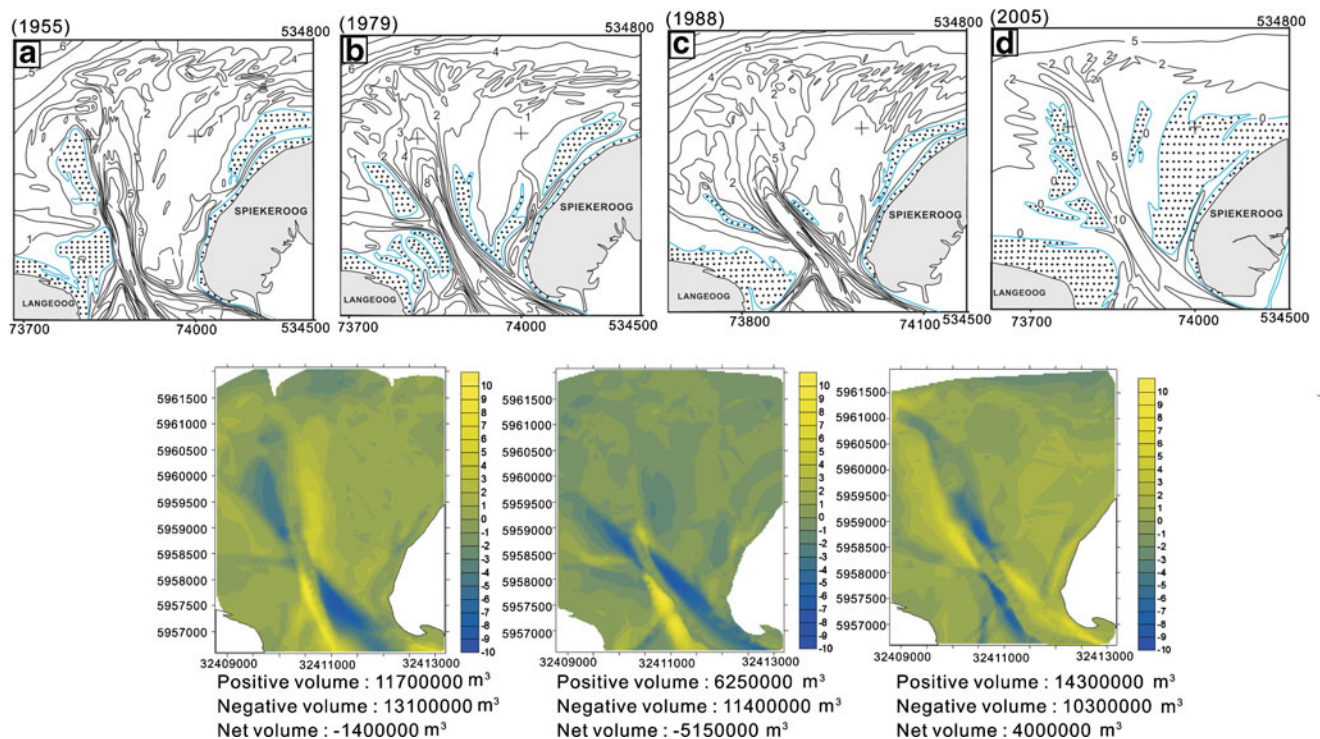


Fig. 4 Topographic and associated volume changes of the ebb-tidal delta in the course of the last 50 years. *Upper panels* Bathymetric charts of the Otzum ebb-tidal delta and inlet located between the

islands of Langeoog and Spiekeroog: *A* 1955, *B* 1979, *C* 1988, *D* 2005. *Lower panels* Volume changes calculated for the individual time intervals on the basis of the digitized maps

clockwise. At the same time, the ebb delta changed its shape from strongly asymmetrical to more symmetrical, accompanied by lateral expansion and lowering of the ebb-delta surface to below chart datum, and the almost complete disappearance of intertidal swash bars. From 1989 to 2005, the rotational direction switched to clockwise, accompanied by a deepening and lengthening of the main channel, and a return to a more asymmetrical shape of the ebb delta. At the same time, strong vertical accretion of sediment occurred above chart datum on both the western and particularly the eastern ebb-delta lobes. This pattern suggests that channel rotation is accompanied by pronounced sediment redistribution processes affecting both ebb-delta shape and elevation.

In order to obtain some indication of the overall sediment volume budgets in the course of channel rotation, successive bathymetric maps were volume-balanced, the resulting negative or positive volumes indicating sediment losses or gains (Fig. 4, lower panels). Although this method is not very precise, it is considered accurate enough to reflect the general tendency. The results suggest that an overall loss of sediment occurred in the period from 1955–1988, which is consistent with the observed flattening of the ebb delta (cf. below). From 1988 to 2005 the situation reversed, the calculated net sediment gain being also reflected in the vertical accretion visible on the 2005 chart. Considering the restricted area of observation, as well as the relatively short time spans and small sediment volumes involved in net loss or gain, it is unclear whether any sediment was actually exported from or imported to the ebb delta in the 50-year period covered by the bathymetric surveys. It would appear more plausible that we have merely been witnessing larger-scale redistribution processes on the ebb delta in response to changing hydrodynamic conditions and involving a somewhat larger area than covered by the present volume balance.

The high mobility of the ebb-delta sands is well documented by the results of the three levelling surveys

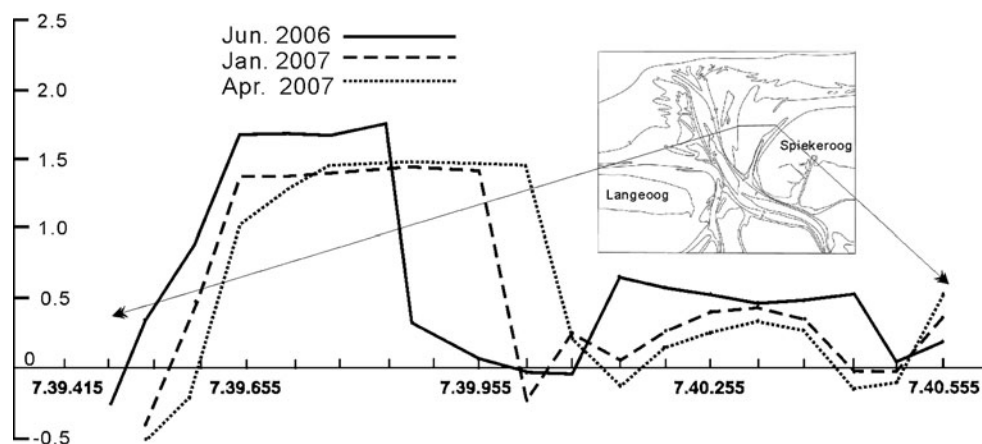
in the central part of the Robben Plate in the 10-month period from June 2006 to April 2007 (Fig. 5). The transect crosses two swash bars which, from west to east, were initially about 1.6 and 0.6 m high, and ca. 300 and 400 m wide respectively in June 2006. The large swash bar in the west was distinctly more asymmetrical than the one in the east, both being composed of cross-bedded medium sand with intercalated shell beds. As illustrated in Fig. 6, the swash bars moved over a base of fine sand. Ten months later, by April 2007, the large swash bar had displaced its stoss slope by ca. 90 m and its lee slope by ca. 200 m towards the east (relative to the transect), at the same time becoming flatter by about 25 cm. The smaller swash bar to the east, by contrast, while remaining almost stationary, shrank considerably in overall size. Since the true migration direction of the swash bars was oblique to the survey transect, i.e. towards the southeast, the changes in morphology and size of the swash bars can be explained by their lateral displacement relative to the transect.

