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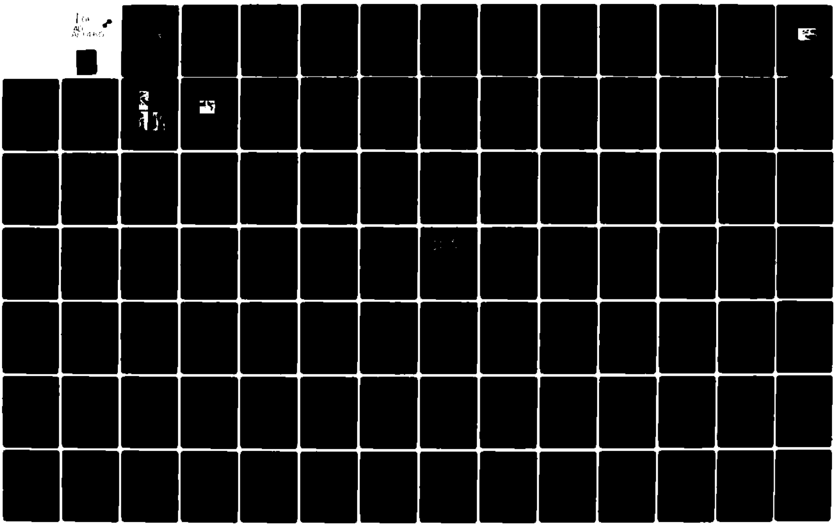

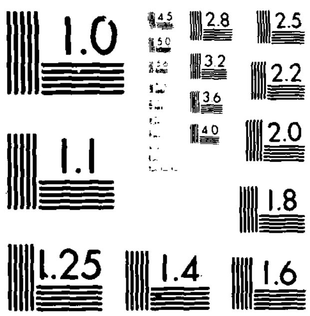

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MORPHOLOGY AND SEDIMENT DYNAMICS OF THE EAST FRIESIAN TIDAL INLETS, WEST GERMANY

by Dag Nummedal

FINAL REPORT
to the
Office of Naval Research
Arlington, VA 22217

for contract no.
N00014-78-0612

Department of Geology
Louisiana State University
Baton Rouge, LA 70803

January 1982

MORPHOLOGY AND SEDIMENT DYNAMICS OF THE
EAST FRIESIAN TIDAL INLETS, WEST GERMANY

Final Report No. 1 to the
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This Collection of Reprints Consists of
the following ONR technical reports.

Technical Report No. 1.
Process-response models for depositional shorelines: the German and the Georgia Bights.
By: Dag Nummedal and Ian A. Fischer

Technical Report No. 4.
Geometry and stratification of selected modern tidal sand bodies.
By: Dag Nummedal

Technical Report No. 5.
Sediment dispersal in Norderneyer Seegat, West Germany.
By: Dag Nummedal and Shea Penland

Abstracts, no. 1-5, also included.

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Department of Geology
Louisiana State University
Baton Rouge, LA 70803

INTRODUCTION

This final report summarizes the results of field investigations along the German North Sea coast performed through support from the Office of Naval Research during the summers of 1978 and 1979. The investigated coastline, the East Friesian Islands, is composed of a series of barrier islands separated by large and deep tidal inlets. The wave energy is high (compared to the barrier island coastline of the eastern United States) and the tide range is about 2.5 meters.

Tidal inlets represent perhaps the most dynamic of all coastal and shallow marine environments. To the navigator this implies continuously shifting channels and shoals, and to the beach developer or property owner it implies great uncertainty about future shoreline positions. To the geologists the tidal inlets represent major sediment sinks in the littoral transport system, sinks which may account for a significant percentage of the sandy components of shallow marine facies in the rock record.

Investigation of sediment dynamics in the East Friesian inlets was undertaken with the objective of understanding the pattern of sediment bypassing of the inlet from updrift to downdrift shores. Only if this could be determined in detail would it be possible to predict, with adequate prec[illegible], the migration of navigation channels, the patterns of erosion and deposition on adjacent shores and the sedimentary facies of the inlet fill itself.

Technical report no. 5, herein, does present such a bypassing model for Norderneyer Seegat. The model is generally thought to be valid also for the other inlets. The pattern of bar migration identified on the reefbow explains the gradual eastward migration of the main navigation channel followed by its avulsion back to a more westerly position. The distribution of tidal current ebb and flood dominance in the inlet throat and back-barrier channels explains the maintenance of stable channels in those regions.

The pattern of bar bypassing of this inlet makes it distinctly different from inlets investigated on the American east coast. This rather regular bypassing pattern, however, does make it possible to explain the stability of the beaches on the downdrift barrier islands. If the migrating bars make landfall at the western tip of the adjacent island, the whole island shore remains stable. In cases where the point of bar attachment is far to the east on the downdrift shore, one develops islands with an erosional western beach and accretionary eastern beach.

The stratigraphy and facies relationships in tidal inlets in general is exceedingly complex. A tentative classification of facies characteristics of wave-dominated versus tidal-dominated inlets is presented in technical report no. 4. A more detailed insight into these facies, however, must await coring within inlet deposits.

Inlet sand body geometries within coastal embayments exhibiting great tide range and wave height variability help reveal the relative significance of tidal and wave processes in the overall sediment dispersal pattern. Such a geomorphic analysis, combining data from the German and the Georgia Bights, is performed in technical report no. 1. This analysis also clearly reveals the basic differences between wave and storm-dominated inlet sand bodies. Wave-dominated shores generally have shallow and fairly unstable inlets with the largest sand bodies deposited on the landward side of the inlet throat (flood-tidal deltas). Tide-dominated inlets, on the other hand, generally develop large shoals on the seaward side of the inlet (ebb-tidal deltas). Many tide-dominated inlets experience net seaward sediment transport. Therefore, flood-tidal deltas are generally small or non-existent. Based on the relative amount of preserved ebb or flood-delta deposits among ancient shallow marine facies one might, in places, be able to differentiate ancient wave and tidal dominated shorelines.

Department of Geology
Louisiana State University
Baton Rouge, LA 70803

Technical Report no. 1

Process-Response Models for Depositional Shorelines: the German and the Georgia Bights.

Dag Nummedal and Ian A. Fischer
1979

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CHAPTER 70

PROCESS-RESPONSE MODELS FOR DEPOSITIONAL SHORELINES: THE GERMAN AND THE GEORGIA BIGHTS

by

Dag Nummedal
Department of Geology
Louisiana State University
Baton Rouge, Louisiana
70803, USA

and

Ian A. Fischer
Mobil Oil Corporation
1001 Howard Avenue
New Orleans, Louisiana
70113, USA

ABSTRACT

Sediment dispersal patterns in tidal inlets within the German and the Georgia Bights are found to be controlled by three major environmental factors: (1) the tide range, (2) the nearshore wave energy, and (3) the geometry of the back-barrier bay. Both embayments chosen for study are characterized by high wave energies and low tide ranges on their flanks, and low wave energies and high tide ranges in their centers. The spatial variability in inlet morphology, therefore, contains information on the relative role of tides and waves in inlet sediment dispersal. The paper concludes by proposing a simple model for inlet morphologies for successively greater relative role of tidal currents in the sediment dispersal.

INTRODUCTION

Investigations of process-response characteristics of tidal inlets along the southeast coast of the United States (Bruun, 1966; Finley, 1976; FitzGerald et al, 1976; Hubbard et al, 1977; Nummedal et al, 1977) have demonstrated that the geometry of the inlet entrance and the associated sand schoals depends upon three major environmental factors: (1) the tide range, (2) the nearshore wave energy, and (3) the bathymetry of the back-barrier bay.

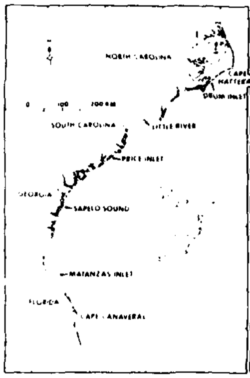
The relative magnitudes of factors 1 and 2 control to a large extent the inlet stability. Inlets along the Georgia coast, which has high tide range and low wave energy, are much more stable than those along North Carolina's Outer Banks where the wave energy is high and the tide range relatively low. These observations support, in a qualitative sense, Bruun's (1966) stability criterion which is based on the ratio between the tidal prism and the longshore sediment transport rate.

The third factor listed above, the bathymetry of the bay, controls the degree of velocity asymmetry through the inlet gorge (Nummedal and Humphries, 1978). The bays in the southeastern United States are typically filled with intertidal salt marsh (Spartina alterniflora being the dominant grass species), leaving only about 20 per cent of the total bay area as open water (tidal creeks). The consequent large variation in water surface area during the tidal cycle tends to develop strongly ebb-dominant flow in such a bay-inlet system. The peak ebb current and the consequent seaward-directed sediment transport, far exceed that moving landward during flood. In cases where the back-barrier bay is essentially all open water (as in the lagoons behind the Outer Banks of North Carolina) there is no such tendency for ebb dominance.

In order to determine the response of the tidal inlets to the three controlling factors one must examine coastal segments within which all factors undergo significant changes in magnitude according to a well-known geographic pattern. The coastal segments chosen for this investigation were the southeast coast of the United States from Cape Hatteras to Cape Canaveral (Fig. 1) and the northwest coast of Europe from the Netherlands to the west coast of the Jutland peninsula in Denmark (Fig. 2). For short, the first region will be referred to as the Georgia Bight, the second one as the German Bight.

TIDE RANGE

Along the east coast of the United States the open coast tide range is primarily a function of shoaling of the tidal wave across the continental shelf. Therefore, the wider the shelf, in the direction of advance of the tidal wave, the larger the tide range (Redfield, 1958; Silvester, 1972). Figure 3 (from Nummedal et al, 1977), shows the regional tide range variation along the U.S. east coast as well as the accompanying variation in shelf width. The tide range dependency on shelf width can clearly be seen.



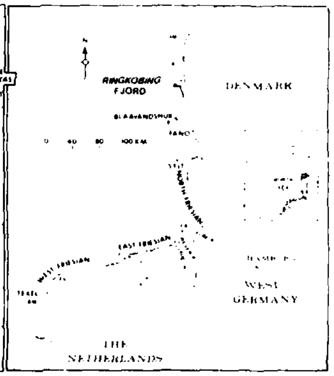
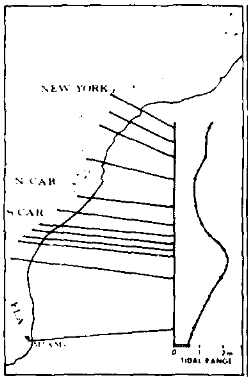


Fig. 1. Location map of the Georgia Bight.

Fig. 2. Location map of the German Bight.



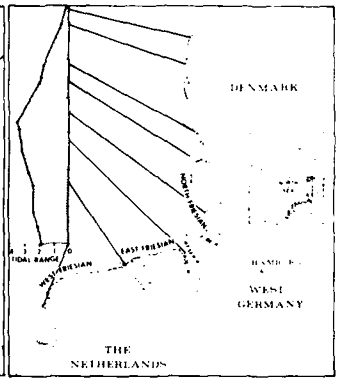


Fig. 3. Mean tide range along the east coast of the United States. Data from: National Oceanic and Atmospheric Administration, 1978.

Fig. 4. Mean tide range along the shores of the German Bight. Data from Deutschen Hydrographischen Institut, 1978.

In the North Sea, the entire region is essentially a continental shelf. The variation in open-coast tide range within the German Bight, therefore, is largely controlled by the amphidromic system. Classical models of the M_2 tide within the North Sea (Defant, 1958), demonstrate the existence of a counter-clockwise rotation of the tidal wave in the North Sea around an amphidromic point between Jutland and the east coast of England. Iso-range lines are nearly concentric around this point. Therefore, the central part of the German Bight which is further away from the amphidromic point than is the northwest Netherlands or the coast of Jutland, has the larger tide range. The tide range variability within the coastal segment of interest in this study is plotted in figure 4.

By comparing figures 3 and 4 it is evident that both the Georgia and the German Bights are characterized by low tide range at their flanks and high tide range in the center. Mean tide range in the center of the Georgia Bight exceeds 2 meters; in the center of the German Bight it exceeds 3.5 meters.

WAVE ENERGY

Evaluations of the regional variability in nearshore wave climate is presently impossible because reliable wave records are very scattered and typically of too short duration to be of much use in long-range sedimentation studies. In order to derive a consistent picture of wave energy variability, therefore, it was decided to utilize the Summary of Synoptic Meteorological Observations (SSMO - data) published by the U.S. Naval Weather Service Command (1974, 1975). Wave energy flux distributions within pre-established data squares were calculated by a procedure outlined in Nummedal and Stephen (1978). In this same article the authors have also discussed in some detail the assumptions and problems associated with the utilization of SSMO-data in studies of coastal sedimentation dynamics. Results of the wave energy flux calculations for data squares off the southeast coast of the United States and in the North Sea are summarized in figures 5 and 6, and tables 1 and 2.

The deep water energy flux shows a distinct southward decrease along the U.S. east coast from a total onshore flux at Cape Hatteras of $7.7 \cdot 10^3$ Watts/m to $4.6 \cdot 10^3$ Watts/m at Jacksonville. In spite of this deep water trend, however, the mean annual breaker height in northeast Florida exceeds that of the central part of the Georgia Bight (58 cm at

Daytona Beach versus 12 cm at St. Simon Island; Coastal Engineering Research Center, 1975) probably because of the steeper inner shelf profile off the Florida coast (Nummedal et al, 1977).

Table 1. Deep water wave energy flux values for the southeast U.S. SSMO data squares. Energy flux in units of 10^3 Watts/meter.

Data Square Direction	Cape Hatteras	Charleston	Jacksonville	Miami
N	4.8	3.2	4.2	1.9
NE	3.3	3.5	2.2	2.2
E	1.3	1.9	1.3	2.4
SE	1.2	1.3	1.1	1.2
S	1.9	2.2	1.8	.8
SW	2.8	2.5	1.6	.8
W	3.0	3.2	1.9	.7
NW	2.7	2.6	3.2	1.3

Table 2. Wave energy flux values for SSMO data squares along the margins of the North Sea. Energy flux in units of 10^3 Watts/meter.

Data Square Direction	Edinburg	Grimsby	Rhine Delta	Bremer-haven	Esb-jerg	Stavan-ger
N	2.1	1.5	.8	.7	2.1	5.1
NE	.5	1.5	.7	.3	1.0	1.4
E	3.3	1.5	.5	.8	1.8	4.5
SE	3.4	.8	.3	.3	1.0	7.8
S	1.8	2.1	.7	.5	2.3	3.8
SW	1.7	2.8	2.1	1.5	5.0	5.4
W	3.0	2.3	1.9	2.9	5.5	9.8
NW	3.3	2.7	1.4	2.4	6.3	11.8

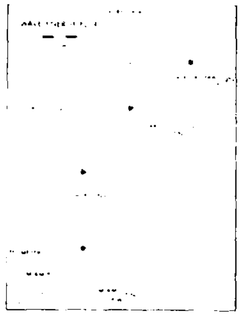


Fig. 5. Wave energy flux distribution off the southeast coast of the U.S.

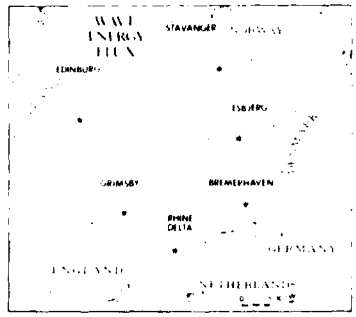


Fig. 6. Wave energy flux distribution along the margins of the North Sea.

