Morphological and Sedimentological Development of a Tidal Inlet and its Catchment Area (Otzumer Balje, Southern North Sea)

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ABSTRACT


Morphological and sedimentological changes over the last 30 years of the catchment area of the tidal inlet Otzumer Balje between the East Frisian Islands at Langeoog and Spiekeroog have been studied by using older topographic maps and former investigations of sediment distribution. Also, a topographic survey and aerial interpretation of the sediment distribution of the tidal flats and inlet were done in 1990 to obtain an actual basis and to test the use of aerial photos for the sedimentary survey. Another purpose of the study was to develop fundamental methods for the interpretation of sedimentological results for future use as a functioning instrument for the analysis of morphological developments in the coastal zone.

Various sediment classifications complicate a direct comparison. Therefore, the results of the sedimentological investigations give only a rough reference to the development of sediment distribution. The tidal inlet is characterized by a sinistral rotation associated with a straightening of the transition to the tidal channel of Schillbalje. There is also a general shifting of tidal channels and flats to the southeast.

The tidal flats near the island of Spiekeroog and the mainland coast are under continuous erosion.

ADDITIONAL INDEX WORDS: Sediment transport, aerial survey, inlet stability, tidal flats, morphodynamic parameters.

INTRODUCTION

Distributions and textures of beach, bar and tidal flat sediments are subjected to interactions of morphodynamic parameters and biological factors. The forming forces induced by tides, waves and currents as well as by biological effects are impressed in the sediments, as well as seasonal variations (e.g., RAGUTZKI, 1978, 1984; REINECK and SINGH, 1980). A parameterization of the active processes is difficult because of the complicated measuring process required due to various morphological boundary conditions; the flora and fauna are naturally subjected to considerable, often not causally duplicable, variations by population dynamics, eutrophication effects etc. However, a reliable sediment classification is possible with a little effort (e.g., SINDOWSKI, 1973; RAGUTZKI, 1973, 1982; REINECK and SIEFERT, 1980; Figge, et al., 1980). Aerial photos have been used as an additional aide in obtaining reliable sedimentary surveys (e.g., RAGUTZKI, 1982). This method enables a synoptic and quick determination of sediment distributions in extended study areas.

Erosion and accretion areas can often be identified by typical sedimentary textures associated with morphological structures. For example, decreasing turbulence inputs are characterized by an increase of finer sediment particles (RAGUTZKI, 1978). Furthermore, sand losses on beaches are associated with a heavy mineral enrichment (KOMAR and WANG, 1984; FRIHY and KOMAR, 1991) and sediment coarsening (e.g., WESTHOFF, 1990; EITNER, 1993, 1995a,b).

Changes of sedimentary textures often show changes of transport processes before those effect morphology. Thus, an extension of sandy tidal flats is a sign of higher energy inputs.

Location of the Study Area

The study area comprises the tidal inlet of the Otzumer Balje and its catchment area. It is situated between the East Frisian Islands of Langeoog and Spiekeroog. They belong to a system of barrier islands and tidal flats which extends from Den Helder in the Netherlands to Skallingen in Denmark (Figure 1). The present shape of the

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southern North Sea coast is the latest transitional stage of a dynamic and in no way completed geological process (Cameron et al., 1993). The East Frisian Islands are siliciclastic barrier islands developed by the complex interaction of tides, waves, currents and wind. According to the morphodynamic classification of shorelines by Hayes (1979), the catchment area of the Otzumer Balje can be typified with a mean tidal range of 2.7 m at the gauge of Spiekeroog and 2.9 m at the gauge of Neuharlingersiel (BSH, 1993) as mesotidal. The catchment area of the Otzumer Balje comprises $114 \cdot 10^6$ m$^2$ and can be subdivided into two other geomorphological sub-catchment areas: Hullbalje and Schillbalje (Figure 2).