Spatial grain-size patterns

The mean grain sizes trace the morphology of the ebb delta and the inlet channel (Fig. 7). The main body of the ebb delta is composed predominantly of fine sand, whereas the inlet channel and the swash bars consist of medium sand. In addition, isolated patches of coarse sand, consisting mainly of shell hash, occur in the main channel. Of particular interest is the semicircular arrangement of the medium-grained sand patches in the main channel and on the eastern ebb-delta lobe. As will be shown below, this pattern traces the arcuate route of sediment recycling reconstructed on the basis of the dip directions of cross-bedded sands on the ebb delta. It is important to note here that the swash bars on the western ebb-delta lobe also consist of medium sand.

In terms of individual size fractions (Fig. 8), the patches of coarser sediment (0–1 and 1–2 phi fractions) are mirror-imaged by the areas where fine and very fine sand contents

Fig. 5 Elevation changes (in meters) along an east–west transect on the ebb-tidal shoal in the course of 10 months (June 2006 to April 2007). Note the rapid eastward migration of the large swash bar on the right



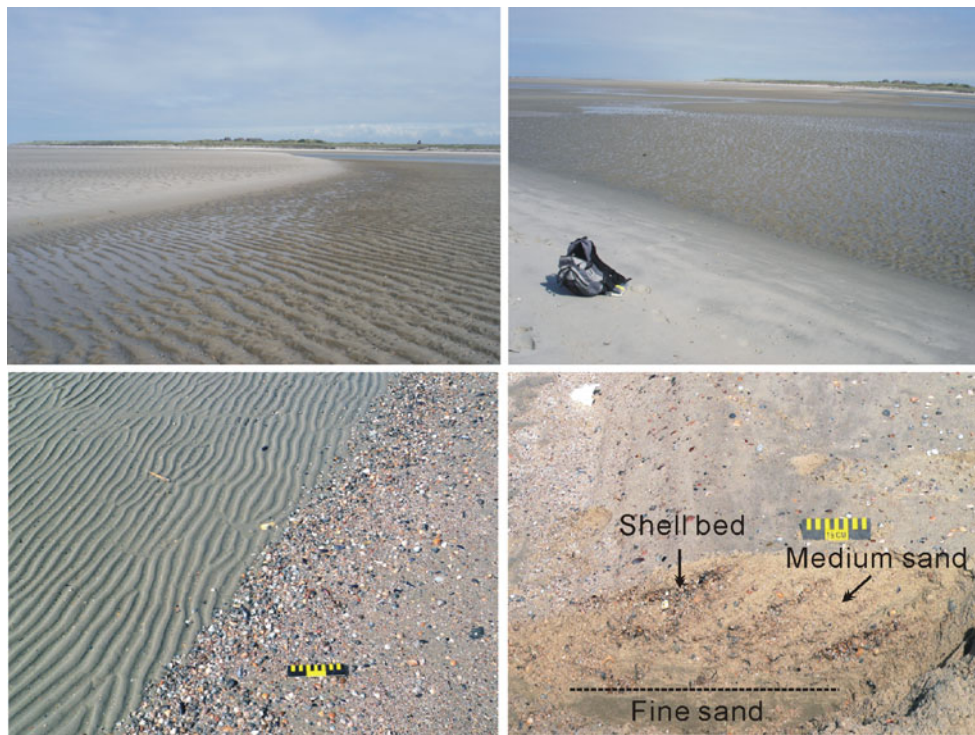


Fig. 6 Photographic documentation of major features on the ebb-tidal shoal (Robben Plate). *Upper panels* Swash bars (*light colour*) superimposed on the main ebb-delta body (*dark colour*). *Lower panels* Close-up pictures illustrating the difference in grain size between the swash bar and the main ebb-delta body (*left*), as well as

the internal sedimentary structures of the swash bar (*right*). Note that the swash bars consist of moderately sorted medium sands containing substantial amounts of shell hash, whereas the main ebb-delta body is composed of very well sorted fine sand

are low (2–3 and 3–4 phi fractions). In the field, the coarser size fractions were always associated with swash bars superimposed on the finer-grained sediment composing the ebb-delta body (Fig. 6). This is reflected in the sheet-like appearance of the fine and very fine sands, as opposed to the patchy appearance of the medium and coarse sands. Typical grain-size distributions of a swash bar and the ebb-delta body are illustrated in Fig. 9.

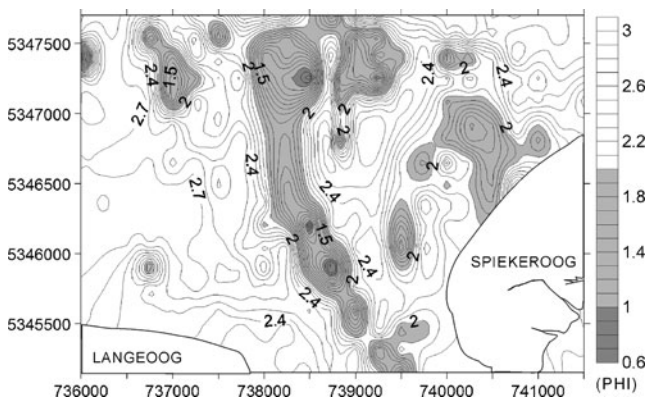


Fig. 7 Distribution of mean grain sizes in the inlet/ebb-tidal delta system. Note that the area as a whole is dominated by fine sand, whereas the channel bed and isolated patches (swash bars) on the ebb delta consist of medium sands

The textural characteristics of the inlet and ebb-delta sediments suggest that much of the ebb-delta sediment comprises mixtures of the two distinct grain-size populations shown in Fig. 9. Thus, although the sediments are mostly well to very well sorted, a distinct trend occurs from better sorting in the finer sands to poorer sorting in the coarser sands (Fig. 10, left panel). This probably reflects a mixing sequence in which progressively more material of the coarser population is admixed to that of the finer population, thereby gradually increasing the mean diameter and decreasing the sorting. This is also reflected in the skewness coefficients (Fig. 10, right panel), i.e. the best-sorted fine sands are predominantly negatively skewed due to small admixtures of medium and coarse sand. As mean grain size increases and sorting decreases, the skewness gradually changes from negative to positive values, i.e. the coarser population gradually becomes dominant but has varying proportions of fine sand admixed to produce positive skewness. The textural parameters thus reveal that the sediments of the ebb-delta body consist mainly of well to very well sorted, negatively skewed fine sand, whereas the main ebb channel and swash-bar sediments consist predominantly of positively skewed and more poorly sorted medium to coarse sands (Fig. 11).