Along the southeast coast of the North Sea one also finds a distinct southward decrease in total wave energy flux. This is thought to reflect a combination of a decrease in storm frequency as well as westerly fetch in the same direction. Total onshore wave energy flux in the Esbjerg data square (Fig. 6) is about $17 \cdot 10^3$ Watts/m, compared to $7 \cdot 10^3$ Watts/m along the North Friesian Islands and only $3.5 \cdot 10^3$ Watts/m along the East Friesian Islands.

By combining the information presented on the wave energy and tide range variations one can derive a generalized pattern of wave and tide dominance along the shores of these two bights (Fig. 7). The flanks have high wave energy and low tide range. They are wave dominated. Further towards the center the two factors will both be of major importance; therefore, this will be a zone of mixed energy. In the center of both bights the tidal currents clearly control the sedimentation patterns. These areas are tide dominated.

INLET MORPHOLOGY

Both the Georgia and the German Bights show distinct and similar trends in inlet morphologic changes as one progresses from the flanks toward the centers. These changes provide unambiguous evidence regarding the relative role of tidal and wave induced sediment dispersal in the total inlet circulation pattern. This paragraph will review the characteristics of inlet morphology, moving from the wave dominated embayment flanks to increasing tidal dominance at the embayment centers.

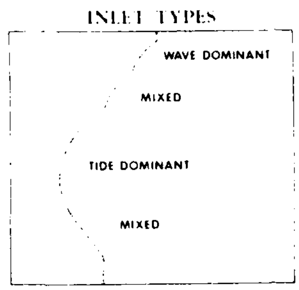


Fig. 7. Generalized distribution of wave and tide dominance along an embayment coast

Fig. 8. Oblique air photo of Drum Inlet, North Carolina. Photo, May 1977, courtesy of Albert C. Hine.

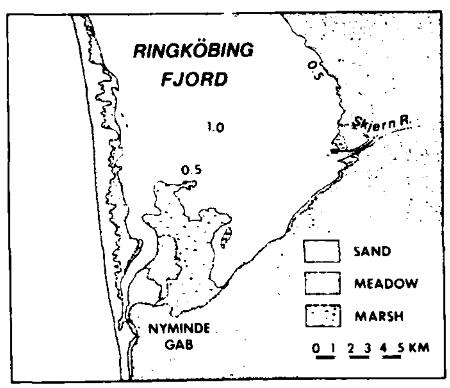


Fig. 9. Map of the southern part of Ringkobing Fjord, including the old flood-tidal delta at Nyminde Gab. Depth contours in meters.

Inlets along the wave dominated coastal segments of both bights are typified by Drum Inlet, North Carolina, at the northern flank of the Georgia Bight (Figs. 1 and 8). Although the Drum Inlet flood-tidal delta was developed over a very short time immediately after the inlet was artificially opened in 1972 its morphology is typical of the much larger deltas behind Ocracoke, Hatteras and Oregon inlets as well. Today, the Drum Inlet flood-tidal delta is rather inactive (Hubbard, 1977).

Within the German Bight the wave dominated barrier-lagoon coast is restricted to the west coast of Jutland. Furthermore, all these lagoons now have artificially cut and maintained entrances. However, it is clear from old maps and the present lagoon morphology that the natural entrance to Ringköbing Fjord was associated with a large flood-tidal delta, the remains of which are clearly recognizeable at Nyminde Gab (Figure 9).

The morphology of an inlet at a wave dominated coast is summarized in frame 1, figure 10.

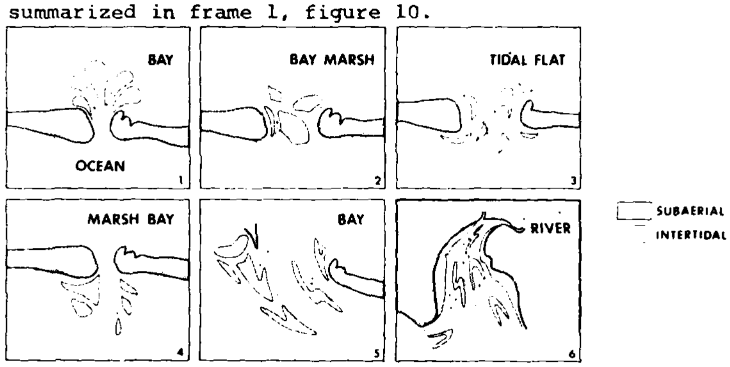


Fig. 10. Tidal inlet morphological models. Frames 1 through 6 reflect an increasing role of tidal currents in inlet sediment dispersal.

As illustrated, such an inlet is characterized by sand bodies exclusively on the landward side of the inlet gorge. The gorge itself is relatively stable, the ebb tidal delta (outer shoal) is present only as a minor subtidal shoal.

With an increase in tidal range, and consequent tidal current capacity for sediment transport, one observes an intriguing change in inlet shoal configuration. Both Little River inlet on the North Carolina-South Carolina border

(Fig. 11) and Matanzas Inlet in northeast Florida (Fig. 12) are good examples of this inlet type which will be called mixed energy, low tide range, inlets.

Based on the distribution of sand bodies within these inlets the generalized model shown in frame no. 2, figure 10, was developed. This type of inlet has a smaller, and less continuous, flood-tidal delta than inlet type no. 1, it has a wide and rather unstable inlet gorge, and a significant ebb-tidal delta reflecting main channel ebb-current dominance (Hayes et al., 1973).

The inlets between the East Friesian Islands on the coast of Lower Saxony, Germany, must also be termed mixed energy inlets. However, both tide range (Fig. 4) and wave energy (Fig. 6) exceed those within the Georgia Bight. As the gross differences in morphology appear to reflect primarily the larger tide range, these inlets are classified as mixed energy, high tide range, inlets. Excellent examples would be the inlet between Norderney and Baltrum (Fig. 13), and the Harle Inlet between Spiekeroog and Wangerooge (Fig. 14).

As demonstrated by Luck (1976) these Friesian inlets have a large ebb-tidal delta with a nearly continuous arc of swash bars along its margin, the "reef-bow." The high wave energy appears to cause rapid swash bar migration contributing to the instability of the seaward end of the main ebb channel. The inlets are very wide and the ones that are not yet stabilized by sea walls and groins on the adjacent island shores typically have multiple channels. According to historical studies by Luck (1975) prior to stabilization the Harle Inlet also had multiple sand bars in the gorge section and two or three major channels. Reduction in tidal prism as a function of the reclaiming of large areas of back-barrier tidal flat appears to be the main factor contributing to the changes morphology of the Harle Inlet.

A generalized morphological model of the Friesian inlets is presented in frame no. 3, figure 10. The only essential difference from model no. 2 is the larger ebb-tidal delta, projecting further out to sea in response to much stronger tidal currents. Strong wave action also produces a more continuous series of swash bars along the swash platform margin.

Fig. 11. Oblique air photo of Little River Inlet, North Carolina-South Carolina border. Photo, May, 1977, courtesy of Dennis K. Hubbard.

Fig. 12. Oblique air photo of Matanzas Inlet, Florida. Photo, April, 1977, courtesy of Dennis K. Hubbard.

Fig. 13. Oblique air photo of Wichter Ee, the inlet between Norderney and Baltrum, Lower Saxony. July, 1978.

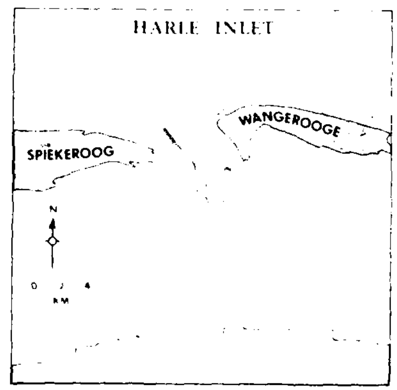


Fig. 14. Bathymetric map of Harle Inlet, Lower Saxony. The contour interval is 2 meters.

True tide dominance characterizes the inlets of the central part of the Georgia Bight. Although the tide range there is less than that along the Friesian coast, tidal dominance is brought about by the extremely low nearshore wave energies. Though small, Price Inlet (Fig. 15) illustrates well the morphology of the larger tidal inlets along this segment of the coast. Descriptions, photos and maps of numerous other inlets in the central Georgia Bight can be found in Hubbard (1977), Nummedal et al. (1977), Oertel (1975), and FitzGerald et al., (1978).

Fig. 15. Oblique air photo of Price Inlet, South Carolina. Photo, March, 1977.

The morphology of tide dominated inlets is generalized in frame no. 4, figure 10. These inlets consist of a single, straight, and deep main ebb channel, a large swash platform projecting far out to sea, and numerous, often large swash bars migrating towards the inlet gorge across the swash platform. There are no sand bodies in the inlet gorge section nor on its landward side, reflecting strong ebb dominance in the main inlet channel.

With a further increase in the ratio between tide range and wave energy, beyond the conditions found in the central part of the Georgia Bight, barrier islands with distinct individual tidal inlets cease to exist. As an example one can consider the central part of the German Bight where the mean tide range in places exceeds 3.5 meters (Fig. 4).

As shown in the bathymetric maps of the entrance to the Weser estuary (Fig. 16 and 17), small, unstable, supratidal sand bodies like Alte Mellum, have replaced the barrier islands of lower tidal range. A series of linear, lunate and sigmoidal shoals dominate the estuary entrance. Their long axes are typically parallel to the main estuary axis. The total sand body associated with this estuary is large and extends much further out to sea than any of the tidal deltas of the mixed energy inlets between the Friesian Islands further west.

Inlets (or estuary entrances) of this type are summarized in frame 5, figure 10. They are high tide range, tide dominated inlets.

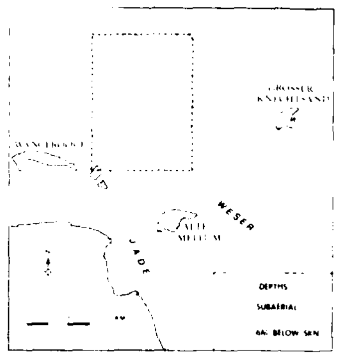


Fig. 16. Bathymetry of the entrances to the Weser and Jade estuaries.

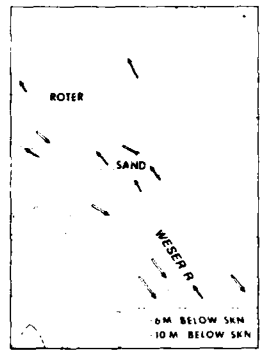


Fig. 17. Bathymetry of the area enclosed by frame in figure 16. Arrows refer to hydrographic data obtained by Barthel (1976). Open arrows indicate flood dominance, solid arrows show ebb dominance.

The high tide range end member of this spectrum of inlet types had to be found outside the German or the Georgia Bights. Hayes (1975) and Hayes and Kana (1976) present maps of Nushagak Bay, Alaska, as an example of a macrotidal embayment. Extremely high tide ranges, as in Nushagak Bay, can only develop in narrow embayments where there is a significant funneling of the tidal wave. The strong tidal currents, in turn, prevent the development of barrier islands across the embayment entrance. As indicated in the simplified morphological model of frame 6, figure 10, the shoal distribution within an embayment like Nushagak Bay is fairly similar to that of the high tide range, tide dominated embayment of frame no. 5. The main difference appears to be the degree of development of the sigmoidal shoals. An increase in tide range, and the associated tidal current strength, appears to develop larger sigmoidal shoals and more distinct flood and ebb segregated channels.

DISCUSSION

The paper demonstrates that there clearly exists a continuum of tidal inlet morphologic types. Examples of most types within this continuum can be found within the Georgia and the German Bights because of large regional variations in tide range and wave energy.

The wave dominated inlets (frame 1, figure 10) typically have the majority of the shoals on the landward side of the inlet gorge because the net direction of wave induced sand transport will be towards the lagoon. Furthermore, the existence of a largely open-water lagoon rather than a marsh or tidal flat in the back-barrier environment will reduce the ebb dominance of the main inlet channel and cause flood dominance of some inlets (Nummedal and Humphries, 1978). Complex wave-current interactions on the swash platform have been found to produce a higher concentration of suspended sediment on flooding than on ebbing tide at one inlet (Hubbard, 1977). This factor might also contribute to the landward-directed net sediment transport at some wave dominated inlets.

The mixed energy inlets within the Georgia and German Bights are all hydraulically ebb dominated, because of the extensive back-barrier marshes and tidal flats (Nummedal and Humphries, 1978). The seaward extent of the swash platform must reflect an equilibrium between the capacity for seaward transport by the ebb flow and landward transport by wave breaking on the platform. Consequently, the primary change in the ebb-tidal delta with an increase in the ratio of tidal range to breaker energy will be its seaward growth. Secondly, the inlet gorge will become better defined and less subject to changes due to bar migration as wave-induced bar development will take place on platform margins further away from the inlet. These patterns of response to increasing tidal influence on the sediment dispersal mechanism are well illustrated in models two, three and four in figure 10.

Barrier islands cease to exist along depositional coast of high tide range because the longshore sediment movement due to wave action becomes completely subordinate compared to the on-offshore movement of sediment by the tides. For the wave energy of the German coast the critical tide range appears to be about 3 meters (Fig. 4). The development of sigmoidal shoals in these high tide range embayments is an expected consequence of the deflection of a current around the leading face of any sedimentary deposit formed by anoth r current flowing in the opposite direction. This causes strongly segregated channels for ebb and flood flow, hence the sigmoidal shape of the bar crest. This segregation of ebb and flood flow in the Weser estuary has been well documented by Barthel (1976).

CONCLUSIONS

1. The pattern of variability in tidal inlet sand body geometries within the Georgia and the German Bights suggests the existence of continuum of inlet morphologic types. In this continuum the shoals assume a configuration which directly reflects the relative capacity for sediment transport by waves and tidal currents. Six discrete stages of inlet morphology are presented in figure 10.

2. The diagram applied by Hayes (1979) to classify barrier island shorelines is used here to show the relationship between the inlet morphologic types and the two dominant environmental parameters: wave height and tide range (Fig. 18). To establish the boundaries, 19 inlets were classified, based on shoal geometry, as wave dominated, mixed or tide dominated. The mean tide range was well known for each, mean annual breaker heights, however, are much less precisely known. Nevertheless, a distinctive pattern did emerge, permitting the establishment of fairly precise boundaries for each inlet type on this bivariate graph. The boundaries slope such that with an increase in mean annual wave height an increase in tidal range is required to produce the same type of inlet shoal geometry.

3. The regional variability of the inlets within the Georgia and German Bights can be represented by the arrow in figure 18. Towards the center of both bights one finds an increase in tidal range and a decrease in the mean annual wave height. Therefore, the inlet change from wave dominated ones at the flank to tide dominated ones at the centers.

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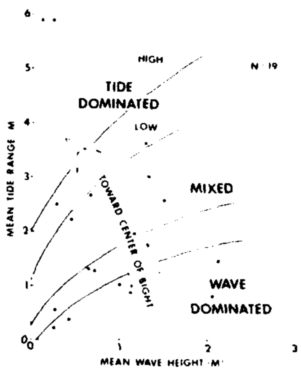

Fig. 18. Inlet morphologic types as functions of mean annual wave height and tide range. 19 barrier island coasts in North America and Europe were used to establish the boundaries.

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Sediment dispersal patterns in tidal inlets within the German and the Georgia Bights are found to be controlled by three major environmental factors: (1) the tide range, (2) the nearshore wave energy, and (3) the geometry of the back-barrier bay. Both embayments chosen for study are characterized by high wave energies and low tide ranges on their flanks, and low wave energies and high tide ranges in their centers. The spatial variability in inlet morphology, therefore, contains information on the relative role of tides and waves in inlet sediment dispersal. The paper concludes by proposing a simple model for inlet morphologies for successively greater relative role of tidal currents in the sediment dispersal.

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Department of Geology
Louisiana State University
Baton Rouge, LA 70803

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Geometry and Stratification of Selected Modern Tidal Sand Bodies.