**Historical Morphological Development**

The historical maps of the coastal zone of Niedersachsen at the scale of 1:50,000 (edited by the Forschungsstelle Küste) reflect the topography of the islands, tidal flats and channels as well as the coastline of the mainland in 1650, 1750, 1860 and...
Figure 3. Historical morphological development of the coastal zone of Spiekeroog (after Homeier, 1961).

Table 4. Historical morphological development of the island of Spiekeroog, the Otzumer Balje tidal inlet and its catchment area (after Luck, 1975).

Figure 5. Distribution of the Tönning-Klei on the island of Spiekeroog (from Siodowski, 1973).

1960. The latter one is more or less equivalent to the course of the dyke. These maps can be used to show the long-term morphological changes over more than 300 years (Figures 3, 4).

Generally, a southeastern migration of all East Frisian Islands is indicated over the last three
centuries; the tidal inlets and the watersheds have been shifted to the east (Figure 8). The island of Juist demonstrates this development in a classical manner (Eitner, 1995c). Research has substantiated the southeastward migration of the island of Wangerooge over the last two thousand years, as well (Figure 8).

The length of the island of Spiekeroog to the east is due not only to southeastward migration driven by the sea-level rise but primarily to land reclamation measures, especially the blocking of the Harlebucht. On the western spit of Spiekeroog, there is a humic, non-calcareous clay overlying dark tidal flat deposits covered by beach and wind-borne sands. The clay only outcrops at a few sites. It is assumed that the clay extends, covered by younger sediments, to the north and northwest (Figure 5). Stratigraphically, the clay is named

Figure 6. Area growth of the island of Spiekeroog since 1650 (modified after the Historical Map No. 7 of the Forschungstelle Kuste, from Sindowski 1973).

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Figure 7. Bar attaching zones and dune formation on Spiekeroog since 1650 (from SINDOWSKI, 1973).

Figure 8. Migration of the water sheds in the East Frisian Wadden Sea (based on the Historical Maps of the Forschungsstelle Küste, from FITZGERALD and PENLAND, 1987).

Tönning-Klei analogous to the outcrops on the islands of Langeoog and Wangerooge and is part of the Pewsum-Formation, deposited approximately 2,000 years ago. Therefore, it can be assumed that a supratidal bar or island might have existed at the beginning of the period (SINDOWSKI, 1973). Two smaller islands (Lüttejöog and Oldøog) are recorded southwards and southwesterwards of Spiekeroog on topographic maps from the 17th Century. Both islands broke off from the island of Spiekeroog due to its extension during the 18th century (Figure 6).

The western spit of Spiekeroog has migrated approximately 1 km to the east during the last 300 years. The eastern part grew due to sand accretion; therefore, the eastern spit of the island migrated almost 6 km to the east. The extension of the eastern section was enforced by the migration of the bar attaching zone from the northwestern to the northern beach of the island (Figure 7). In the beginning of the last century, the silting-up of the western Harle tidal inlet actually permitted the eastward growth of the island.

The cross-section decrease can be mainly explained by the step-wise closure of the Harlebucht which led to a reduction of the catchment area of the Harle Inlet and the tidal prism (FITZGERALD et al., 1984). The catchment area of the Ötumer Balje expanded and simultaneously, as another consequence, the watershed migrated ca. 5.5 km to the east (HOMEIER, 1961, Figure 8).

The geomorphological dune structure of the island demonstrates a large compactness compared to the other East Frisian Islands (HEMPEL, 1985). Younger dune generations succeed from the older dune core to the east due to predominant winds from a northwesterly direction (Figure 7). During the second half of the 19th Century, increasing dune erosion could be prevented and restricted by dams, dykes, groynes and revetments. Destroyed dune ridges recovered partly.

METHODS

Morphological investigations are based on topographic maps of the Wadden Sea from 1960, 1975, 1980 and 1990. The comparison of contour lines allows a determination of the migration of channels and gullies. Profiles are another presentation mode of morphological development. The transposition of profiles of the same orientation from various times demonstrate morphological changes.