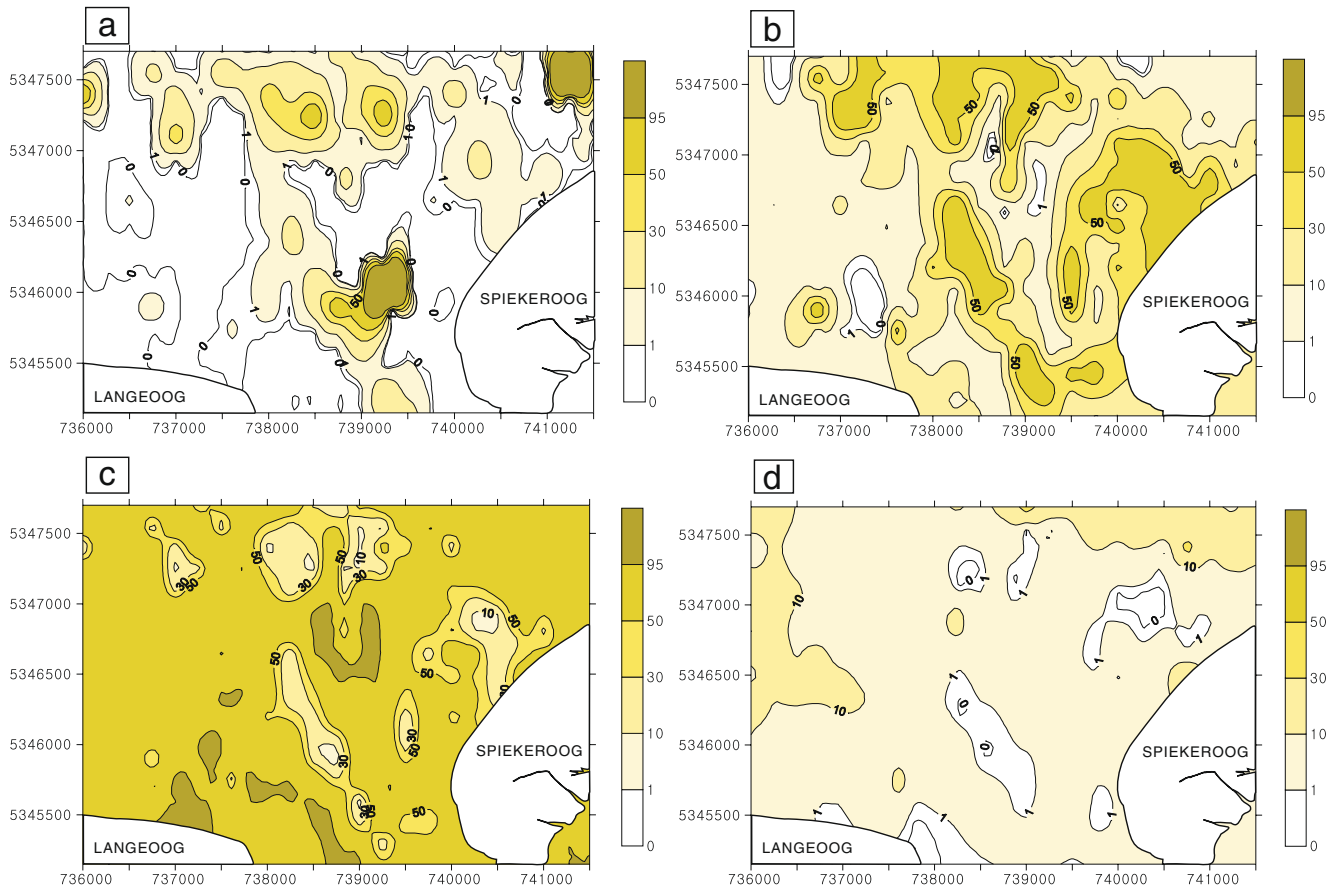


Fig. 8 Distribution patterns of individual grain-size fractions (wt%): **a** 0–1 phi, **b** 1–2 phi, **c** 2–3 phi, **d** 3–4 phi

Internal sedimentary structures

A selection of typical summer/winter sedimentary structures obtained from box-cores collected on the Robben Plate is illustrated in Fig. 12. The resin peels in the upper

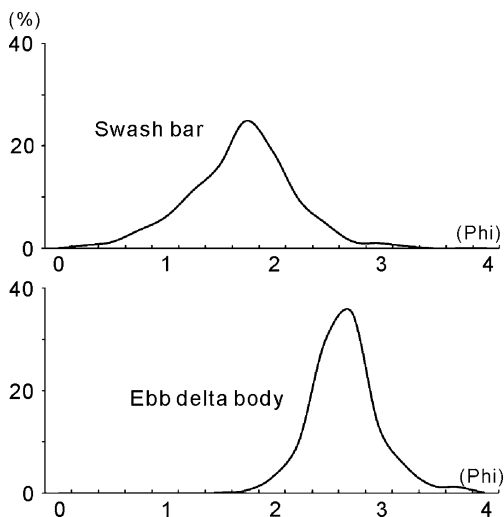


Fig. 9 Grain-size frequency curves of a swash bar (*upper panel*) and the main ebb-delta body (*lower panel*)

panels represent the winter season, those in the lower panels the summer season. Each seasonal pair was obtained from the same location (cf. Fig. 1c). The peels of each seasonal pair show almost identical primary sedimentary structures, only bioturbation being locally somewhat stronger and deeper in summer than in winter. The grain-size compositions of the box-cores are in good agreement with the general grain-size pattern in the vicinity of the sampling sites (Fig. 6). The fine sand peels show bioturbated sands in the upper parts and cross-laminated sands in the lower parts. Herringbone cross-laminations are observed mostly along channel margins. Bioturbation (cf. polychaete burrows) is a sign of relative shelter associated with low sediment turnover. Such conditions are found preferentially in the lee of large swash bars and along the margin of the eastern flood channel. Here, even mud may be deposited in summer.

The peels from the superimposed swash bars, by contrast, rarely show signs of bioturbation, being instead dominated throughout by upper-plane beds and cross-laminated sands. The occasional occurrence of bubble sand near the surface is indicative of loose packing and rapid sedimentation near the crests and on the lee slopes of the bars prior to exposure at low tide.