Dag Nummedal
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GEOMETRY AND STRATIFICATION OF SELECTED MODERN TIDAL SAND BODIES

Dag Nummedal

Department of Geology
Louisiana State University
Baton Rouge, Louisiana 70803

INTRODUCTION

Tides influence coastal sedimentary processes to a degree directly proportional to the amount of water exchanged during a tidal cycle (the tidal prism) relative to the total volume of water in the environment. Intertidal marshes are completely tidal controlled because most of their water is exchanged every tidal cycle whereas lagoons retain a significant amount of water even at low tide. As a result, the sedimentary environments are dramatically different.

The purpose of this paper is to identify the primary components of tidal-controlled environments, the physical processes operating within each, and to describe the characteristic resulting sand body geometries and internal stratification patterns. Examples will be chosen from the author's areas of experience: the south Atlantic and Gulf coasts of the United States and the German Bight of the North Sea.

ENVIRONMENTS

As a result of longshore and onshore wave-induced sediment transport, extensive barrier island chains have developed during the last few thousand years of Holocene sea level rise along depositional shorelines. Some developed through the gradual separation of beach ridges from the mainland by rising water (Hoyt, 1967), others grew by downdrift spit accretion (Gilbert, 1885), and others probably formed by vertical growth of offshore bars (De Beaumont, 1845). The American coastline has well-documented examples of all types.

The growth of barrier islands restricted water exchange between the intertidal and open marine environments causing the scour of deep tidal entrances. Sediment, either scoured from these channel floors or delivered to the inlets through longshore transport, was deposited in the two primary zones of tidal

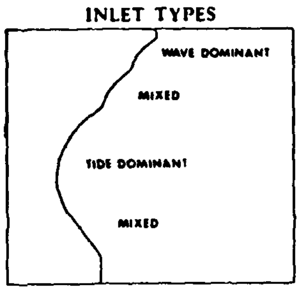

Figure 1. Generalized distribution of wave and tide dominance along an embayment coast. From Nummedal and Fischer (1798).

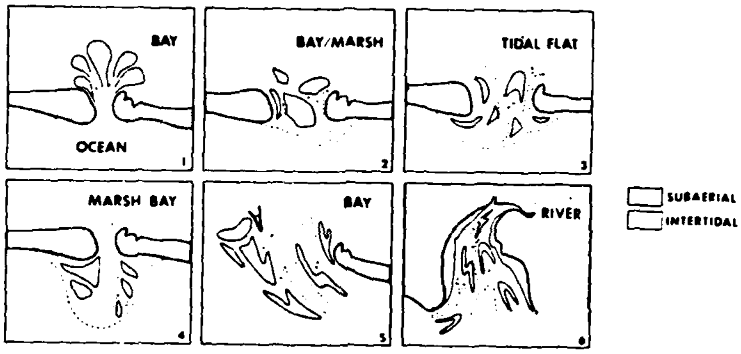

Figure 2. Tidal inlet morphologic models. Types one through six reflect an increasing role of tidal currents in inlet sediment dispersal. From Nummedal and Fischer (1978).

current divergence: on the seaward side of the inlet in the form of ebb-tidal deltas and on the landward side in the form of flood-tidal deltas (Hayes, 1975). Volumetrically, these tidal deltas are the largest coastal tidal sand bodies. Along the Georgia coast their volumes equal that of the adjacent barrier islands. Their geometry and stratification are functions of tidal range, wave energy, the configuration of the bay, inlet history and, recently, man's management.

Landward of the flood-tidal delta the environment changes to an open lagoon or to meandering tidal creeks dissecting marshes or tidal flats. Tidal channel migration causes the growth or sandy or muddy point bars and tributary mouth bars. Aperiodic storm tides occasionally inundate areas above astronomical high water, developing a distinct sedimentary environment: the wind-tidal flat. Wind-tidal flats are presently best developed adjacent to the lagoons of the semi-arid south Texas coast.

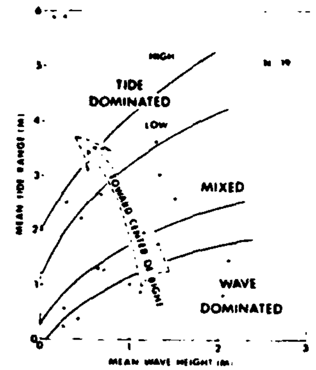

Figure 3. Inlet morphologic types as functions of mean annual wave height and tide range. Nineteen barrier island coasts in North America and Europe were used to establish these boundaries. From Nummedal and Fischer (1978).

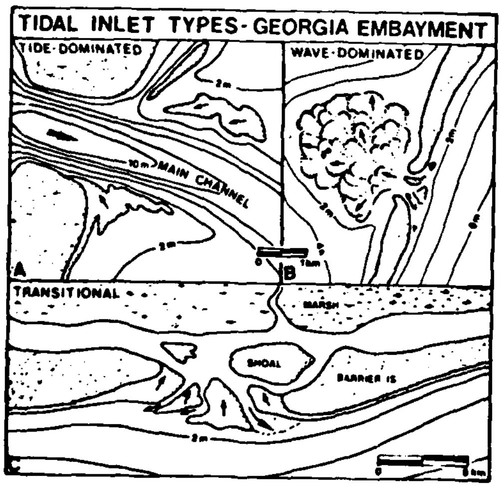

Figure 4. Tidal inlet types in the Georgia embayment. Tide-dominated inlets (A) are characterized by a deep central channel flanked by extensive channel margin bars. The main channel is ebb dominant. In contrast, wave-dominated inlets (B) are generally dominated by landward transport. The ebb-tidal delta is small and often breached by numerous and shallow channels. The flood-tidal delta is large and multi-lobate. Transitional inlets (C) are characterized by shoals contained in the inlet throat. The break in the barrier island system is maintained by the segregation of landward and seaward transport through the inlet throat (arrows show dominant transport direction). From Hubbard *et al.* (1979).

TIDAL DELTAS

Morphology

Within a regional coastal embayment one usually observes a pattern characterized by wave dominated shorelines at the flanks and tide dominance in the center (Price, 1955; Nummedal and Fischer, 1978; Fig. 1). This pattern of change in environmental physical parameters usually is accompanied by a succession of tidal inlet sand body geometries (Fig. 2). All of the sand body geometries depicted in Figure 2 may not necessarily be present within any one embayment. Which particular inlet geometry will exist at a given locality will depend both on the absolute tide range and the mean wave height (Hayes, 1979; Fig. 3).

Wave-induced sediment transport dominates in areas of small tide range. Ebb-tidal deltas have little chance to develop; the sand brought seaward by the ebb is quickly dispersed longshore by surf-zone wave action. Large flood-tidal deltas commonly form because the sand which is brought landward generally is protected from wave reworking. If these microtidal barriers are backed by open lagoons, the flood-tidal deltas assume the configuration of multilobate sand shoals radiating from the inlet (Fig. 4B). The localized deposition of sand immediately behind the inlet is a result of the rapid landward reduction of velocity as the flood current diverges into a large open bay (Barwis and Hubbard, 1976). Development of large flood-tidal deltas is also, in part, due to the fact that the hydraulics of inlets leading into open bays generally creates flood dominance in the velocity asymmetry of the inlet throat (Nummedal and Humphries, 1978).

The back-barrier environment is commonly filled with inter-tidal *Spartina* marsh, as in the southeastern United States, or with extensive tidal flats as in Germany. Tidal flow is confined to narrow channels. In this case, high current velocities are maintained far away from the inlet. The tidal sand bodies become distributed along channel banks or as elongate mid-channel bars.

In areas of intermediate tide range the ebb currents are able to maintain large seaward shoals or ebb-tidal deltas (Fig. 4A). Tidal currents scour deep channels. The marsh or tidal flats which invariably characterize the back-barrier environments of mesotidal shorelines establish an inlet hydraulics pattern which creates ebb dominance in the velocity asymmetry of the inlet throat (Nummedal and Humphries, 1978). Because the source of sand generally

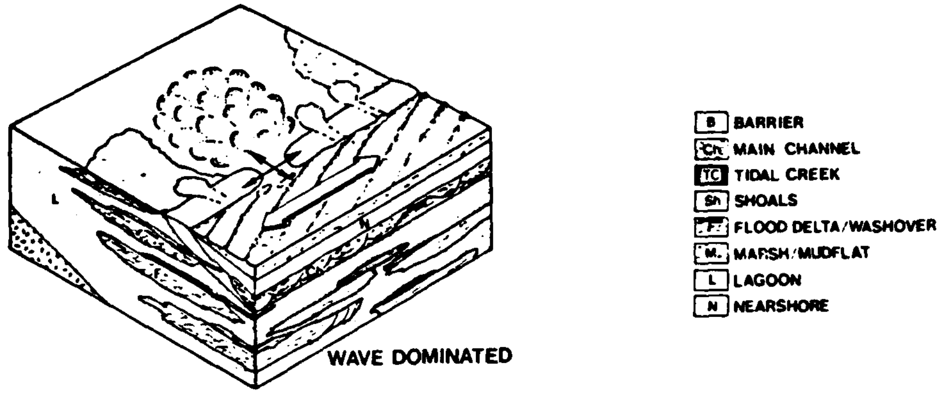

Figure 5. Block diagram showing hypothesized nature of sand bodies produced by wave-dominated inlets. The relative importance of longshore sediment transport vs. tidal transport is indicated by small black arrows. The large white arrow indicates the relative range of migration of the inlet. Note legend on the right. From Hubbard *et al.* (1979).

is the wave-induced longshore transport system, such inlets have no mechanism for a net landward sand transport. Flood-tidal deltas, therefore, are generally non-existent. In some wide tidal inlets, as for example those on the German coast, multiple transport paths exist permitting the development of landward sand shoals even if the main inlet channel remains ebb dominated. Such inlets can best be characterized as transitional (Fig. 4C).

In areas where the tide range exceeds a limiting value of about 4 meters, the on-offshore directed sediment transport caused by the tidal currents dominates over the longshore transport caused by wave-generated currents. Under such conditions, barrier islands cease to exist. These macrotidal estuaries generally are filled with large sigmoidal, lunate or linear sand shoals, with distinctly segregated ebb and flood channels. Extensive tidal flats flank the mainland shores.

Stratigraphy

The preservation of tidal deltas in the stratigraphic record depends on the depth of the tidal channel (i.e., the thickness of the sand body), the local relative sea level change, the migrational history of the inlet and the regressive/transgressive nature of the shoreline.

The weak tidal currents in wave-dominated inlets, combined with strong

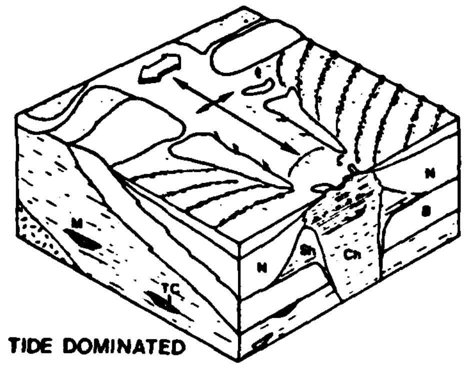

Figure 6. Block diagram showing hypothesized sand body geometries of tide-dominated inlets. Symbols have the same meaning as in Figure 5. From Hubbard *et al.* (1979).

longshore sediment transport, have a tendency to create inlets which migrate rapidly downdrift. Consequently, a tabular shore-parallel sand body, made up of many abandoned flood-tidal deltas, is commonly observed on the bay side updrift of the inlet. By the same process of inlet migration the barrier island will generally be underlain by extensive inlet-fill deposits (Fig. 5). The resulting sand body, whatever its extent, should be bounded on either end by the original channel margin.

In terms of small-scale stratification, the wave-dominated inlets are characterized by landward-directed trough cross-stratification and plane laminations. Washover deposits abound on the adjacent barrier islands. There is generally not a distinct vertical change in grain size or scale of sedimentary structures (Hubbard *et al.*, 1979).

Tide-dominated inlets are generally deep and much more stable. As a consequence, the channel fill will form an isolated cut through the barrier island sands. Inlet fills would be frequent and quite regularly spaced. The individual tidal-delta sand bodies will form lenticular units of limited extent. The long axis of the sand body is likely to trend normal to local shoreline strike (Fig. 6).

In vertical section, a tide-dominated inlet sand body would have a lag of shell hash or other coarse clasts at the base of the sequence. This would be overlain by bidirectional trough cross-stratification from the main channel and bidirectional (herringbone) or ebb-oriented planar and trough cross-strata from the shallower channels. The top of the sequence would be dominated by swash-generated planar laminations formed on channel-margin and swash platform bars (Fig. 6).

Macrotidal embayment sand bodies would be conspicuous in terms of their great thicknesses and lateral extents. There would be a distinct vertical and lateral segregation of ebb-oriented and flood-oriented planar and trough cross-strata. Set thicknesses of planar cross-strata would commonly greatly exceed the set thicknesses of individual cross-stratified units in other inlet types. Paleoflow directions would be parallel to the axis of the macrotidal embayment. Finally, the tidal sand bodies would be continuous, and no barrier island sands would be present in the section.

TIDAL FLATS

The tidal flats are readily separated from the inlet-associated sand bodies in terms of finer grain size, extensive bioturbation, minor primary sedimentary structures and thin cut-and-fill units reflecting the migration of generally shallow tidal channels. The sub-environments show a distinct shore-normal gradation: towards the mainland the sediments become generally finer, the biologic reworking more complete, and the individual channel sand bodies less frequent and smaller. In a regressive shoreline sequence, the tidal flat environment will form a laterally continuous fining-upward unit (Klein, 1977).

CONCLUSIONS

Tidal inlet sand body geometry reflects primarily the relative importance of wave and tidal energy along the shoreline. Factors like tidal prism, inlet cross-section, and the geometry of the back-barrier bay also affect the size and distribution of individual sub-environments. The overall sand body geometry as well as the lateral and vertical facies variability should permit differentiation of wave and tidal-dominated inlets.

The spatial distribution of inlet types follows the regional pattern of the shoreline arc: tide dominance in the center and wave dominance at the flanks.

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Discussions with Dennis Hubbard, Duncan FitzGerald and Miles Hayes contributed immensely to the ideas here put forth. Field work in Germany was sponsored by the Office of Naval Research, Geography Programs, through contract no. N00014-78-C-0612 to Louisiana State University.

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The spatial distribution of inlet types follows the regional pattern of the shoreline arc: tide dominance in the center and wave dominance at the flanks.

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Department of Geology
Louisiana State University
Baton Rouge, LA 70803

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Dag Nummedal and Shea Penland

1981

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SEDIMENT DISPERSAL IN NORDERNEYER SEEGAT, WEST GERMANY.

Dag Nummedal
Shea Penland
Department of Geology
Louisiana State University
Baton Rouge, LA 70803 USA

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INTRODUCTION

The relative magnitude of wave versus tidal energy has long been recognized as the most crucial factor controlling tidal inlet sand body geometries. Bruun (1966) considered this when he quantified inlet stability, and sediment bypassing mechanisms, in terms of the ratio between tidal prism and littoral transport rate. More recently, O'Brien (1976) applied the concept to formulate a "closure index", defined as the ratio between tidal prism and wave power. Jarrett (1976) and Walton and Adams (1976) discovered, through statistical analysis of inlets along the coastline of the United States, that both the cross-sectional area of the inlet gorge and the volume of the associated ebb delta increase with the tidal prism and decrease with increasing wave energy. These results are all consistent with the concept advanced by Inman and Frautschy (1966) which states that the equilibrium size of an inlet is controlled by a balance between the scouring action of the tidal currents and the infilling by sediment in longshore transport.