Classification of Tidal Flat Sediments

In the last 50 years, several scientists developed different classifications for tidal flat sediments (WOHLENBERG, 1937; LINKE, 1937; PLATH, 1943; MÜLLER, 1960; RUYTER, 1961; SINDOWSKI, 1961, 1973; RAGUTZKI, 1973, 1984; REINECK, 1980; FIGGE et al., 1980). Mostly grain size is the determining parameter (Figure 9). Tidal flat sediments mainly comprise three fractions, fine sand, silt and clay. These fractions occur in certain relations and many classifications use these three fractions.
Plath (1943) was the first who divided tidal flat sediments into three groups based on a concentration triangle with the grain size fractions >0.1 mm (fine sand), 0.05–0.1 mm (silt) and <0.05 mm (mud). Müller's (1960) classification is based on a concentration triangle with grain size fractions >0.1 mm, 0.02–0.1 mm and <0.02 mm: sand flats, mud-sand flats and mud flats.

According to the grain size classes >0.06 mm (sand), 0.002–0.06 mm (silt) and <0.002 mm (clay), Sindowski (1961) divided tidal flat sediments into 7 groups, which do not overlap like the classes of
Reineck and Siefert (1980)

Figure 9. Continued.

PLATH (1943) and MÜLLER (1960): sand, mud-sand, sandy mud, mud, silty mud, clayey mud, and strongly clayey mud. In another classification, SINDOWSKI (1973) differed tidal flat sediments from their clay content (<0.002 mm): sand (0–5%), mud-sand (0–8%), strongly sandy mud (8–17%), strongly silty mud (8–17%), sandy mud (17–25%), silty mud (17–25%), silty-clayey mud (25–35%), clayey mud (35–50%) and strongly clayey mud (50–75%). REINECK and SIEFERT (1980) used the sand content, i.e. the portion >0.063 mm for the classification: sand flats (>90%), mixed flats (90–50%), mud flats (50–15%) and clayey mud flats (<15%).

FIGGE et al. (1980) described a similar classification but used the mud content (<0.063 mm): sand flats (<10%), sand flats in a narrow sense (<5%), weakly muddy sand flats (5–10%), mixed flats (10–50%), sandy mixed flats (10–25%), muddy mixed flats (25–50%), mud flats (>50%) and strongly clayey mud flats (>85%).

RAGUTZKI (1973) left the former classification mode of tidal flat sediments. He classified sediments according to their soil physical properties. In this connection, plasticity index (Ip) and die effective grain size (d_{50}) are important: mud (d_{50} 0.01 mm, Ip: >10% medium-strongly cohesive), mud-sand (0.01 mm < d_{50} < 0.06 mm, Ip: 0–10%) and sand (d_{50} < 0.06 mm, Ip: 0% non-cohesive). RAGUTZKI (1982) additionally used the organic content which especially characterized mud flats. The median (d_{50}) is a classification factor for sand and mud-sand: mud (clay content (<0.002 mm) >8%, organic content >4%, Ip >10%), mud-sand (0.074 mm < d_{50} < 0.095 mm, d_{50} < 0.063 mm), sand (d_{50} > 0.095 mm, d_{50} > 0.063 mm).

Based on experiences during surveying sediment distribution in tidal flat areas along the German North Sea coast (RAGUTZKI 1982, 1983), LIEBIG and RAGUTZKI (1987) investigated the possibility of a cluster analysis of tidal flat sediments. The investigation was carried out using data gained

<table>
<thead>
<tr>
<th>Period</th>
<th>Total</th>
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<tr>
<td>1960-1975</td>
<td>10</td>
<td>0.7</td>
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<tr>
<td>1975-1980</td>
<td>3</td>
<td>0.6</td>
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<td>1980-1990</td>
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<td>2</td>
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<td>1990-2000</td>
<td>28</td>
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Table 1. Rotation of the channel axis of the Otsumer Balje based on the changes of the NN-10 m contour line.

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in a survey of the Jadebusen tidal flats. There was a considerable correlation between the results of the numerical and the conventional classification method. Insignificant deviations were easy to explain. The numerical method is a useful instrument for the sorting, evaluation and classification of sediment parameters.