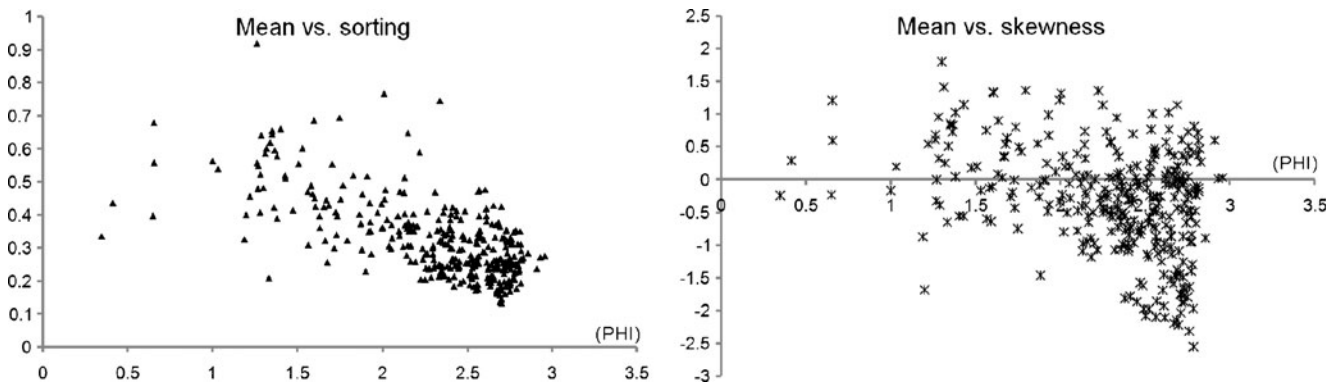


Fig. 10 Comparison of textural parameters: *left panel* sorting in phi versus mean grain size in phi; *right panel* skewness versus mean grain size in phi

On the basis of the dip directions of the cross-beds observed in the box-cores, and the orientation of flow-transverse bedforms (small dunes) observed in the channels and on the ebb-delta shoal, a map of sand transport directions was constructed. As clearly evident from Fig. 13, the dominant sediment transport direction is seawards in the main ebb channel, whereas on the ebb-delta shoal it is towards the inlet, either directly or via the flood channel. It should be noted here that all observations and corings were performed at about low tide, i.e. after the ebb tidal phase. Despite the ebb current having also flowed across the ebb-delta shoals, the vast majority of the internal sedimentary structures remained flood-oriented, indicating that—on the ebb-delta shoal—the ebb current is not strong enough to reverse previously formed flood-oriented bedforms, not even in the fine sand. Only in the main channel do we observe ebb-dominance.

The sedimentary structures preserved at depth in the longer cores, on the other hand, are quite different from those observed nearer the surface in the box-cores. It should be noted that the upper 30 cm or so of the vibro-cores had been strongly disturbed during coring and core extraction operations, making comparisons of these core sections with the box-cores impossible. However, there is no reason to assume that the sedimentary structures in the

upper sections of the vibro-cores would not have matched those of the box-cores. All deeper vibro-core sections are generally dominated by parallel-laminated sands and occasional shell beds, indicating high-energy conditions associated with either winter storms or channel migration (Fig. 14). Occasional thin mud layers, inferred to reflect deposition in the low-energy summer season, are preserved on cross-beds in the lower parts of vibro-cores recovered at or near the margin of the flood tidal channel (core Robben-15). Bioturbation is rarely observed in the vibro-cores, except for the core obtained in the southernmost part of the shoal (Robben-10), which has bioturbated beds intercalated at regular intervals. This probably indicates rapid deposition after extended periods of stagnation during which burrowing polychaetes could have established.

Discussion

Many authors have postulated sediment transport in the vicinity of tidal inlets to be dominated by inlet bypassing resulting from littoral drift associated with wave-driven longshore currents (e.g. FitzGerald 1996; Kraus 2000; FitzGerald et al. 2001; van de Kreeke 2006; Cheung et al.

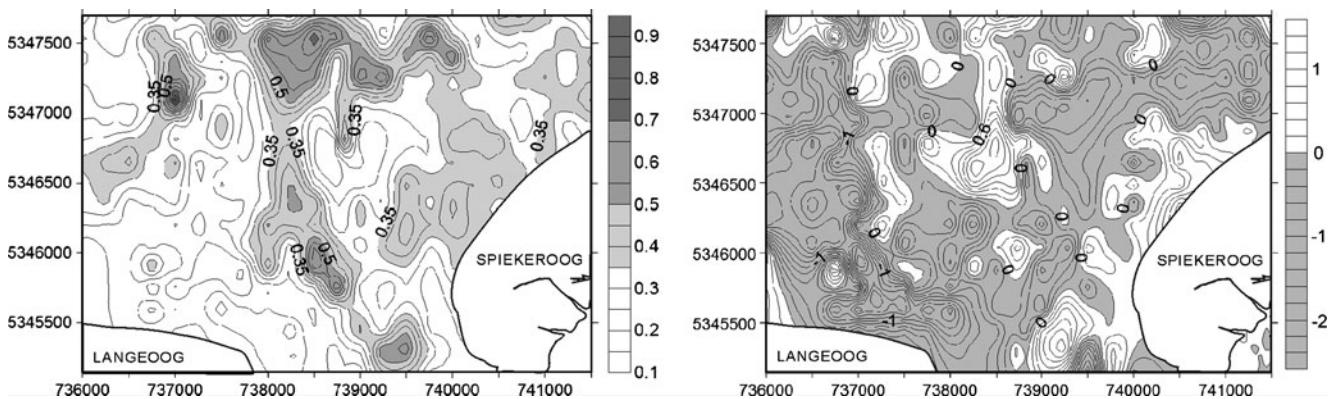


Fig. 11 Comparison of the spatial patterns produced by sorting (*left panel*) and skewness (*right panel*)