These discoveries suggest that there should be a direct link between the ratio of wave energy to tide energy and the size, geometry, location and sedimentary structures of inlet-associated sand bodies. A series of recent papers have investigated this problem. Following the discovery by Price (1955) that coastal embayments generally are wave-dominated at the flanks and tide-dominated in the center, the approach in these studies has been to compare morphology and sedimentation patterns between inlets in different positions within the embayment. The strongly tide-dominated inlets on the southern South Carolina and Georgia coasts (FitzGerald _et al._, 1976; Oertel, 1975) are but one extreme of a spectrum which ranges through transitional inlets in northern South Carolina and north-east Florida (Hubbard et al., 1977; Penland, 1979) to wave-dominated inlets at North Carolina's Outer Banks (Nummedal et al., 1977). A very similar regional pattern of variability is found in the southeastern embayment of the North Sea (Nummedal and Fischer, 1978).

Studies of inlet sand-body geometries within both the German and the Georgia Bights have lead to the identification of a continuum of inlet morphologic types; from the completely wave-dominated ones with large flood-tidal deltas and very small ebb-tidal deltas to the completely tide-dominated ones with non-existent flood-tidal deltas and large ebb-tidal deltas (fig. 1).

The geometries of these sand bodies and the internal stratification, reflect the dominant pathways of sand dispersal within the inlet system. Given the fact that a wide range of inlet geometries occur, there is a corresponding range in inlet sediment dispersal and bypassing mechanisms. Detailed documentation of sand dispersal has been presented for only a few inlets on the American east coast; all of these are subject to rather low wave energy. The primary objective of this paper is to present a sediment dispersal model for an inlet with a high tide range situated in a high-wave energy environment. The chosen site is Norderneyer Seegat on the Friesian coast of West Germany (fig. 2). The geometry of this inlet would correspond to frame no. 3 in figure 1. Norderneyer Seegat falls in the mesotidal inlet category, using the tide range classification proposed by Davies (1964) and inlet models first proposed by Hayes (1975).

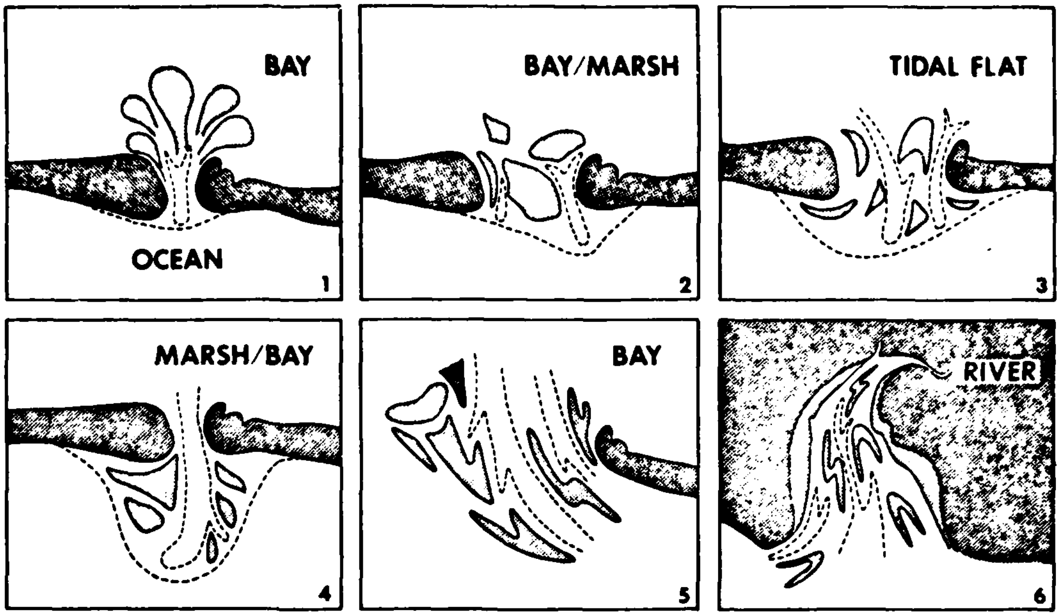


Fig. 1. Schematic display of inlet and sand-body geometries observed in the German and Georgia Bights. Frame 1 identifies the typical floodtidal delta of a wave-dominated inlet into a coastal bay, frames 2 and 3 show the progressive displacement of sand-bodies in a seaward direction as the tidal influence increases; frame 4 identifies the typical ebb-tidal delta of a strongly tide-dominated inlet on the South Carolina or Georgia coast; frame 5 shows the sand-body geometries at the entrance to the Weser estuary where the tide dominance is so strong that barrier islands are about to disappear; and frame 6 schematically displays sand-bodies in Nushagak Bay, Alaska, a large macrotidal coastal embayment. From Nummedal & Fischer (1978).

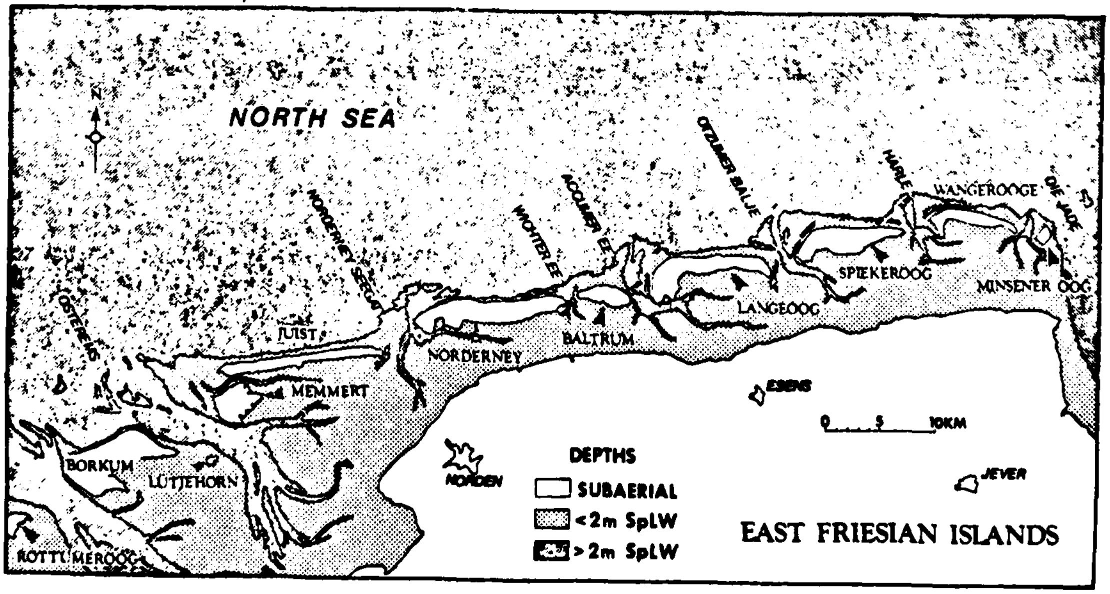


Fig. 2. Map of the East Friesian Islands in the province of Lower Saxony, Republic of Germany. Depth is referred to mean spring low water (SpLW). For location of this area, see Fig. 4.

PHYSICAL PARAMETERS

The variation in tide range along the open coast of the German Bight is controlled by the North Sea amphidromic system. Classical models of the M_2 tide demonstrate the existence of a counter-clockwise rotation of the tidal wave around an amphidromic point between Jutland and England (Defant, 1958). Iso-range lines are nearly equidistant about this point. Therefore, the central German Bight, which is further away from the amphidromic point than is Jutland and the northwest corner of the Netherlands, has the greater tide range (fig. 3). The mean tide range at Norderneyer Seegat is 2.5 m. Tide range increases eastward to 2.9 m at Harle and about 3.8 m at the entrance to the Jade, Weser and Elbe Rivers (Deutsches Hydrographisches Institut, 1979).

Evaluations of the regional variability in nearshore wave climate is presently impossible because reliable wave records are very scattered and typically of too short duration to be of much use in long-range sedimentation studies. In order to derive a consistent picture of wave energy variability, therefore, it was decided to utilize the Summary of Synoptic Meteorological Observations (SSMO - data) published by the U.S. Naval Weather Service Command (1974). Wave power distributions within pre-established data squares were calculated by a procedure outlined in Nummedal and Stephen (1978). In this same article the authors have also discussed in some detail the assumptions and problems associated with the utilization of SSMO-data in studies of coastal sedimentation dynamics.

SSMO-derived deep-water wave power values for data squares along the periphery of the North Sea are summarized in table 1 and figure 4. One observes a distinct southward decrease in total wave power. This decrease is clearly fetch controlled. The dominant and prevailing winds at

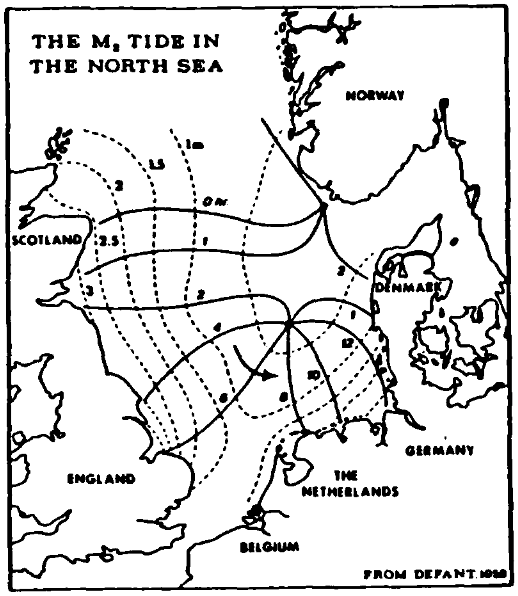


Fig. 3. Co-tidal lines of the M_2 tide in the North Sea (solid lines) and co-range lines (dashed). The tide affecting the German coast rotates counter-clockwise about an amphidromic point near the middle of the North Sea. Figure modified after Defant (1958).

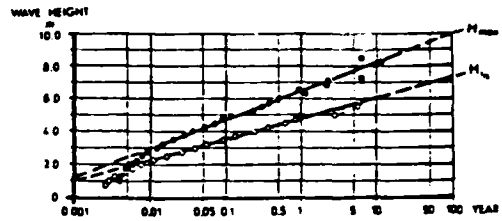


Fig. 5. Wave height-frequency diagram for a station in 8 m of water off Sylt. H_{max} and $H_{1/3}$ refer to maximum and significant wave heights, respectively (from Dette, 1977).

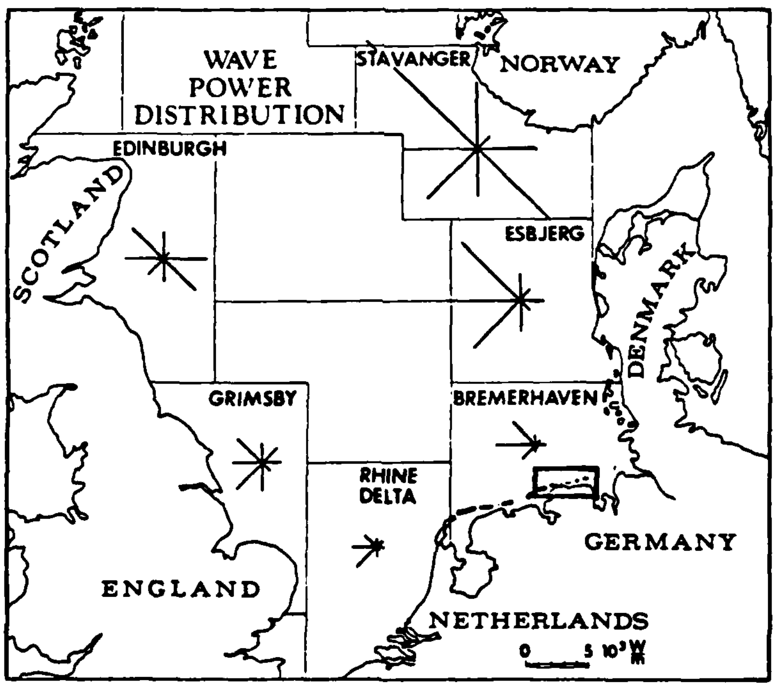


Fig. 4. Wave power distributions along the periphery of the North Sea. Calculations are based on data published by the U.S. Naval Weather Service Command in the Summary of Synoptic Meteorological Observations (SSMO). The length of the bars is proportional to the mean annual wave power from each direction, i.e. the power diagrams are plotted like wind roses (from Nummedal & Fischer, 1978). Dark rectangle identifies area shown in Fig. 2.

Norderney come from the southwest (Luck, 1976a). This wind direction causes the wave power directed along the shore to exceed that directed perpendicularly onto shore.

Table 1. Wave power values for SSMO data squares along the margins of the North Sea. Wave power in units of 10^3 Watts/m.

Data Square / Direction	Edin-burg	Grims-by	Rhine Delta	Bremer-haven	Esb-jerg	Stavan-ger
N	2.1	1.5	.8	.7	2.1	5.1
NE	.5	1.5	.7	.3	1.0	1.4
E	3.3	1.5	.5	.8	1.8	4.5
SE	3.4	.8	.3	.3	1.0	7.8
S	1.8	2.1	.7	.5	2.3	3.8
SW	1.7	2.8	2.1	1.5	5.0	5.4
N	3.0	2.3	1.9	2.9	5.5	9.8
NW	3.3	2.7	1.4	2.4	6.3	11.8

onto the shore all along the East Friesian coastline. The resultant power for the Bremerhaven data square points to the east-southeast (azimuth = 101°). This resultant vector yields a net eastward longshore power component of 4.44×10^3 Watts per meter.

Nearshore wave data, based on in-situ gages, are available for Norderney (Niemeyer, 1978) and for Westerland at Sylt (Dette, 1977). Niemeyer's primary objective was to analyze the wave damping across the tidal delta bars. A long-range time series for proper evaluation of a wave high-frequency curve is not yet available. The measurements obtained, however, indicate an average significant wave height ($H_{1/3}$) exceeding 1.6 m in 10 meters of water depth. Dette (1977) presents wave height-frequency diagrams for a station in 8 m of water off Sylt. These data indicate that significant wave heights exceed 1 m on a daily basis, 4.8 m on an annual basis and (extrapolated) 7.3 m once every one hundred years (fig. 5).

HISTORIC-MORPHOLOGIC EVOLUTION

The Forshungsstelle Norderney has published a map series at a scale of 1:50,000, which reconstructs the Friesian coast at approximately one hundred-year intervals since year 1650 (see for example Luck, 1975). The map series has been produced under the principal direction of Mr. Hans Hommeier.

According to these historical maps, Norderney's existence can be traced back to a breaching of the barrier island of Buise between 1350 and 1400 A.D. (fig. 6). Following the breach, Osterende (later:Norderney) began to grow while Buise decreased in size and ultimately disappeared as a subaerial island by the year 1750. The disappearance of Buise correlated with the eastward growth of Juist.

The subaerial size of Norderney increased by 117 per cent between 1650 and 1960 (Luck, 1975). At the same time Norderneyer Seegat migrated an insignificant amount to the east. The inlet appears to be anchored in a major erosional valley which extends northwards from Norddeich (Luck, 1970). This relationship demonstrates conclusively that there is an efficient pathway of sediment bypassing around Norderneyer Seegat (fig. 7).

It has been pointed out by Oertel (1975, 1977), Nummedal et al. (1977) and Hubbard et al. (1979) that the pattern of asymmetry in an ebb-tidal delta directly reflects the relative magnitudes and directions of wave-induced and tidal-induced sediment transport. Oertel's (1977) schematic representation is reproduced in figure 8.

The asymmetric, strongly eastward-directed net wave power and a residual tidal current combine to produce a skewed ebb-tidal delta at Norderneyer Seegat. The general bathymetry (fig. 9) demonstrates that this inlet corresponds closely to Oertel's (1975) type B inlet.