### Sedimentary Surveys by Aerial Photographs

The sediment distribution of the intertidal and supratidal zones of the study area was investigated by using aerial photographs taken during low tide on 27 July 1990. They have a scale of 1:15,000 and have been rectificated on a scale of 1:15,000.
1:10,000. Unfortunately, the rectifications are not accurate in all parts because of a lack of fiducial marks. The deviations of the surveyed sedimentary boundaries are within the range of accuracy reached by common field surveys of the sediment distribution. Sedimentary surveys by aerial photographs have the advantage that they reduce the efforts of field investigations. Moreover, aerial photographs demonstrate the sediment distribution synoptically.
Figure 11. Morphological changes of the catchment area of the Schillbalje within the periods of 1960–1975 and 1975–1980.
RESULTS
Morphological Changes of the Otzumer Balje

The morphological changes of the Otzumer Balje is characterized by an anti-clockwise rotation of the main channel axis (Figure 10, Table 1). The rate of the mean annual rotation seemed to have increased since 1980. The annual rate was less than 1° in the 1960’s and the 1970’s; then, it increased up to 2°.

The rotation of the Otzumer Balje is due to sediment transport processes within the ebb delta. The westward migration of the Westerriff and the eastward sand transport in the Süderriff area and the Mittelplate caused the rotation of the northern part of the Otzumer Balje towards the
west and the southern part towards the east, respectively. The Robbenplate has been identifiable as an individual bar or shoal since 1960. Before it was a part of the Nordschleife and the Mittelplate. Together they did not rise above the NN $-2$ m level. There is a marked difference between Mittelplate and Robbenplate on the 1975 map. These ebb shoals have continuously migrated toward the island of Spiekeroog since 1960. This sediment transport caused a migration of the alongshore channel between the shoals and the beach of 100 m in the same direction (Homeier and Luck, 1978).

Morphological Changes of the Hullbalje

According the Ehlers (1988), the flood delta of the Hullbalje grew in the period between 1960 to 1975. The main channel shifted—based on the NN $-1.5$ m contour line—approximately 100 m towards the west and southwest respectively, associated with an extension of the intertidal flats (Figure 14).

This is only a temporary phenomenon, because reverse development occurred in the following period. Thus, the Hullbalje migrated ca. 120 m eastwards and broadened 80 m from 1975 to 1980. The change of the NN $+1.0$ m contour line demonstrated erosional features at the northern side of the eastern part of Langeoog; accretion took place at the southern side. The morphological development continued in the 1980’s. The channel migrated 400 m further towards the east until 1990; the channel profile broadened ca. 180 m at the same time. The mean annual migration to-

Figure 12. Continued.

Figure 13. Catchment area of the Schillbalje at various water levels.
Towards the east was twice as high as in the previous period.

This partly reverse development of the catchment area of the Hullbalje demonstrates short and medium-term variable dynamics. The main channels are relatively stable in association to their catchment areas, but in some branch areas, there have been migrations of more than 100 m during one decade. A prediction of the morphological development of smaller areas is difficult because of the changing hydrodynamic influences.

The cross-section of the Otzumer Balje decreases within the mouth area of the Otzumer Balje due to a southeastward migration of the Süderiff at the eastern spit of the island of Langeoog. Stephan (1989) assumed that this is a result of changes within the catchment area and a decrease of stream power potential in the catchment area of the Hullbalje.

**Morphological Changes of the Schillbalje**

**1960–1975**

The northern part of the Schillbalje between the former landing of Spiekeroog and the Janssand represents a morphological stable area. The southern part demonstrates a slight eastward migration which can be seen by the NN – 2 m contour line (Figure 11). The strongest changes can be recognized within the area of the Landbalje. Generally, there is an extension and raising of the intertidal flats. Despite the extension of the flats, the channel cross-sections have not become smaller or larger due to a channel deepening at the same time (Figure 12). The gully origins have been shifted towards the east because of the channel deepening. Besides this eastward trend, there is also a northward trend in the area of the Schwinn-plate. The morphological changes are connected with the erosion at the southern side of Spiekeroog.