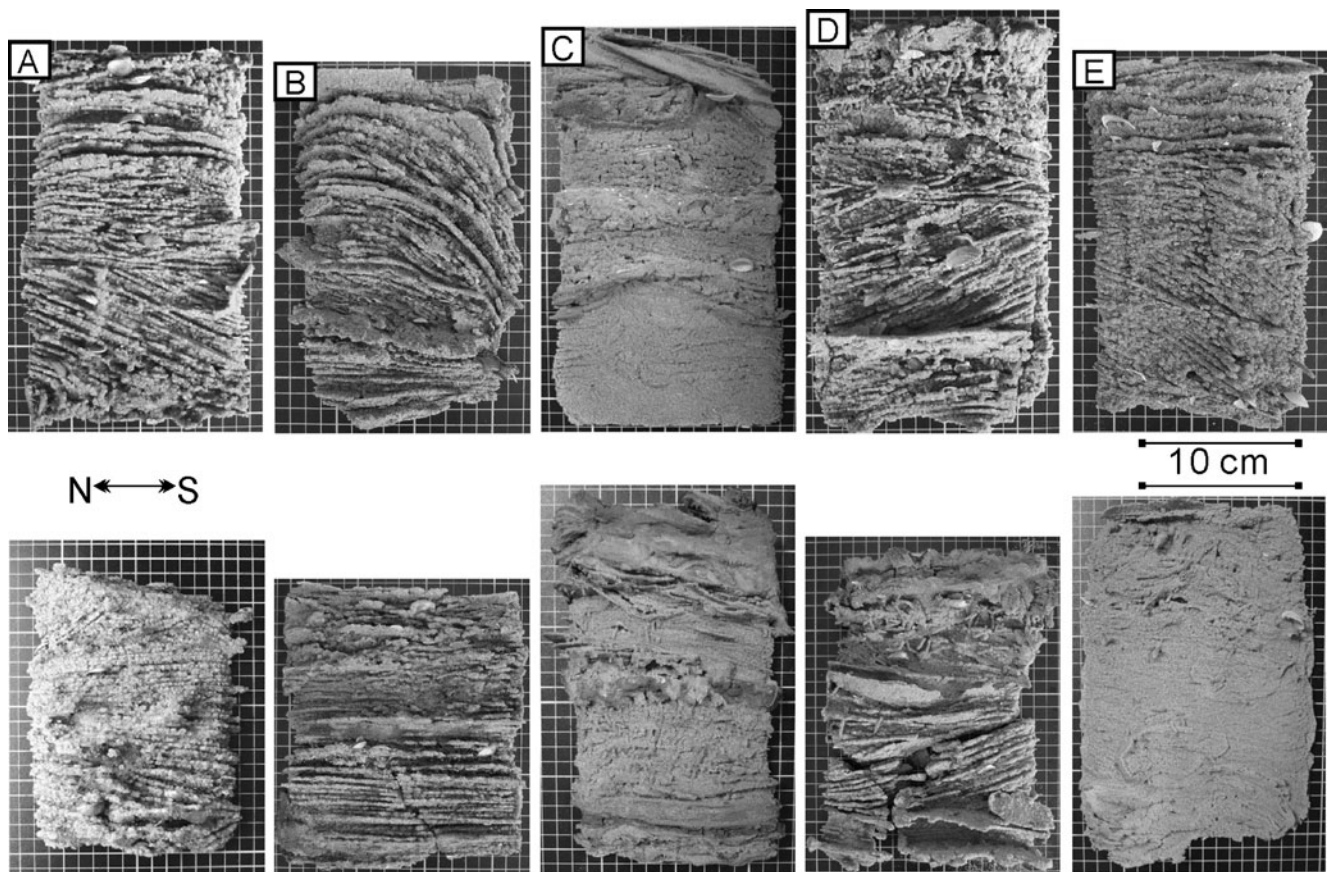


Fig. 12 Seasonal sedimentary structures in selected short box-cores from the ebb-tidal shoal (Robben plate; cf. Fig. 1b for locations A–E): *upper panels* winter season, *lower panels* summer season

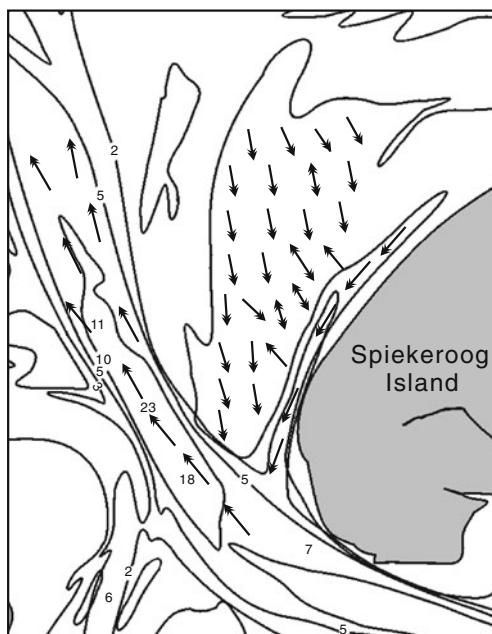
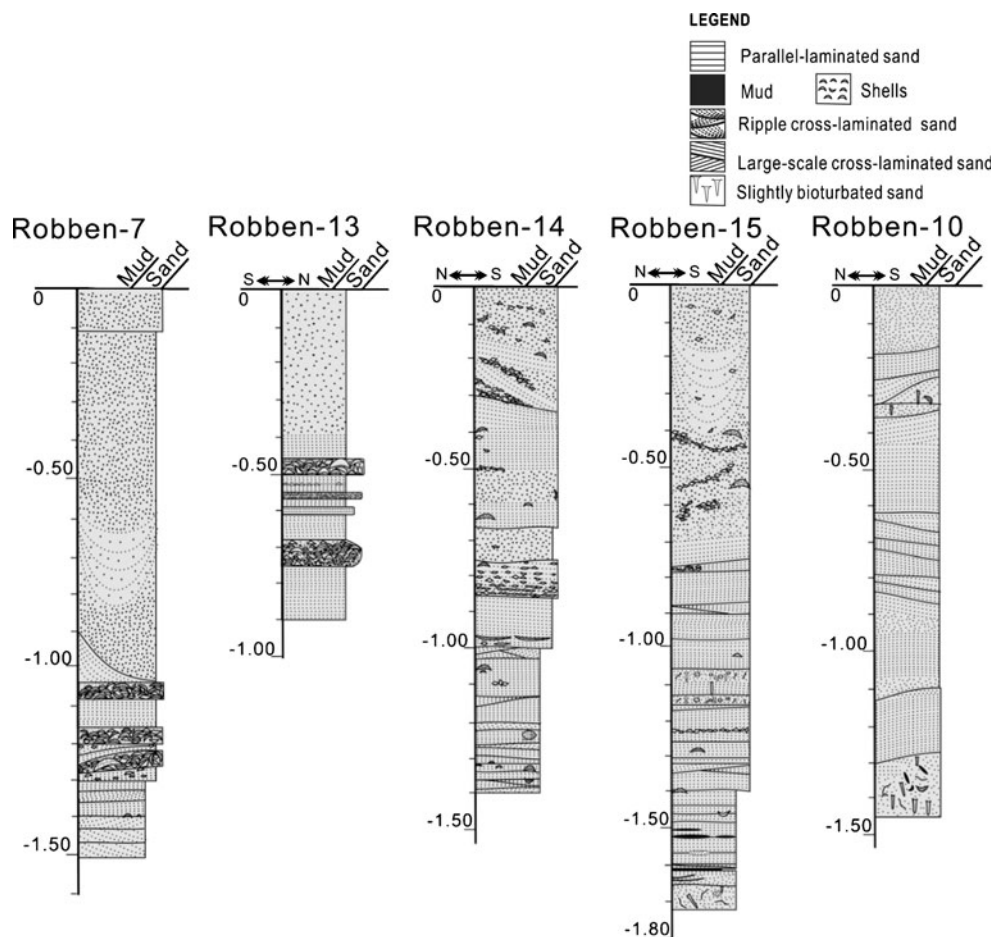


Fig. 13 Dip directions of large-scale cross-beds in intertidal sediments and orientation of flow-transverse bedforms on the ebb-tidal shoal and in the channels. Note the southerly directions on the ebb-delta shoal and in the flood channel, and the northerly direction in the main channel

2007). While this may well be true for open ocean coastlines, it may not be applicable to the south-eastern North Sea. Although most storms and, hence, wave fields approach from the west or northwest and would thus potentially produce an easterly-directed longshore current along the southern North Sea coast, it is unclear to what extent such currents can actually develop. Due to the pile-up of water in the funnel-shaped German Bight (cf. Fig. 2, lower panel) during the build-up phase of storms, one would expect leakage in the form of return flows along the coast and the deeper seabed, i.e. in a direction opposite to that of the storm-driven water masses. As a consequence, any wave-induced longshore current would either be counter-balanced or, at least, be severely dampened to the point that substantial littoral sediment transport towards the inner German Bight is forestalled. This argumentation is supported by evidence suggesting onshore/offshore, rather than alongshore, transport of sediment off the Frisian barrier islands (Veenstra 1982), and offshore transport into the German Bight along the seabed during storms (Reineck and Singh 1972).