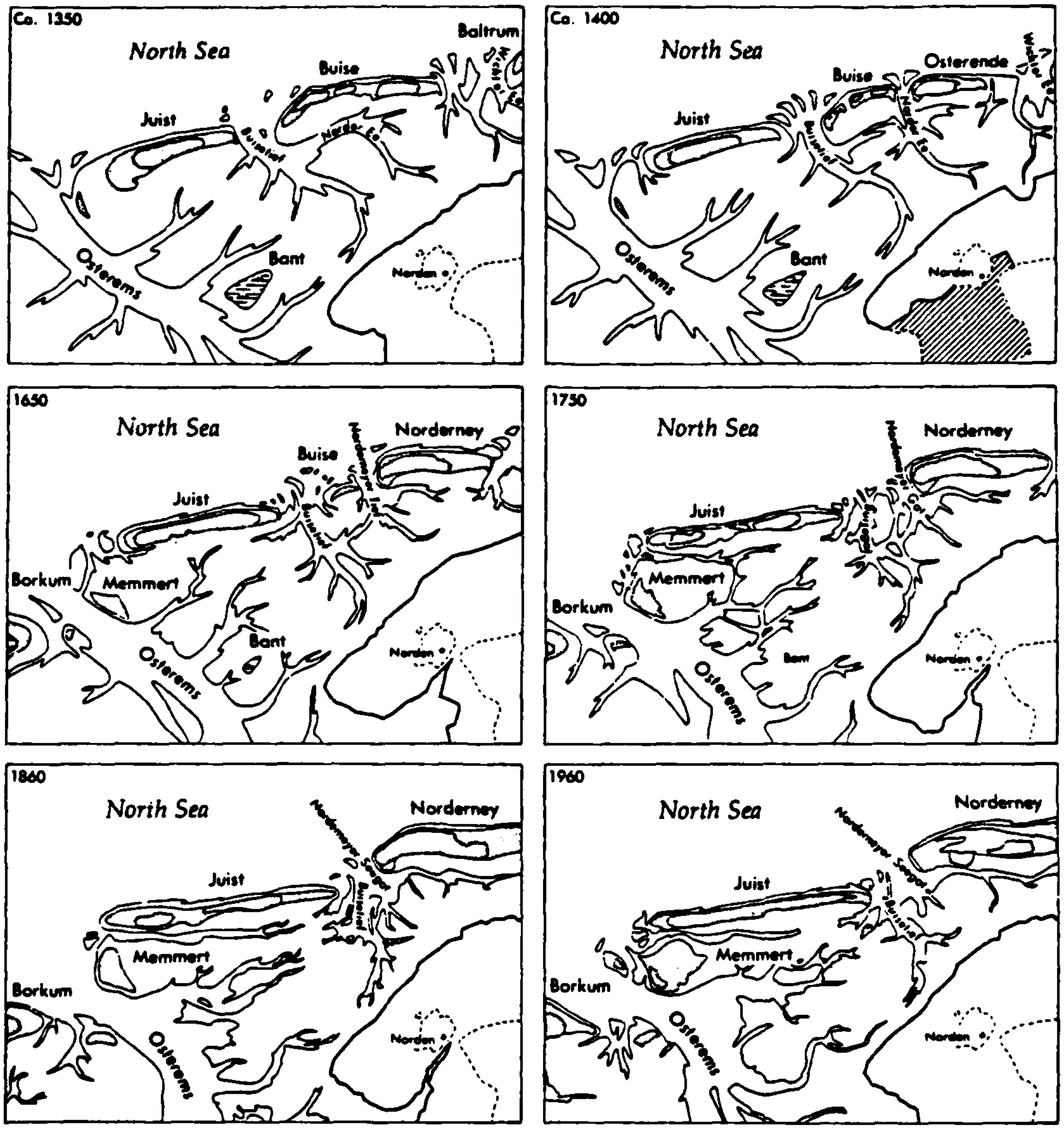


Fig. 6. Historic-morphological maps of the Norderneyer Seegat region from 1350 to 1960. Note the disappearance of Buise between years 1650 and 1750 and the eastward displacement of Busetief in response to the growth of Juist. Norderneyer Seegat has remained stationary (from Luck, 1970).

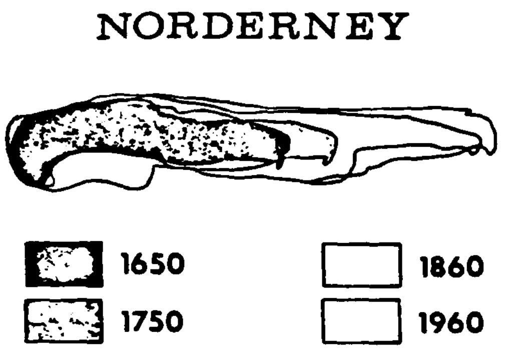


Fig. 7. Growth of Norderney above the mean high water line since 1650. The figure is based on the 1:50,000 historical map series of the coast of Lower Saxony (see Luck, 1975).

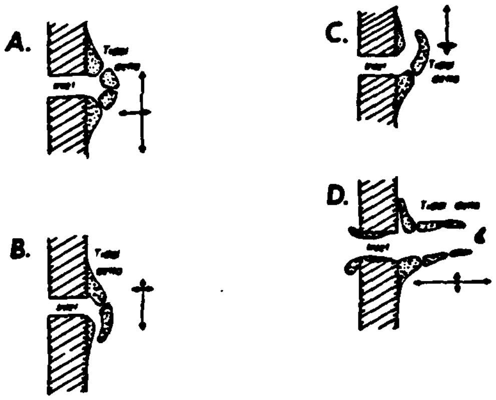


Fig. 8. Ebb-tidal delta asymmetries observed along the Georgia coast, reflecting different relative magnitudes of tidal and longshore currents. Arrow lengths are proportional to relative current magnitudes (from Oertel, 1975).

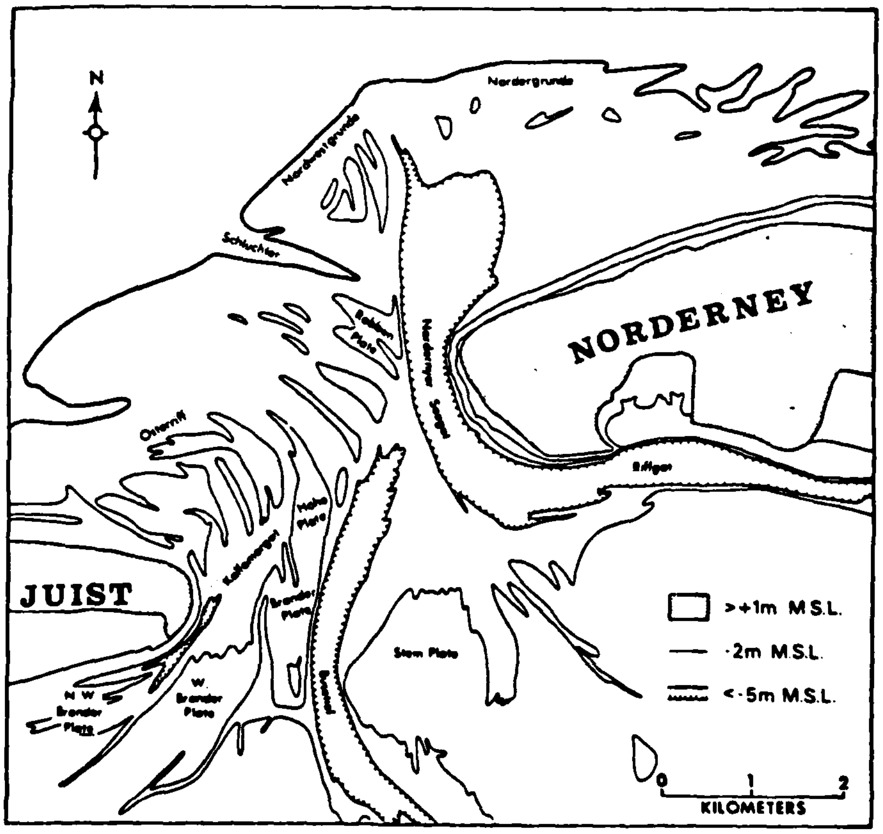


Fig. 9. Bathymetric map of Norderneyer Seegat with labels identifying the major channels and sand shoals (*platen*). This map is based on bathymetric chart no. 5 by the Forschungsstelle Norderney. The original map was published in 1962.

Through combined use of historical data, bedform orientation maps, tracer dispersal data and current velocity observations an attempt will now be made to describe and explain the tidal delta asymmetry and the complex interactions of sediment dispersal responsible for the configuration of the sand bodies in Norderneyer Seegat.

THE NORDERGRÜNDE BARS

A set of historic-morphological data of direct relevance to the understanding of inlet dynamics are the time sequence maps of tidal delta bars (in German: riffbogen). These bars are refered to as the "reef-bow" by Luck (1975, 1976b). Some of these bars would correspond to delta margin "swash bars" in the terminology of Hayes et al. (1973) and Hayes (1975).

Annual mapping of the bars was carried out between 1926 and 1957 (Hommeier and Kramer, 1957). Several annual maps are illustrated in figure 10 to document the rates and patterns of morphological change. Figure 11 presents summary data on the paths of movement of the centers of gravity of selected individual bars between 1926 and 1957. The rate of bar movement is remarkably uniform, averaging 406 meters per year, with a standard deviation of only 85 m/year. Furthermore, the paths traveled by the center of gravity of individual bars from Nordwestgründe, through Nordergründe and onto the beach at Norderney, all follow essentially the same pattern. The inner bars generally move somewhat slower than the more exposed ones, and weld to the shoreline further west. This pattern of trajectories is established as a long-range path of dynamic equilibrium between the seaward-directed momentum of the expanding ebb

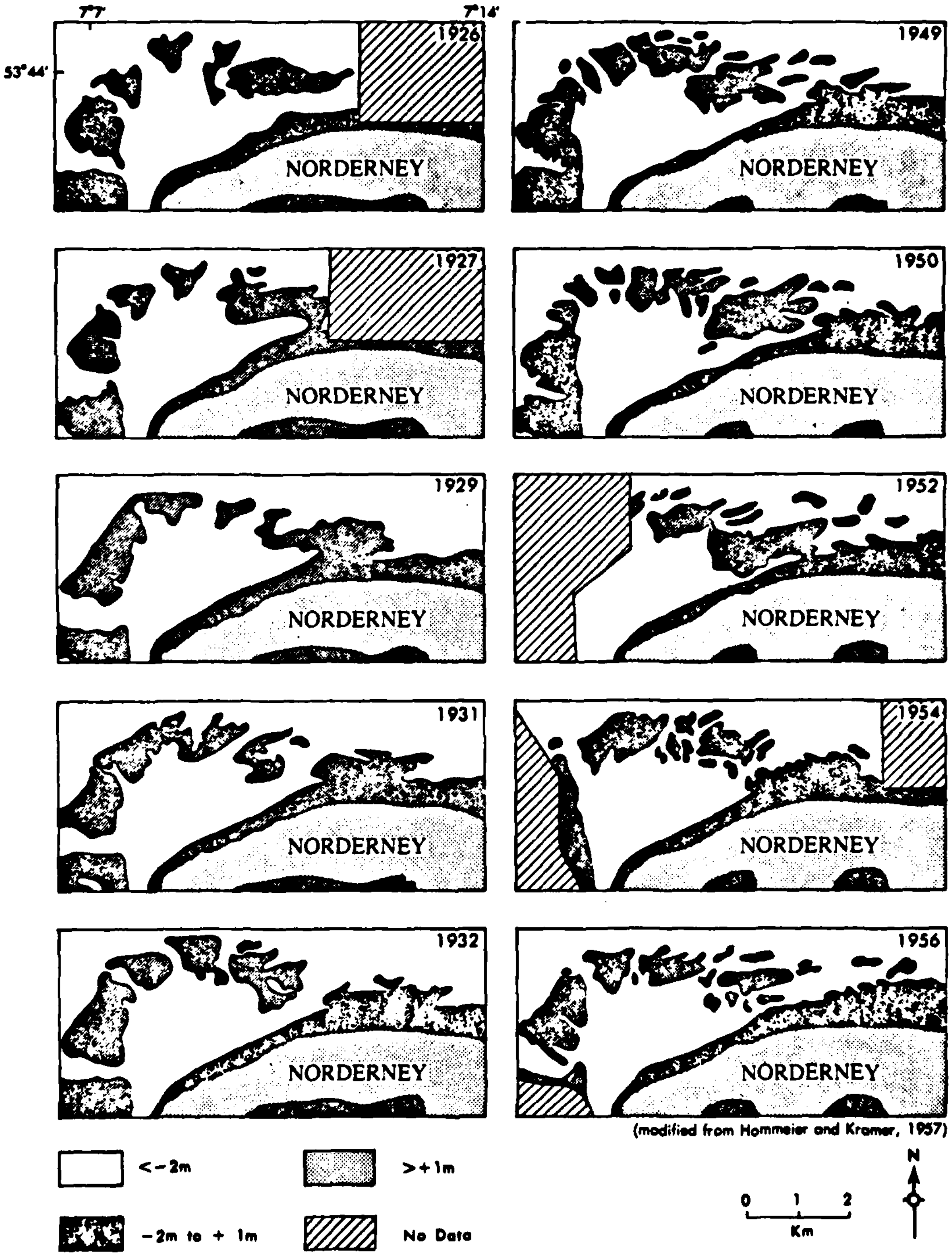


Fig. 10. Morphological changes in the ebb-tidal delta bars at Norderneyer Seegat for two selected time periods illustrating bar welding on to Norderney (from Homeier & Kramer, 1957). For additional information see Luck & Witte (1973).

current and the landward and eastward directed momentum of the shoaling waves. The residual tidal current on the shelf immediately seaward of the Norderneyer Seegat tidal delta is also oriented to the east.

The morphology of these bars along the ebb-tidal delta margin changes distinctly as one moves east from Schlucter. At Nordwestgründe most bars are crescentic in shape, their long axes are oriented NW-SE (fig. 12A). They consist of a high crest along their NE flank, which acts as a flood shield (terminology from Hayes et al. 1969, Klein, 1970). Their wide, gently sloping SW flank is covered with large ebb-oriented sand waves. Within the Nordergründe complex the bars are of more variable shape.

In the west, near Dovetief, there is still some evidence of tidal current control. Multiple surveys in this region in the summer of 1979, with a precision depth recorder (PDR), failed to detect any large-scale bedforms or swash-bar slipfaces. There is no preferred bar orientation. Further east in Nordergründe the bars develop a more shore-parallel orientation and a landward-dipping slipface (fig. 12B). This indicates that tidal currents in this area play a subordinate role. These bars correspond to the "swash bars" in Hayes (1975) model. The final stage of attachment involves an extension of the bar parallel to the beach (fig. 12C, Hommeier and Kramer, 1957) followed by the classical process of landward migration of a ridge-and-runnel system to form a beach berm (Davis et al. 1972). Similar patterns of swash-bar beach attachment have been documented for North Inlet (Finley, 1976; Nummedal and Humphries, 1978) and Price Inlet (FitzGerald et al., 1978) in South Carolina.