**1975–1980**

The morphological changes reversed in the following period as far as erosion and accretion are concerned (Figures 11, 12). The channel became deeper before 1975 and it is now more shallow. The channel profiles broadened due to erosion of tidal flats and channel edges; therefore, the cross-section stayed constant. The nearshore areas of the island and the mainland have further eroded.

**Medium-Term Changes**

The observation of the morphological changes on a longer time scale makes it possible to divide these changes into zones with various morphodynamic tendencies: (1) zone with an eroding ten-
Figure 15. Aerial photograph of the catchment area of the Schillbalje (27 July 1990).

dency, (2) zone with an accretional tendency and (3) zone with a variable tendency. A cross-section through the catchment area of the Schillbalje shows that almost all intertidal flats and channels have a variable morphodynamic tendency (Figure 12).

At certain periods, eroding forces are predominant for a short time; periods with depositional conditions follow. Only the tidal flats along the southern side of Spiekeroog and the mainland are subjected to medium-term erosion. Whether or not this causes a continuous erosion within a shorter period could not be determined because of insufficient topographic information. Therefore, it is possible that temporary deposition occurs in these areas.

The contour lines have been used for a calculation of the catchment area at different water levels (Figure 13). There is a slight increase of the intertidal area in contrast to the subtidal areas. The further closure of the Harlebucht, the migration of the tidal inlet as well as the water sheds are connected with this condition.

Morphological Structures on the Groninger Plate

Often flood deltas are formed landward of tidal inlets. According to Hayes (1980), four morphological structures are significant for flood deltas:
(1) flood ramps, (2) flood channels, (3) ebb shields and (4) ebb spits.

Hayes (1980) described a model of a flood delta which continues landward in meandering channels and gullies. This model is mainly based on conditions as found along the American east coast. These conditions differ from those along the Frisian coast. The entire catchment area of the Otzumer Balje is a flood delta with smaller deltas with similar structures. For example, the Gröninger Plate exhibits all the characteristics of a flood delta (Figures 15, 16).

Changes of Sedimentary Textures

The sedimentary surveys by Müller (1969, 1966) and Sindowski (1973) are based on field work and sediment samples and have been classified according to models by Müller (1969) and Sindowski (1973), respectively. Müller’s (1969, 1966) investigations only comprised an approximately 1–2 km wide stripe along the mainland. The survey by Ragutzki (1982) is based on former investigations and interpretations of aerial photographs (Figure 17); Ziegler (1989) used a 250 m sampling raster. In contrast to Grotjahn (1990), who applied a 1,000 m raster, these investigations reflect a more exact picture of the sediment distribution on the tidal flats (Figures 18, 19). Despite the methodological differences, a comparison is used in order to determine temporal and spatial changes of sedimentary textures in the study area.

Percentile area portions of certain sediment types have been calculated in order to determine the temporal development of the sediment distribution (Figure 20). The comparison of the distribution of sand and mixed flat sediments shows considerable differences. Both sediment types have a relation of 1:1 in the survey by Ziegler (1989) and 1:2 in the survey by Grotjahn (1990). Both studies were carried out in Summer 1988. Therefore, the deviations are due to methods and raster differences.

In 1990 the sediment distribution on the tidal flats of the catchment area of the Otzumer Balje were surveyed using aerial photographs. Contrary to field investigations, the sediment can only be classified by the grey tones and the surficial structures on the aerial photographs. A classification and division by grain size analyses or soil physical
Figure 17. Sediment distribution on the tidal flats of the catchment area of the Otzumer Balje (after Raugurtzki, 1982).

properties is not possible; however, different sedimentary textures cause distinct grey tones on the photograph. Characteristic sedimentary structures are another classification property. The trinominal classification of intertidal sediments into sand, mixed and mud flat sediments, mainly based on grain size distributions, can be used for a sedimentary interpretation of aerial photographs, because sediments with different water contents cause varying grey tones. The water content depends on the grain size.