Based on the evidence provided in the present study, the sediment bypassing mechanism in the form of swash-bar

Fig. 14 Sedimentary structures in vibro-cores from the ebb-tidal shoal (Robben Plate; cf. Fig. 1c for locations)



migration from west to east around the periphery of ebb deltas, as proposed for the East Frisian coast by Homeier and Kramer (1957), Lüders et al. (1972), Nummedal and Penland (1981) and FitzGerald et al. (1984), needs to be reconsidered. The above authors derived this model purely on the basis of morphological changes observed on a limited number of temporally widely spaced aerial photographs and without verification by ground-truthing. As shown by this study, neither the sediments nor the sediment transport directions recorded on the ground support the bypassing model. Thus, the sediment of both up- and down-drift shores and foreshores is composed of fine sand (180–200 μm ; e.g. Veenstra 1982; Flemming and Davis 1994), whereas the swash bars, which are supposed to act as the main transfer mechanism bypassing the inlet, consist of medium to coarse sand (250–600 μm). This alone precludes the swash bars as representing the main vehicle by which sand bypasses the inlet. In addition, the semicircular pattern produced by the swash-bar sediments suggests recycling, rather than bypassing.

The same conclusion is reached on the basis of the sediment transport directions reconstructed from the dip directions of cross-bedded sands in a large number of well-spaced box- and vibro-cores. These clearly confirm the

recycling mechanism inferred from the grain-size distribution pattern. In this model (Fig. 15), the source of the swash-bar sediments is the ebb-dominated main channel. Ebb-domination of this channel has been demonstrated by both direct current measurements (Bartholomä et al. 2009) and modelling (Stanev et al. 2009). Fine, medium and coarse sands (including shell hash) comprising the bed sediments of the main channel are transported towards the outer margin of the ebb delta. Once they reach the shallowest part of the channel, the coarser sediments are pushed onto the eastern ebb-delta lobe by the combined action of the flood current and waves to form swash bars which then migrate in a southerly/south-easterly direction across the ebb-delta shoal until they reach the main channel. From here the cycle repeats itself. The fine sand delivered to the ebb delta is recirculated in much the same way, the only difference being that it is rapidly segregated from the coarser sediment to be transported by the flood current, separately from the swash bars, in the form of small dunes across the ebb-delta shoal towards the marginal flood channel. The flood channel then feeds the fine sand back into the main channel from where the cycle repeats itself. An analogous circular sediment transport pattern has been postulated by Elias et al. (2006) for the Texel tidal inlet in The Netherlands.

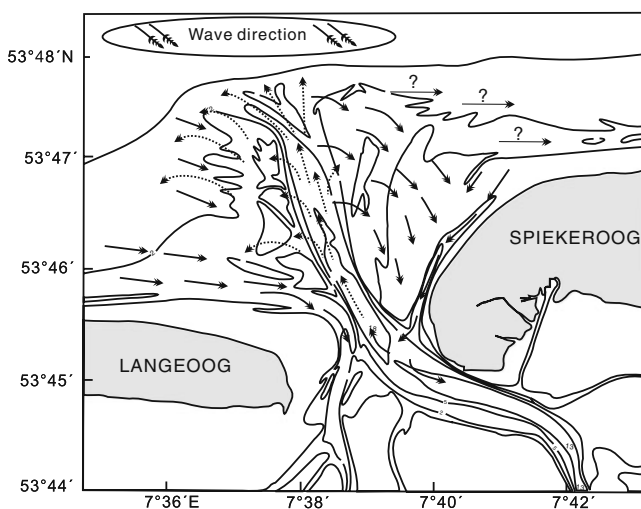


Fig. 15 Schematic sediment transport routes on the Otzum ebb-tidal shoal and in the inlet channels. Note the recycling of sediment

The recirculation model emphasises the role of waves in swash-bar dynamics on the ebb delta, in particular during winter storms. Several other local studies have dealt with storm effects along the coast of the southern North Sea, from the back-barrier tidal basins to the shoreface (Flemming and Davis 1994; Davis and Flemming 1995; Chang et al. 2007). Similar observations were made for an inlet along the coast of Normandy, France, where the onshore migration rate of swash bars increased from 0.13 m day^{-1} during fair weather to 1.1 m day^{-1} during storms (Robin et al. 2007). In the case of the Barra Nova inlet, southern Portugal, an onshore migration rate of 50 m in 2 weeks ($\sim 3.6 \text{ m day}^{-1}$) was recorded after a major storm (Balouin et al. 2004). In the present study, the migration rate was 0.78 m day^{-1} during the winter months of 2007 (January to April), whereas the mean for the whole measuring period (ca. 10 months, June 2006 to April 2007) amounted to 0.61 m day^{-1} . From these observations it is inferred that the swash bars on the Otzum ebb delta are continuously affected by waves due to frequent strong winds and storms regardless of the season, the migration rate in the more energetic winter months being slightly higher than the average for the whole period.

The recirculation model presented in this study deals mainly with the processes acting on the eastern ebb-delta shoal. The processes on the western ebb-delta shoal are less well understood because this part of the ebb delta was difficult to access for coring, so that internal sedimentary structures were not available for a reconstruction of sediment transport directions. However, sediment being supplied to the main channel from the west or northwest by the flood current and by wave action would either be returned to the western shoal by the ebb current or be fed into the recirculating system of the eastern shoal described

above. In the former case, the existence of a smaller recirculation cell is postulated for the western ebb-delta lobe. Although this interpretation is speculative at this stage, it is supported by the investigations of Hanisch (1981) on the western lobe of the Harle ebb delta located between the islands of Spiekeroog and Wangerooge.

Entirely unclear is whether some fine sand actually does manage to bypass the ebb delta beyond the area investigated in this study. Any such mechanism would have to act along the seaward subtidal margin of the ebb delta and be entirely independent of the processes acting on the ebb delta itself. No direct evidence exists for such a process, while the existence of a well-developed flood channel on the western side of the ebb delta (i.e. along the eastern shore of Langeoog island) strongly mitigates against such a mechanism because any sediment supplied from the west would be fed into this channel and transported towards the inlet. Furthermore, Krögel (1995) has shown that during storms large amounts of sediment are transported into the inlet.

Finally, the selective preservation potential of sedimentary structures is remarkable. The predominant sedimentary structures in the upper sediment column (box-core depth) are cross-laminated sands and, locally, also strongly bioturbated sands. At greater depth (vibro-cores), by contrast, they are dominated by parallel-laminated sands and shell beds indicative of high-energy conditions. This means that the sedimentary structures generated near the surface are short-lived, having a low preservation potential. What is preserved in the long term are the sedimentary structures produced by episodic storms.