The eastward movement of bars from Nordwestgründe to the beach at Norderney appears to occur under the influence of flood and ebb-segregated tidal currents (Nordwestgründe), wave-induced longshore currents (Nord-

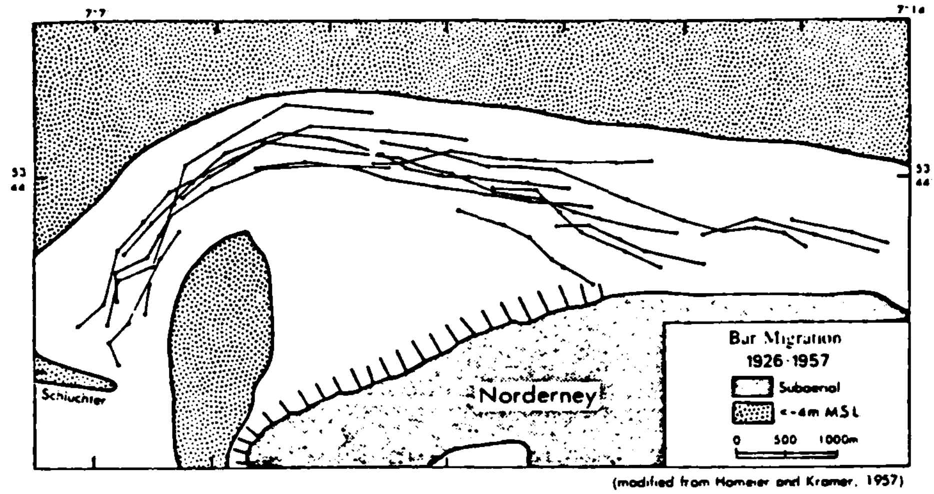


Fig. 11. Map depicting the annual displacement of the centres of gravity (dot) of individual bars between 1926 and 1957. Bar migration is consistently from left to right (from Homeier & Kramer, 1957).

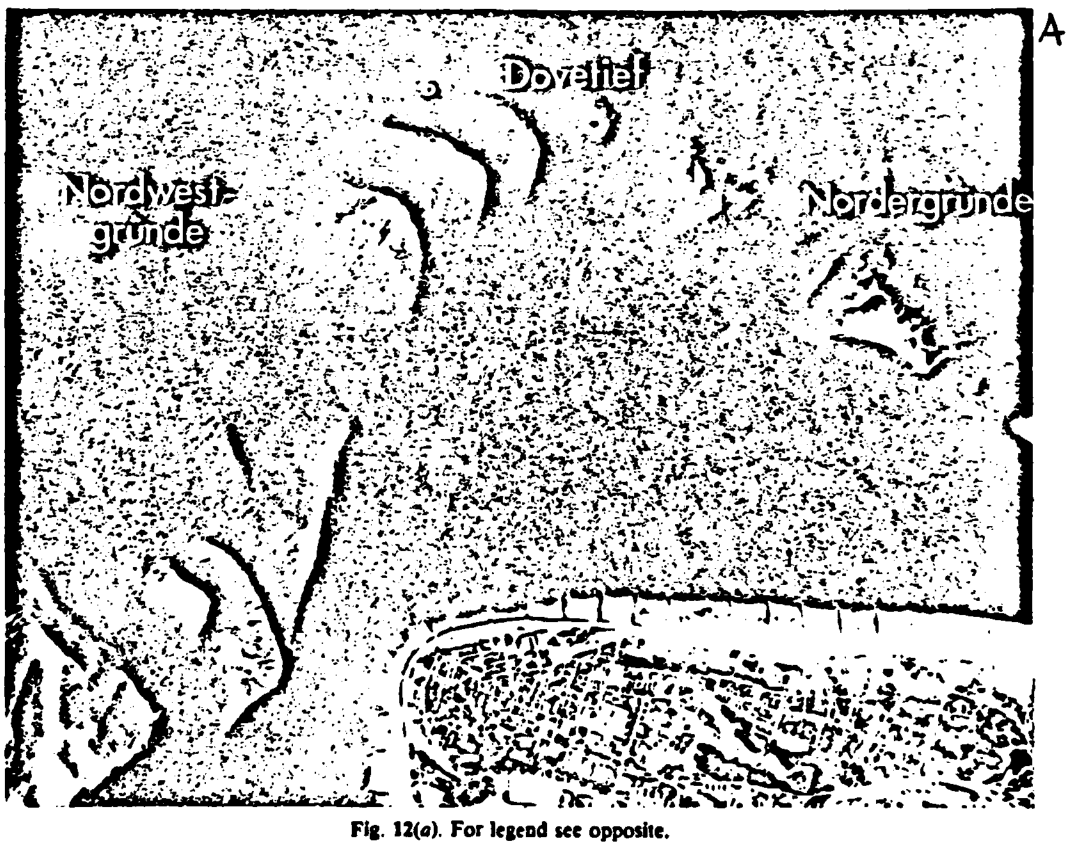


Fig. 12(*a*). For legend see opposite.

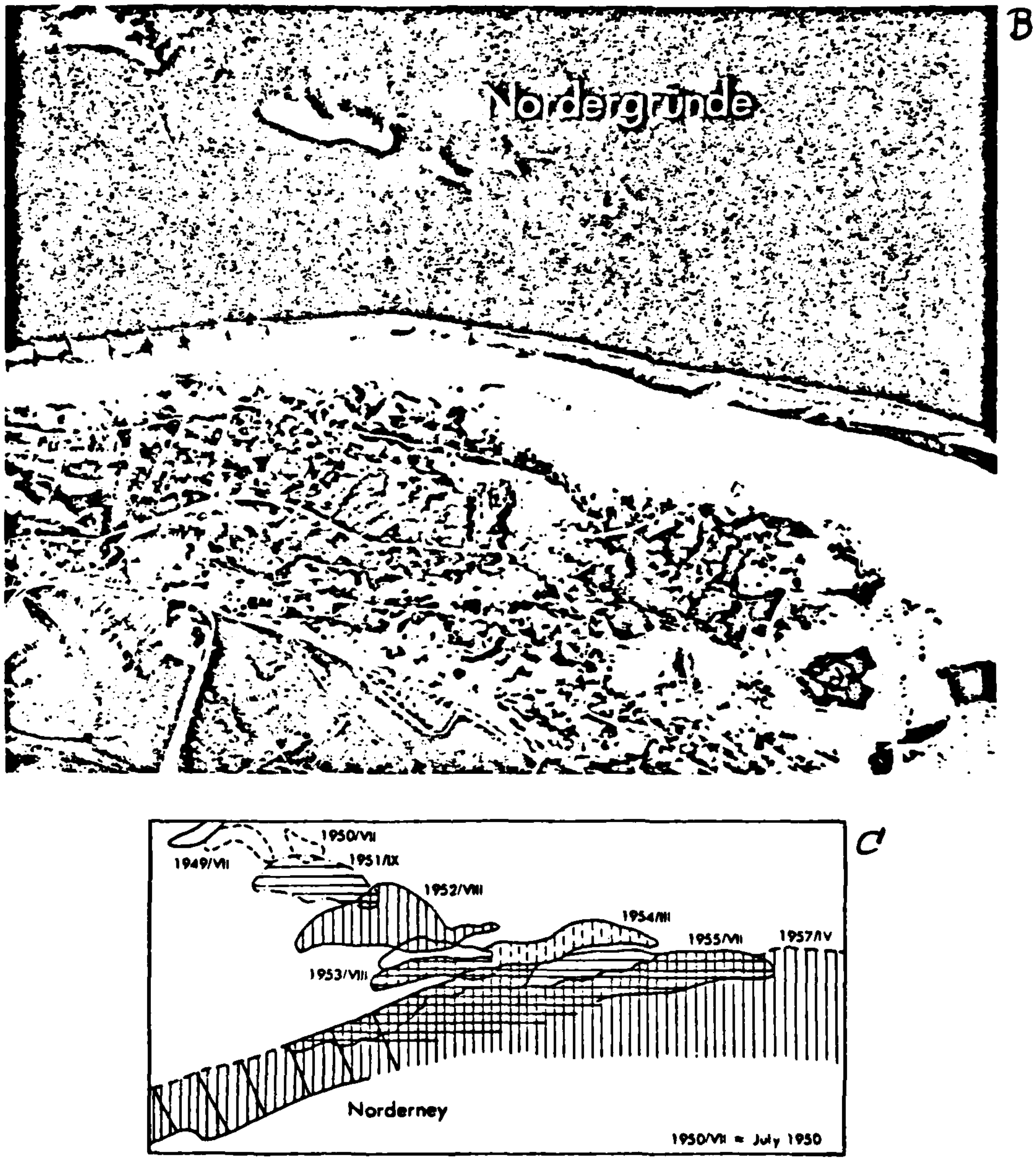


Fig. 12. Illustration of morphological changes associated with the migration of the bars from Noidwestründe to Norderney. (A) Vertical airphoto (23 June 1973) of Nordwestgründe and central Nordergründe. Note bedforms and the crescentic bar shape demonstrating strong tidal-current influence within the western (left) two-thirds of this region. (B) Vertical airphoto (23 June 1973) of the nearshore region of the Nordergründe swash-bar complex. Note landward-dipping slipfaces on the bars. These indicate that sediment movement here is controlled by breaking waves. Both airphotos were obtained through the courtesy of the Forschungsstelle Norderney. (C) Map of the beach attachment process of a single large swash bar in the period between 1949 and 1957. Note the gradual bar extension in a shore-parallel direction during the attachment process (from Homeier & Kramer, 1957).

ergründe), wave swash (east Norderergründe) and the eastward-directed resultant inner-shelf tidal current.

The bar complex has steadily grown in size since 1926 (Hommeier and Kramer, 1957). There is, however, no evidence of bar migration towards the inlet gorge. This latter pattern of migration is quite prevalent for some of the South Carolina inlets (FitzGerald et al. 1978). The strong longshore component of wave power at Norderney appears to favor bar-bypassing rather than return of sediment to the inlet gorge by wave swash.

OSTERRIFF AND SCHLUCHTER

Prior to 1700 the inlet east of Juist was Buisetief (fig. 6). With the disappearance of Buise most of Busetief's drainage was diverted into Norderneyer Seegat, greatly diminishing the water exchange through the channels at the east end of Juist, now named Kalfamergat. Recently, however, Kalfamergat has increased in cross-section. Data used for the bathymetric chart of figure 9 were compiled prior to 1962. At that time Kalfamergat had a maximum depth of 5 meters. The July 1979 survey demonstrated that the channel gorge now is 16 meters deep; it has also increased greatly in width. Figure 13 further demonstrates that the main Kalfamergat channel bifurcates to the north, with the western channel branch feeding the southern lobe of the Osterriff spillover lobe complex, the eastern branch leading into the region of the previously existing Spaniergat. In fact, it is here hypothesized that the infilling of Spaniergat is a direct consequence of the enlargement of Kalfamergat. This, in turn, is related in a complex was to changes in back-barrier drainage.

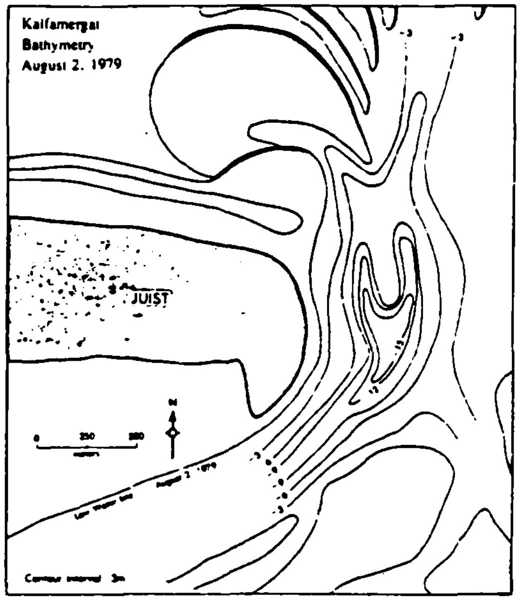


Fig. 13. Bathymetric map of the Kalfamergat region based on multiple PDR surveys in a radial pattern from the beach at Juist.

Fig. 14. Oblique airphoto towards the north of Brander Plate (A), Kalfamergat (B), Osterriff (C), and Hohe Plate (D). The Brander Plate region and Osterriff constitute the flood- and ebb-tidal deltas, respectively, with reference to Kalfamergat.

The seaward depositional lobes related to the Kalfamergat channels constitute Osterriff (fig. 14). At its western margin, near the north shore of Juist, the Osterriff bars assume the characteristic morphology of an ebb-spillover lobe (fig. 15A). Persistent ebb-oriented sand waves characterize the broad center of the lobe (fig. 15B). The bar crest acts as a flood-shield. The seaward margins of the flood shields and the immediately adjacent channels act as conduits for landward sediment transport due to the momentum flux of obliquely breaking waves (Longuet-Higgins, 1970) and the effect of "wave-pumping" (Bruun and Kjelstrup, 1977). The tidal component of the current along this outer bar flank is probably also flood dominant. A similar interaction of current components has been proposed to explain the maintenance of the marginal flood channel at Price Inlet, South Carolina (Huntley and Nummedal, 1978).

Bars at the northern margin of the Osterriff complex are lunate with an ebb-dominated gently westward-sloping surface and a steep flood-dominated east flank (fig. 15C). Large flood-dominated sand waves exist in slightly deeper water behind the bars (fig. 15D). The spatial arrangement of flood- and ebb-dominated paths in this bar complex is not yet completely determined. Suffice it here to say that pathways do exist for alternating landward and seaward sand transport. This tidal flow is superimposed on a net eastward-directed wave-induced mass movement across the bar complex. The net result is sand movement to the east. The distribution of intertidal bedforms in Osterriff is consistent with this dispersal pattern (fig. 16).

Sand moving across the Osterriff complex from the shoreface at Juist may reach the Nordergründe swash bars and thence Norderney, through two separate pathways: (a) across Schluchter to feed the Nordwestgründe bars,

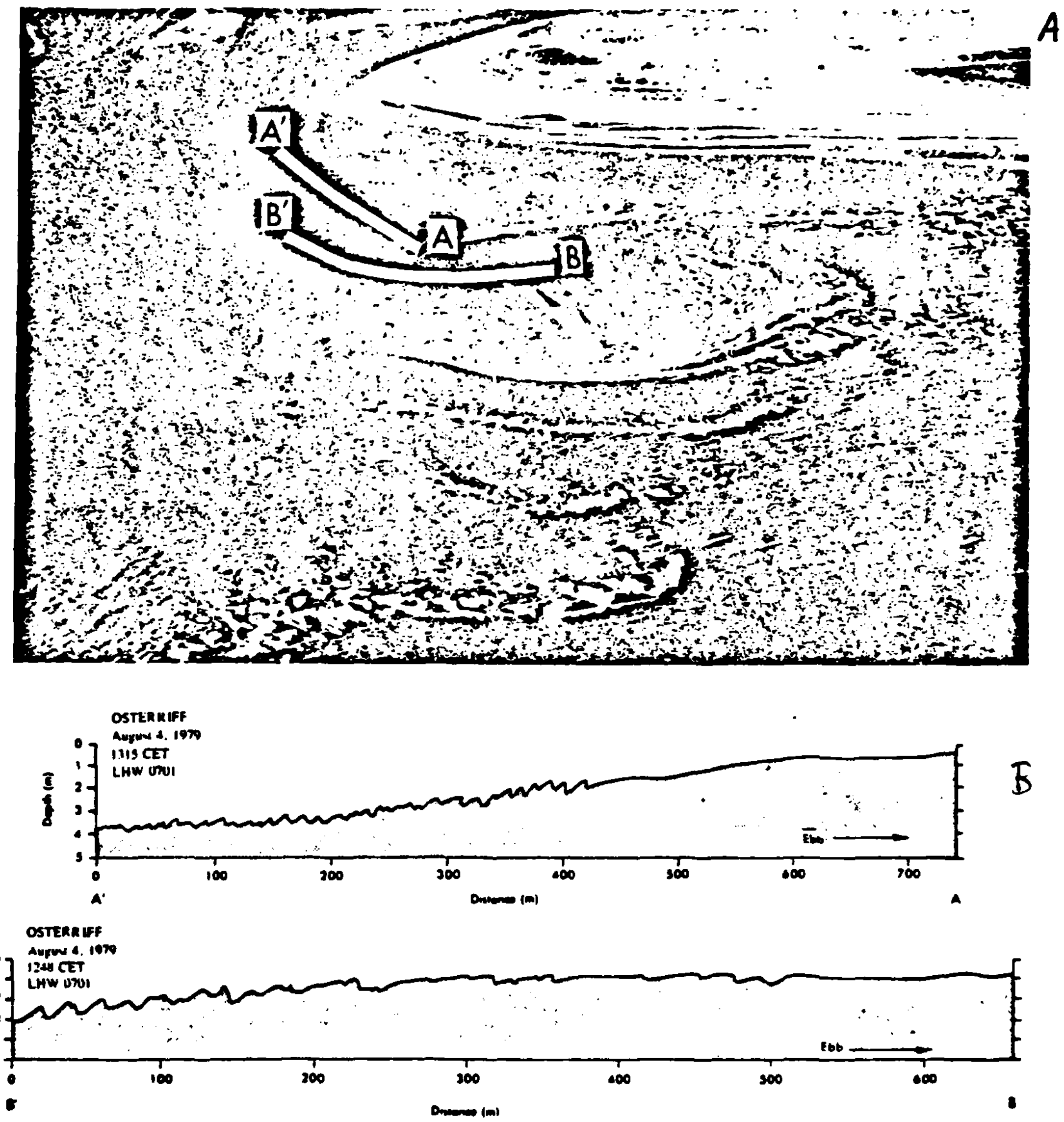


Fig. 15(*a*) and (*b*). For legend see opposite.