The sand flat sediments have relatively low water contents of 20–30% and cause a light grey tone. In wide areas, there are often characteristic sedimentary structures as subaquatic dunes, ripple marks etc., which will be described in detail further on.

The mixed flat sediments show a slightly darker grey than the sand flat sediments. The delineation of mixed and mud flat sediments is difficult because of a similar grey tone.

The mud flats present a low-energy deposition environment which is mainly formed along the mainland coast line. The natural sedimentary succession of sand, mixed and mud flats is often interrupted. This phenomenon is especially pronounced opposite tidal inlets. Salt marshes and/or mud flats cannot develop because of the high energy conditions, filtered only by ebb delta shoals but not by the barrier islands, e.g., along the dyke portion west of Neuharlingersiel which is situated vis a vis the Otzumer Balje. Mud flats can only develop in groyne fields in front of the dyke, where the hydrodynamic energy input is artificially re-
duced so that finer grained sediments are deposited (EITNER and RAGUTZKI, 1993, 1994). The mud flat areas at a further distance from the mainland which are indicated on some maps are often not mud flats in the strictest sense, because the mud deposition is not induced by the same processes as along the dyke. The energy gradient which exists at these sites would not allow a mud deposition. It is caused by mussel beds which cause a reduction of the energy input. Therefore, these areas should not be indicated as mud areas, but as mussel beds. Moreover, mud flats develop along channel and gully edges and low-lying tidal flat areas. At these sites, the hydrodynamic forces are weaker; these areas are rather small, so that they are not indicated on large-scale maps.

Mussel beds show significant structures on aerial photographs which can be easily recognized. The area along the watershed between the catchment areas of the Otzumer Balje in the east and the Accumer Ee in the west have a very dense settlement of mussel beds.

The sediments of the intertidal beach are only slightly different from the intertidal sediments of the bars and shoals of the ebb tidal delta because of similar hydrodynamic boundary conditions. Therefore, a differentiation is only possible by the physiography. The sediments of the backshore and of the island salt marshes as well as aeolian sediments do not allow a distinction because of fluent transition and anthropogenic superimposition in some parts. The characteristic morphology of dunes permits a separation of other aeolian deposits.
Sedimentary Structures Within the Ebb Delta

The most obvious sedimentary structures are in the ebb delta due to high current velocities. They can be well recognized on aerial photographs (Figures 21, 22). Subaquatic dunes (sometimes also named as megaripples or sand waves) often have a width of more than 10 m and are formed under current velocities of 70-150 cm/sec (BOOTHROYD, 1985) or of more than 60 cm/sec (REINECK and SINGH, 1980). The orientation of the subaquatic dunes and some ripple marks can be used as a directional marker for currents (Figure 23). Often only ebb and flood orientated structures can be distinguished because of the combined influences of waves and tidal currents on the sediment which does not allow an association of the morphology and sedimentary structures to ebb and flood currents. This limitation only refers to ripple structures with a length of less than 2 m, the maximum length which can be reached by wave ripples (REINECK and SINGH, 1980). The ebb currents are most significantly developed in channels and gullies and become apparent in ebb spits or spillover lobes in the flood delta (HAYES, 1980).

In the ebb delta, the bars and shoals are formed by wave activity. The bar inside the ebb delta, near the main tidal channel that has a maximum depth of about 20 m in the Otzumer Balje area, is additionally influenced under a large extension of ebb currents. Characteristic bar edges demonstrate the ebb current influence, e.g., at the
western side of the Mittelriff or at the northeastern edge of the Westerriff.

The sediment transport within the ebb delta is subjected to two hydrodynamic factors: (1) the sediment, which is deposited in the surf and swash zone of the ebb delta, is transported by wave-dominated currents alongshore (Boothroyd, 1985); and (2) this alongshore transport is interrupted by the main ebb current in the tidal inlet. Therefore, sediment of the back barrier tidal flats is transported by the ebb current to the ebb delta (e.g., Dechend and Richter, 1953; Westhoff 1990).