Conclusions

The main conclusions of this study can be summarized as follows:

1. According to nautical charts, the size of the Otzum ebb-tidal delta has slightly shrunk over the past 20 years when the lateral oscillation of the main ebb-channel reversed from counter-clockwise to clockwise. At the same time, the ebb delta became more asymmetrical in shape, accompanied by sediment accretion on the eastern ebb-delta lobe and characterized by a series of large superimposed swash bars which migrated towards the tidal inlet.
2. Overall, the sediments of the inlet and the ebb delta consist of two hydraulic populations consisting of medium and fine sand respectively. The main ebb-delta body is composed of fine sand, whereas the channel and swash-bar sediments are dominated by medium sands containing fair amounts of coarser shell hash. The two sediment populations are transported

separately from each other, the former mainly by tidal currents, the latter by the ebb current in the main channel and by wave action on the ebb-delta shoal.

3. Although most sedimentary structures in short box-cores comprise cross-laminated and bioturbated sand, these have little preservation potential. Instead, the structures preferentially preserved in the long term are parallel laminations as well as shell beds, both indicative of high-energy storm conditions.
4. Sediment transport on the Otzum ebb-tidal delta follows a semicircular pattern by which the sediment is constantly being recycled. This pattern results from the interaction of tidal currents and north-westerly storm waves. No evidence for alongshore sediment bypassing was found on the ebb delta.

Acknowledgements This study was supported by a Korea Science and Engineering Foundation grant awarded by the Korean government (M60-2004-000-10524) and partially supported by the BK21 program. We are grateful to Arnulf Moeller, Astrid Raschke and Nicol Mahnken-Rötzer for technical support in the laboratory. In addition, we wish to thank the captain and crew of the RV *Senckenberg* for logistical support in the field. Constructive reviews by J. Bartholdy and R.A. McBride proved useful in improving the original manuscript.

References

- Balouin Y, Howa H (2002) Sediment transport pattern at the Barra Nova inlet, south Portugal: a conceptual model. *Geo-Mar Lett* 21 (4):226–235. doi:10.1007/s00367-001-0087-1
- Balouin Y, Morris BD, Davison MA, Howa H (2004) Morphology evolution of an ebb-tidal delta following a storm perturbation: assessments from remote sensed video data and direct surveys. *J Coastal Res* 20:414–423
- Bartholomä A, Kubicki A, Badewien TH, Flemming BW (2009) Suspended sediment transport in the German Wadden Sea—seasonal variations and extreme events. *Ocean Dyn* 59:213–225
- Barwis JH (1976) Annotated bibliography on the geologic, hydraulic, and engineering aspects of tidal inlets. US Army Corps Eng GITT Rep 4
- Bork I, Müller-Navarra S, Christian K (2005) Modelluntersuchungen zu Extrem-sturmfluten. Mitteilungen des Kuratoriums für Forschung im Küsteningenieurwesen, January 2005, Hamburg, pp 9–11
- Brezina J (1986) Macrogranometer M86. Laboratory manual. Granometry, Heidelberg
- Burningham H, French J (2006) Morphodynamic behaviour of a mixed sand-gravel ebb-tidal delta: Deben estuary, Suffolk, UK. *Mar Geol* 225:23–44
- Buynevich IV, FitzGerald DM (2003) Textural and compositional characterization of recent sediments along a paraglacial estuarine coastline, Maine, USA. *Estuar Coastal Shelf Sci* 56:139–153
- Carver RE (1971) Procedures in sedimentary petrology. Wiley, New York
- Chang TS, Bartholomä A, Flemming BW (2007) Distinction between sortable silts and aggregated particles in muddy intertidal sediments of the southern North Sea. In: Flemming BW, Hartmann D (eds) From particle size to sediment dynamics. Proc Worksh, 15–18 April 2004, Hanse Institute for Advanced Study Delmenhorst, Germany. *Sediment Geol SI* 202 pp 453–463
- Cheung KF, Gerritsen F, Cleveringa J (2007) Morphodynamics and sand bypassing at Ameland inlet, The Netherlands. *J Coastal Res* 23:106–118
- Davis RA, Hayes MO (1984) What is a wave-dominated coast? *Mar Geol* 60:313–329
- Davis RA, Flemming BW (1995) Stratigraphy of a combined wave- and tide-dominated tidal flat system: Martens Plate, East Frisian Wadden Sea, Germany. In: Flemming BW, Bartholomä A (eds) Tidal signatures in modern and ancient sediments. *Int Assoc Sedimentol Spec Publ* 24:121–132
- Ehlers J (1984) Platenwanderung an der ostfriesischen Küste? Ergebnis der Luftbilddauswertung von zwei Befliegungen der Wichter Ee (zwischen Norderney und Baltrum) im Sommer 1982. *Mitt Geol-Paläontol Inst Univ Hamburg* 57:123–129
- Eitner V (1996) Morphological and sedimentological development of a tidal inlet and its catchment area (Otzumer Balje, southern North Sea). *J Coastal Res* 12:271–293
- Elias EPL, van der Spek AJF (2006) Long-term morphodynamic evolution of Texel Inlet and its ebb-tidal delta (The Netherlands). *Mar Geol* 225:5–21
- Elias EPL, Cleveringa J, Buijsman MC, Roelvink JA, Stive MJF (2006) Field and model data analysis of sand transport patterns in Texel tidal inlet (The Netherlands). *Coastal Eng* 53:505–529
- FitzGerald DM (1984) Interactions between the ebb-tidal delta and landward shoreline: Price Inlet, South Carolina. *J Sediment Petrol* 54(4):1303–1318
- FitzGerald DM (1988) Shoreline erosional-depositional processes associated with tidal inlets. In: Aubrey DG, Weishar L (eds) Hydrodynamics and sediment dynamics of tidal inlets. Springer, New York, pp 186–225
- FitzGerald DM (1996) Geomorphic variability and morphologic and sedimentologic controls on tidal inlets. *J Coastal Res SI* 23:47–71
- FitzGerald DM, Penland S, Nummedal D (1984) Control of barrier islands shape by inlet sediment bypassing: East Frisian Islands, West Germany. *Mar Geol* 60:355–376
- FitzGerald DM, Kraus NC, Hands EB (2001) Natural mechanisms of sediment bypassing at tidal inlets. Coastal Eng Tech Note US Army Corps Eng ERDC/CHL CETN-IV-30. US Army Engineer Research and Development Center, Vicksburg, MS
- Flemming BW, Davis RA Jr (1994) Holocene evolution, morphodynamics, and sedimentology of the Spiekeroog barrier island system (southern North Sea). *Senckenberg marit* 24:117–155
- Flemming BW, Ziegler K (1995) High-resolution grain size distribution patterns and textural trends in the back-barrier environment of Spiekeroog Island (southern North Sea). *Senckenberg marit* 26:1–24
- Folk RL, Ward RV (1957) Brazos River bar: a study in the significance of grain size parameters. *J Sediment Petrol* 27:3–26
- Hanisch J (1981) Sand transport in the tidal inlet between Wangerooge and Spiekeroog (W. Germany). *Int Assoc Sedimentol Spec Publ* 5:175–185
- Hayes MO (1975) Morphology of sand accumulations in estuaries. In: Cronin LE (ed) Estuarine research, vol 2. Academic, New York, pp 1–28
- Hayes MO (1980) General morphology and sediment patterns in tidal inlets. *Sediment Geol* 26:139–156
- Hicks DM, Hume TM (1997) Determining sand volumes and bathymetric change on an ebb-tidal delta. *J Coastal Res* 13:407–416
- Homeier H, Kramer J (1957) Verlagerung der Platen im Riffbogen vor Norderney und ihre Anlandung an den Strand. *Jahresber 1956. Forschungsstelle Norderney* 8:37–60
- Hughes SA (2002) Equilibrium cross sectional area at tidal inlets. *J Coastal Res* 18:160–174
- Huntley DA (1980) Tides on the north-west European continental shelf. In: Banner FT, Collins MB, Massie KS (eds) The sea bed and the sea in motion. Physical and Chemical Oceanography and Physical Resources, Elsevier, pp 301–351