d

D

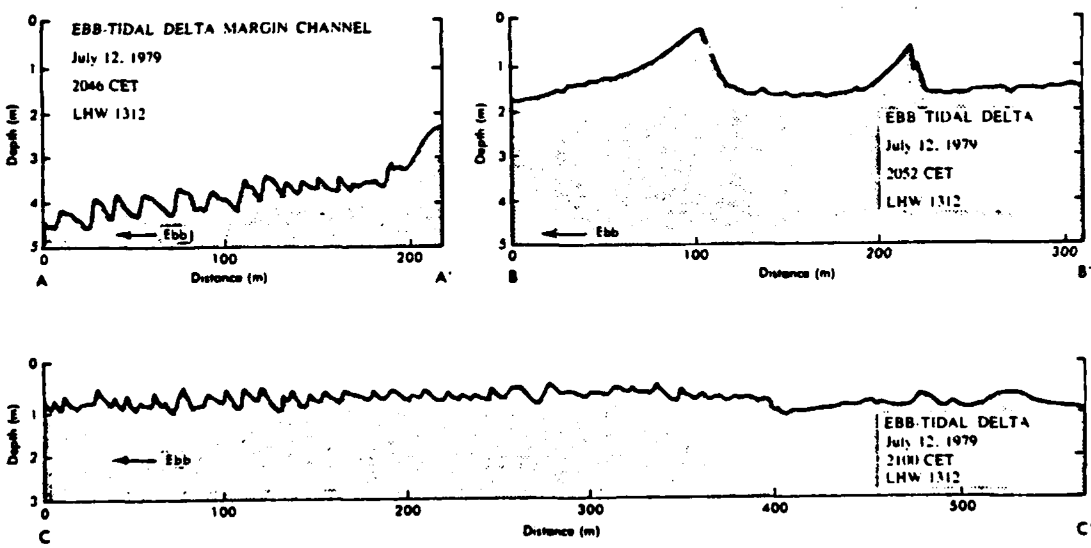


Fig. 15. Morphology and bedforms of the Osterriff bar complex. (A) Ebb spillover lobes near the north shore of Juist. View to the south. White lines indicate locations of PDR profiles shown in (B). (B) Bedform profiles obtained near low water in Osterriff on 4 August 1979. Note ebb-directed asymmetry of all large-scale bedforms. (C) Northern margin of the Osterriff complex. View is to south east, with Hohe Plate in the background. White line indicates location of PDR profile shown in (D). (D) Selected segments of bedform profile obtained near low water in Osterriff on 13 July 1979.

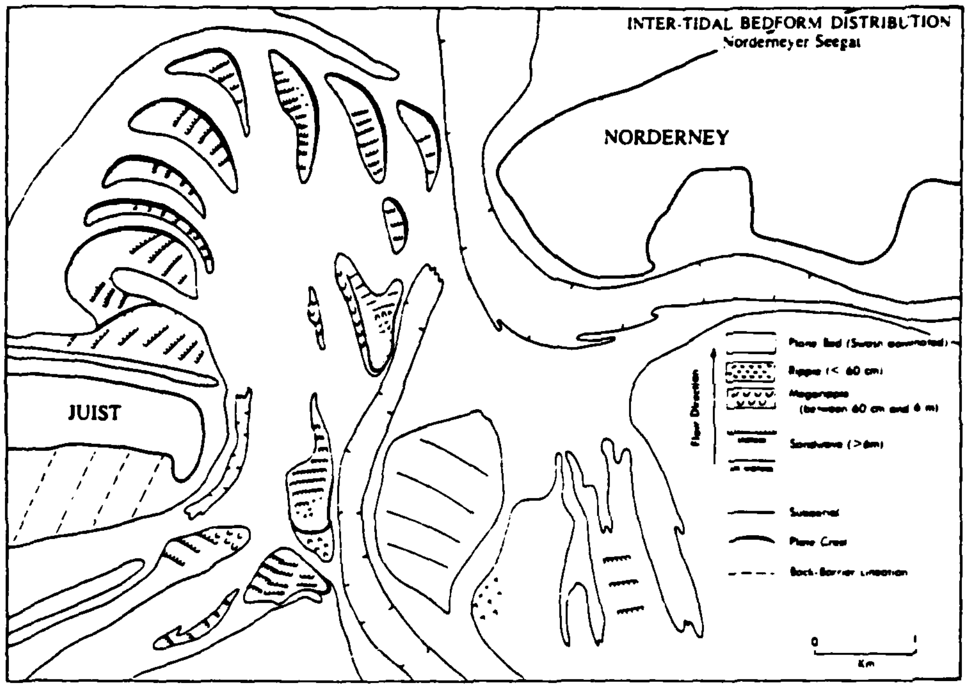


Fig. 16. Map of intertidal bedforms on sand shoals in the central part of Norderneyer Seegat. The map is based on multiple surveys and reconnaissance air flights extending from June to August of 1979. See Fig. 9 for identification of specific shoals. Terminology after Boothroyd & Hubbard (1974).

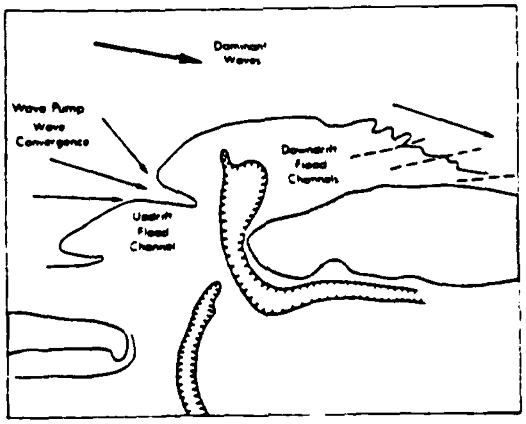


Fig. 17. Schematic illustration of the relative significance of wave pumping on the maintenance of updrift and downdrift marginal flood channels.

and (b) delivery into Norderneyer Seegat and Busetief via Robben Plate, Hohe Plate and Brander Plate; followed by seaward transport through the ebb-dominated main channel of Norderneyer Seegat.

The discussion in this paragraph is limited to path (a). Net sand transport in Schluchter is difficult to ascertain. There are no time-series current data; furthermore, attempts at profiling failed to reveal any bedforms, due to rough seas. There are current data for Spaniergat, however, obtained in 1949, at a time when that channel apparently occupied the same functional role in the Norderneyer dispersal system as Schluchter does today. These data demonstrate flood-dominance under normal conditions, with short periods of ebb-dominance associated with extreme south-westerly winds. The presence of a flood-dominated channel at Schluchter corresponds, in a general sense, to the concept of a marginal flood channel as proposed by Oertel (1972) and Hayes et al. (1973) for inlets along the south-east coast of the United States. Because Osterriff should be considered a separate inlet "nested" within the larger Norderneyer Seegat system, Schluchter occupies the same position relative to Norderneyer Seegat as a typical marginal flood channel in Hayes _et al_'s. (1973) model. Prior to the recent growth of Kalfamergat, Spaniergat probably also played the role of marginal flood channel.

Marginal flood channels develop, in part, in response to the time-lag between ocean and bay tides. Because of this lag (Nummedal and Humphries, 1978) the ocean tide begins to rise while the main inlet channel is still ebbing. The incoming flood currents are initially forced to avoid the expanding ebb jet, and do so by entering the inlet through flood channels across the swash platform margins. If tides alone were responsible for the ebb-delta morphology, marginal flood channels should form symmetrically around the inlet, they should be about equal in size and conduct the same flood discharge. Nature, however, generally displays great asymmetry in the degree of flood channel development. The bathymetric map of Norderneyer Seegat (fig. 9) shows Schluchter to be a deep large channel. Historical maps demonstrate that Schluchter has always been at that location (fig. 10). It has been essentially invariant in size. On the east side of the swash platform, on the other hand, marginal flood channels have been rather ephemeral features. Hommeier and Kramer (1957) report that a major channel, 3 meters deep, once separated the east end of the Nordergründe swash bar complex from the beach at Norderney. This channel reached its maximum size in 1923; but has subsequently been infilled. Smaller marginal flood channels have periodically opened and filled. Periodic opening and closing of downdrift flood channels is a common process (FitzGerald et al., 1978; Nummedal and Humphries, 1978). Updrift flood channels are always more persistent.

Schluchter, and indeed updrift flood channels on the ebb-tidal deltas investigated on the American east coast, face directly into the dominant waves with a funnel-shaped plan form. This is the most effective orientation for a natural "wave pump" (Bruun and Kjelstrup, 1977). It is here proposed that a fundamental driving mechanism, hitherto unrecognized, for the landward current through updrift marginal flood channels is the wave pumping. As a result of this pumping one would expect a persistent mass-flow of the water from Schluchter into Norderneyer Seegat making the channel flood-dominant during all weather conditions except possibly some storms (fig. 17).

Nordwestgründe, consisting of complex ebb-dominated spillover lobes, is formed in response to the flood dominance of Schluchter and the divergent ebb flow out of Norderneyer Seegat. One important source of sediment for this flow is the terminus of Schluchter. Sediment is here effectively fed into the ebb-dominated Norderneyer Seegat system and redeposited at Nordwestgründe.

INNER PART OF SEEGAT

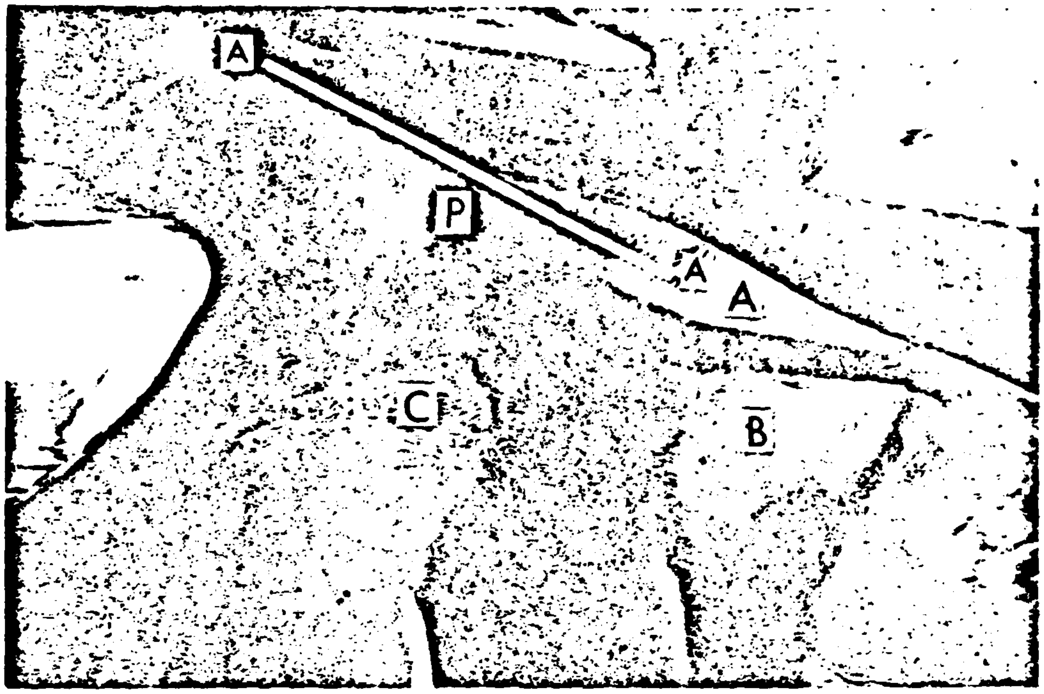
Norderneyer Seegat also contains several shoals ("platen" in German) within, and landward of, the gorge section of the inlet. The main ones are Hohe Plate, Brander Plate and Stein Plate. Two small plates in a general westerly position from Brander Plate were named Brander Plate West and Brander Plate Northwest for identification in the following discussion (fig. 9).

A bathymetric profile across the western extension of Brander Plate demonstrates well the transport pattern in this region (figs. 18A and B). The ridge at P (fig. 18B) appears to be a zone separating a flood-dominated channel to the west from an ebb-dominated one to the east. The transverse bar crest at Brander Plate reflects even more dramatically the net landward sediment movement across the major part of this feature (fig. 18C).

The pattern of intertidal bedforms mapped on these plates in general corresponds to the dispersal pattern determined from subtidal bedform evidence. Intertidal bedform variability and distribution in the inner part of Norderneyer Seegat are shown in figure 16.

Fluorescent tracer techniques were used to provide additional evidence on sediment dispersal directions and rates within the Norderneyer Seegat system. A total of 32 injection stations were used, 23 of which were

A



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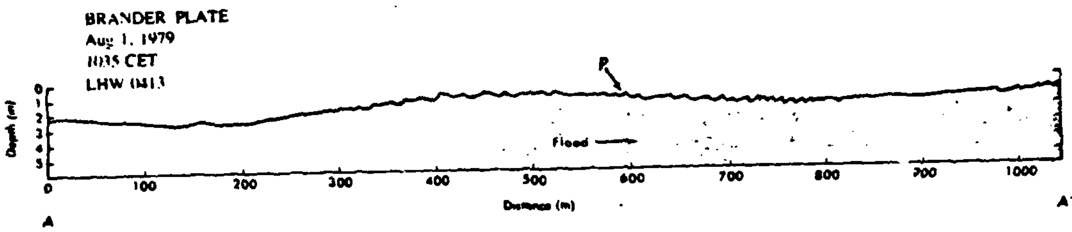

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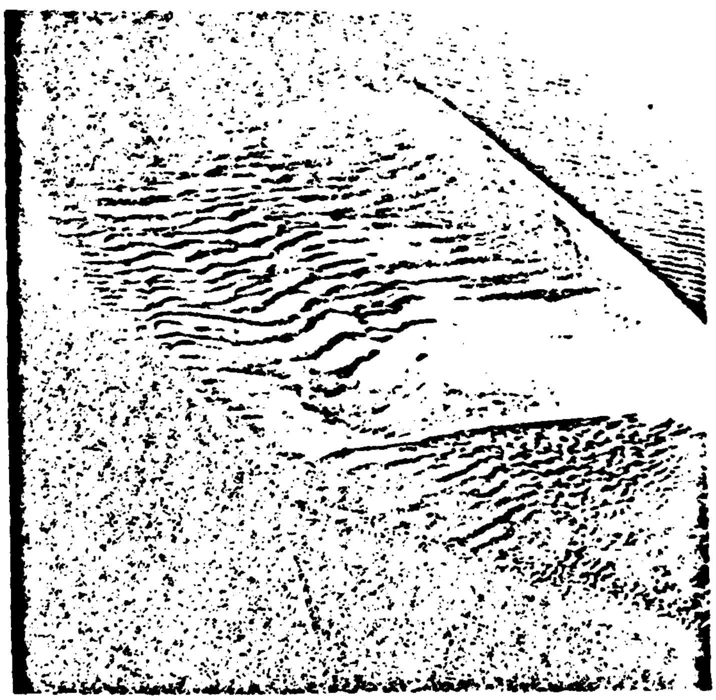

Fig. 18. Morphology and bedforms of the Brander Plate region. (A) Oblique airphoto looking northeast across Brander Plate West (B) and Brander Plate Northwest (C). The east end of the island of Juist is visible on the left side of the photo. Line indicates the location of the PDR profile shown in Fig. 18(B). (B) Bedform profile obtained near low water across the north ramp of Brander Plate. Note the separation between ebb-oriented bedforms left of P and flood-oriented ones to the right. (C) Close-up aerial view of the large transverse bar crest at Brander Plate.

located on the inlet-associated sand bodies discussed in this paper. 2½ kg of native tagged sand, prepared at Forschungsstelle Norderney by the investigators, were emplaced in a 1 m diameter circle at each station. The material was then allowed to disperse over a 12 hr. tidal cycle. Surface concentration patterns were determined during night-time low-tide periods by means of hand-held fluorescent lights. All tracer experiments were carried out during "normal" weather conditions, i.e. moderate winds from the southwest or northwest quadrant.