The energy gradient decreasing from the islands to the mainland is characterized by a decrease of the grain size and of the high-energetic sedimentary structures. Subaqueous dunes, formed under a current velocity of about 100 cm/sec, change into smaller ripple marks which have a characteristic current velocity of 30-50 cm/sec (Boothroyd, 1985).

**DISCUSSION AND CONCLUSIONS**

The morphodynamical development of the channel, gullies and tidal flats within the catchment area of the Otzumer Balje show a significant southeasterward migration which has amounted to several metres during the last thirty years. Investigations on the long-term behaviour of barrier islands and back barrier tidal flats demonstrate that these migrate landward due to sea level rise. This can be seen within the region of the east Frisian Islands, e.g., the island of Juist has migrated 1 km towards the mainland coast during the last 400 years (Eitner, 1995c). The mean sea level rise has been approximately 0.25 m per century. The landward migration is combined with an eastern drift because of the dominant northwestern wave and wind direction. It can be assumed that the morphological changes within the catchment area of the Otzumer Balje might be a result of the sea level rise because of the geomorphic affinities.

This conclusion is not unequivocal because the morphological changes can also be due to land reclamation in the region of the Harlebucht. Luck (1975) describes the morphological dependencies between artificial land reclamation and morphological changes of the tidal inlets and their catchment areas in the East Frisian area.

A sedimentary interpretation of aerial photographs produces the same good results as field investigations and has the advantage of a synoptical determination of large areas. This is valid if only a rough classification of the tidal sediments as sand, mixed and mud flat sediments is done. A more detailed classification requires additional field and laboratory investigations. Sediment distributions can only be used for an additional interpretation of morphological changes in a limited way unless conditions for sediment sampling, analyses and classification can be standardized.

**ACKNOWLEDGEMENTS**

This study was supported by the Federal Environmental Agency, Environmental Research Plan of the Minister for the Environment, Nature Conservation and Nuclear Safety of the Federal Republic of Germany (Grant 108 02 085/02), and by the state of Niedersachsen. This is Publication No. 157 of the project Ecosystem Research Wadden Sea. I thank G. Ragutzki for many discussions.
during the study and for constructive comments on a previous version of this manuscript.

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Figure 23. Sedimentary structures as directional indicators of ebb and flood currents (white and black arrows, respectively).

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Im Rahmen der vorliegenden Untersuchungen wurden auf der Grundlage von topographischen Karten und älteren Untersuchungen zur Sedimentverteilung des Einzugsgebietes der Otzumer Balje die morphologischen und sedimentologischen Veränderungen in den letzten 30 Jahren untersucht. Zusätzlich wurde 1990 eine aktuelle topographische Karte und eine Luftbildkartierung der Sedimentverteilung im Untersuchungsgebiet durchgeführt, um eine aktuelle Basis zu erhalten und die Anwendungsmöglichkeiten von Luftbildern für diese Zwecke zu überprüfen. Darüber hinaus sollten grundsätzliche Methoden für die Interpretation von sedimentologischen Untersuchungsergebnissen weiterentwickelt werden, die in der Zukunft als ein funktionelles Instrumentarium für die Analyse der morphodynamischen Entwicklung im Küstengebiet zur Verfügung stehen.

Verschiedene Sedimentklassifizierungen erschweren den direkten Vergleich. Daher können die Ergebnisse aus den sedimentologischen Untersuchungen nur als grober Hinweis für die Entwicklung der Sedimentverteilung gewertet werden.

Die Otzumer Balje ist durch eine Drehung gegen den Uhrzeigersinn geprägt; gleichzeitig weist sie im Übergang zur Schillbalje einen zunehmend gestreckteren Verlauf auf. Darüber hinaus ist im ganzen Untersuchungsgebiet eine südöstliche Verlagerung der Rinnen und Platen zu erkennen. Die insel- und küstennahen Wattbereiche sind einer anhaltenden Erosion unterworfen.