- Kana TW, Mason JE (1988) Evolution of an ebb-tidal delta after an inlet relocation. In: Aubrey DG, Weishar L (eds) *Hydrodynamics and sediment dynamics of tidal inlets*. Springer, New York, pp 382–411
- Kana TW, Hayter EJ, Work PA (1999) Mesoscale sediment transport at southeastern U.S. tidal inlets: conceptual model applicable to mixed energy settings. *J Coastal Res* 15:303–313
- Kraus NC (2000) Reservoir model for ebb-tidal delta shoal evolution and sand bypassing. *J Waterway Port Coastal Ocean Eng* 126(6):305–313
- Krögel F (1995) Sedimentverteilung und Morphodynamik des Otzumer Ebbdeltas (südliche Nordsee). *Senckenberg marit* 25:127–135
- Lee DT, Schachter BJ (1980) Two algorithms for constructing a Delaunay Triangulation. *Int J Comput Inf Sci* 9:3
- Luck G (1975) Der Einfluß der Schutzwerke der Ostfriesischen Inseln auf die morphologischen Vorgänge im Bereich der Seegaten und ihrer Einzugsgebiete. *Mitt Leichtweiss Inst* 47:1–81
- Lüders K, Führböter A, Rodloff W (1972) Neuartige Dünen- und Strandsicherung im Nordwesten der Insel Langeoog. *Küste* 23:63–121
- NLWKN (2006) Sturmfluten und Klimawandel sowie gewässerkundliche Daten. Sem Bundes der Ingenieure für Wasserwirtschaft, Abfallwirtschaft und Kulturbau (BWK) October 2006, Aurich, no 10, pp 1–23
- Nummedal D, Fischer IA (1978) Process-response models for depositional shoreline: the German and Georgia Bights. In: *Proc Coastal Engineering Conf, American Society of Civil Engineers, Hamburg, West Germany*, pp 1215–1231
- Nummedal D, Penland S (1981) Sediment dispersal Norderneyer Seegat, West Germany. *Int Assoc Sedimentol Spec Publ* 5:187–210
- Nummedal D, Oertel GF, Hubbard DK, Hine AC (1977) Tidal inlet variability: Cape Hatteras to Cape Canaveral. In: *Proc Coastal Sediments'77, American Society of Civil Engineers, Charleston, SC*, pp 543–562
- Oertel GF (1972) Sediment transport on estuary entrance shoals and the formation of swash platforms. *J Sediment Petrol* 42:857–863
- Özsoy E (1986) Ebb-tidal jets: a model of suspended sediment and mass transport at tidal inlets. *Estuar Coastal Shelf Sci* 22:45–62
- Postma H (1982) Hydrography of the Wadden Sea. In: *Wadden Sea working group (eds) Final report on hydrography*. Balkema, Rotterdam
- Powell MA, Thieke RJ, Mehta AJ (2006) Morphodynamic relationships for ebb and flood delta volumes at Florida's tidal entrances. *Ocean Dyn* 56:295–307
- Reineck H-E (1970) Reliefguss und projizierbarer Dickschliff. *Senckenberg marit* 2:61–66
- Reineck H-E, Singh IB (1972) Genesis of laminated sand and graded rhythmites in storm-sand layers of shelf mud. *Sedimentology* 18:123–128
- Robin N, Levoy F, Monfort O (2007) Bar morphodynamic behavior on the ebb delta of a macrotidal inlet (Normandy, France). *J Coastal Res* 23:1370–1378
- Sha LP (1989a) Sand transport patterns in the ebb-tidal delta off Texel inlet, Wadden Sea, The Netherlands. *Mar Geol* 86:137–154
- Sha LP (1989b) Variation in ebb-delta morphologies along the west and east Frisian islands, The Netherlands and Germany. *Mar Geol* 89:11–28
- Sha LP (1990) Surface sediments and sequence models in the ebb-tidal delta of Texel Inlet, Wadden Sea, The Netherlands. *Sediment Geol* 68:125–141
- Sha LP, Van den Berg JH (1993) Variation in ebb-tidal delta geometry along the coast of The Netherlands and the German Bight. *J Coastal Res* 9:730–746
- Smith JB, FitzGerald DM (1994) Sediment transport patterns at the Essex River inlet ebb-tidal delta, Massachusetts, U.S.A. *J Coastal Res* 10:752–774
- Stanev EV, Grayek S, Staneva J (2009) Temporal and spatial circulation patterns in the East Frisian Wadden Sea. *Ocean Dyn* 59(2):167–181
- Tanner WF (1987) The beach: where is the “river of sand”? *J Coastal Res* 3:377–386
- Tilch E (2003) Oszillation von Wattflächen und deren fossils Erhaltungspotential (Spiekerooger Rückseitenwatt, südliche Nordsee). *Berichte, Fachbereich Geowissenschaften, Universität Bremen*, no 222
- van de Kreeke J (2006) An aggregate model for the adaptation of the morphology and sand bypassing after basin reduction of the Frisian inlet. *Coastal Eng* 53:255–263
- van Heteren SV, Oost AP, van der Spek AJF, Elias EPL (2006) Island-terminus evolution related to changing ebb-tidal delta configuration: Texel, The Netherlands. *Mar Geol* 235:19–33
- Veenstra HJ (1982) Size, shape and origin of sands of the East Frisian islands, southern North Sea. *Geol Mijnb* 61:141–146
- Vinther N, Nielsen J, Aagaard T (2004) Cyclic sand bar migration on a spit-platform in the Danish Wadden Sea—spit-platform morphology related to variations in water level. *J Coastal Res* 20:672–679
- Walther F (1972) Zusammenhänge zwischen der Größe der Ostfriesischen Seegaten mit ihren Wattgebieten sowie den Gezeiten und Strömungen. *Jahresber Forschungsstelle Norderney* 23:7–32
- Walton TL, Adams WD (1976) Capacity of inlet outer bars to store sand. In: *Proc 15th Coastal Engineering Conf, American Society of Civil Engineers, Honolulu, HI*, pp 1919–1937
- Weishar LL, Fields ML (1985) Annotated bibliography of sediment transport occurring over ebb-tidal deltas. *US Army Corps Eng CERC-85-11. Coastal Engineering Research Center, Misc Paper*