Results of the tracer experiments are presented in figure 19. The dispersal patterns at Osterriff are somewhat uncertain due to intense wave-induced diffusion at high water. Further seaward wave action was too intense for any meaningful sampling. All tracer at Hohe Plate moved to the south and southeast, consistent with the interpretation of this feature as the southeast termination of a flood-transport path. A steep southeast margin, subject to frequent slumping, confirms that Hohe Plate is being truncated by the actively eroding ebb-dominated currents of Busetief. Tracer dispersal trends on Brander Plate corroborate a transport path similar to that at Hohe Plate. Stein Plate shows uniform landward transport. The western station shows transport to the south-west, i.e. towards the margin of Busetief. Tracer movement is the only available evidence for sediment dispersal at Stein Plate, because both the intertidal shoal and the shallow subtidal ramps at its northern margin are completely devoid of any bedforms carrying directional information.

Tracer dispersal at Brander Plate West and Northwest present a picture consistent with their location relative to Kalfamergat. Brander Plate West is in fact a flood-tidal delta relative to Kalfamergat. Brander Plate Northwest is part of an ebb-dominated lobe responding to

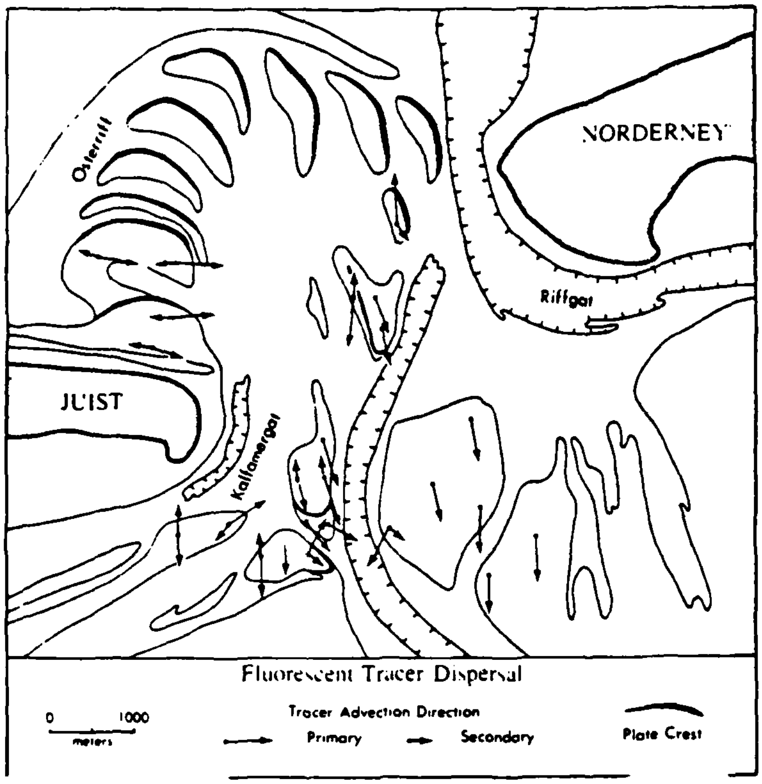

Fig. 19. Directions of dispersal of fluorescent tracer at stations within the central part of the central part of the Norderneyer Seegat drainage basin. All tracer experiemnts were carried out in July 1979, during periods of 'normal' south-west and west winds. Some stations exhibited bidirectional dispersal, indicated by the presence of a secondary arrow in the diagram.

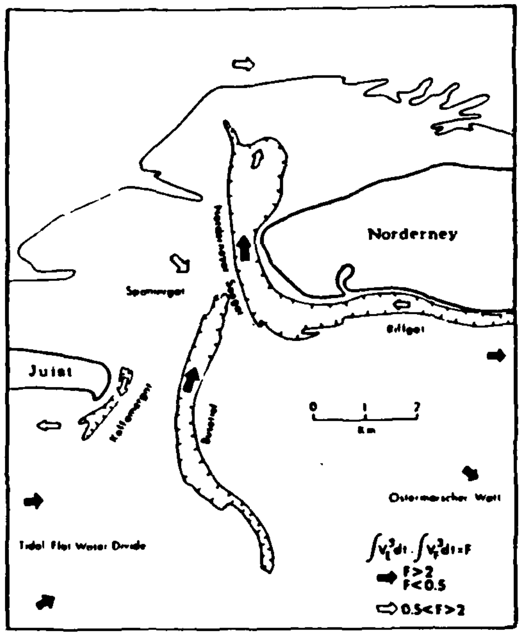

Fig. 20. Map of current dominance in the deep channels of Norderneyer Seegat. Calculations are based on long time series current velocity data provided through the courtesy of Forschungsstelle Norderney.

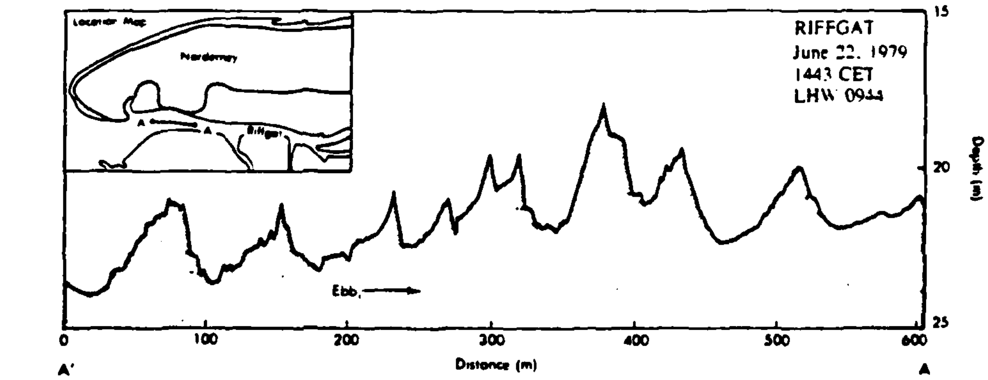

Fig. 21. Profile of large ebb oriented bedforms in Riffgat, southeast of the entrance to Norderney Harbour. Profiles were obtained with a PDR near low water on 22 June 1979.

wind driven flow across the tidal flats behind Juist.

SEDIMENT DISPERSAL IN DEEP CHANNELS

The intensity of sediment transport (volume per unit time per unit width perpendicular to flow) is proportional to probably the third (Maddock, 1969) or perhaps a higher power of the current velocity. The strong tidal currents in the deeper parts of the main channels, therefore, are the primary agents of inlet sediment dispersal. The sand dispersal paths already discussed above have been established in response to these dominant currents. Their effects will here be discussed primarily in light of bedform evidence.

Figure 20 presents a summary of selected hydraulics data demonstrating the distribution of ebb- and flood-dominated channels. Riffgat, south of the entrance to Norderney harbor is strongly ebb-dominated. This was demonstrated in a current velocity time series obtained in 1960 (Kramer, 1961), and is also evident in the directional asymmetry of large bedforms to the southeast of the harbor entrance (fig. 21).

The main channel of Norderneyer Seegat also is ebb-dominated. Long-term current velocity time series and large-scale bedform data (fig. 22) yield a consistent picture. The degree of ebb-dominance, and hence the capacity for net seaward displacement of sediment by tidal currents, rapidly decreases as the ebb jet expands beyond the confined section between Robben Plate and Norderney. This is accompanied by rapid decrease in channel depth.

Busetief is ebb-dominated as well. This is seen most clearly in the asymmetry of the longitudinal profile of Busetief near its confluence with Norderneyer Seegat (fig. 23). The strong ebb-dominance of Busetief, a long distance landward of the gorge of Norderneyer Seegat, appears, in part, to reflect the wind-driven mass flux of water across the tidal flats behind Juist. This water is discharged directly into the western tributaries of Busetief and imparts an asymmetry to the tidal prism: the ebb prism through Busetief will exceed the flood prism.

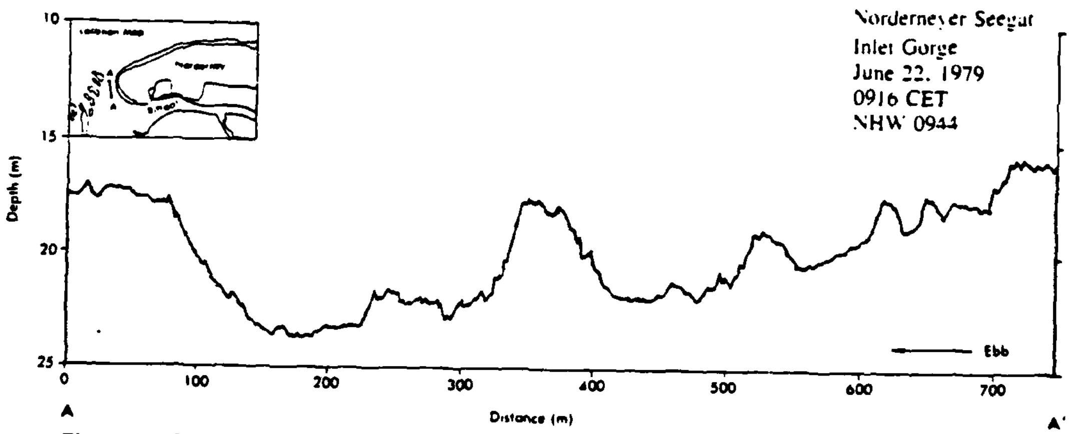

Fig. 22. Profile of bedforms in the Norderneyer Seegat gorge. Small oscillations are due to surface waves.

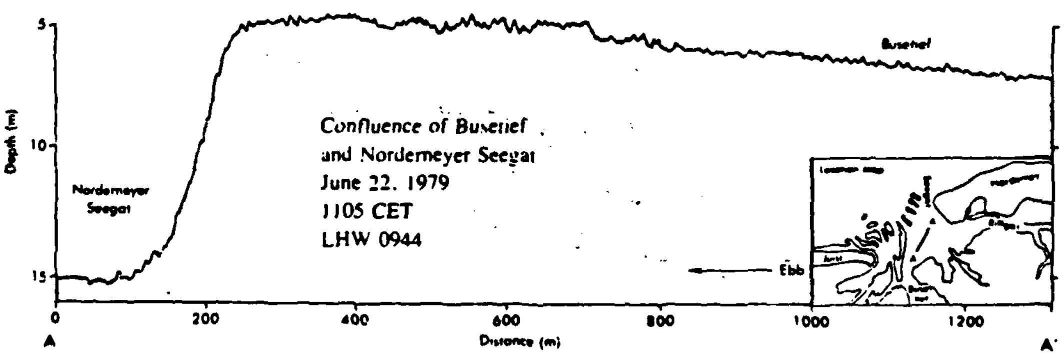

Fig. 23. Profile of Busetief at the confluence with Norderneyer Seegat. The adverse profile to the left followed by a steep bank into Norderney Seegat, suggests a net seaward (left) sediment transport. Small oscillations are due to surface waves.

SUMMARY INLET DISPERSAL MODEL

All available data have been integrated in the proposed sediment dispersal model for Norderneyer Seegat (fig. 24). Historical data, demonstrating growth of Norderney without significant migration of Norderney Seegat clearly prove the existence of efficient sand bypassing (Luck, 1975). Maps of bar locations between 1926 and 1957 (Hommeier and Kramer, 1957) further demonstrate that the bypassing is associated with a steady eastward migration of individual bars. This movement is estimated to supply a minimum of 130,000 m of sand to the Norderney beach per year. Since there is no reason to assume that the bars trap all, or even a majority, of the total sand in transport along the tidal delta margin, the total annual transport rate past Norderney Seegat is undoubtedly greatly in excess of the above figure.

Nordwestgründe is the updrift end of this bar migration path (figs. 9 and 24). The delivery of sediment from Juist to Nordwestgründe follows complex paths. From the shoreface at Juist bedload may either move northward and eastward through Osterriff by a back-and-forth motion in alternating flood and ebb-dominated channels (fig. 15 A, B, C, and D), or landward through Kalfamergat into its "flood-tidal deltas" of Brander plate and Brander Plate West.

Sediment moving through Osterriff has three ultimate destinations: some is delivered via ebb spillover lobes into Schluchter (fig. 15C), some is transported by wave drift via Robben Plate into Norderneyer Seegat and some is brought into Busetief via Hohe Plate. Because of the wave-pump induced flood-dominance in Schluchter, sediment delivered there will also be supplied to Norderneyer Seegat. Although the mechanisms are different,

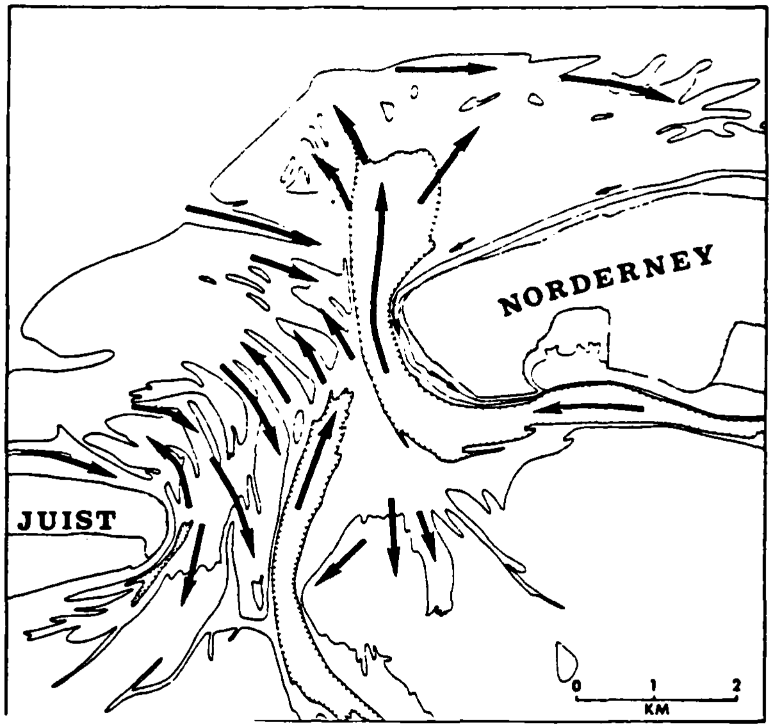

Fig. 24. Integrated sediment dispersal model for Norderneyer Seegat system. This model is based on historic-morphological data, channel and intertidal bedform orientation data, tracer dispersal data and time-series current velocity data. Arrows qualitatively depict net sediment transport directions regardless of which mechanisms operate at any given location.

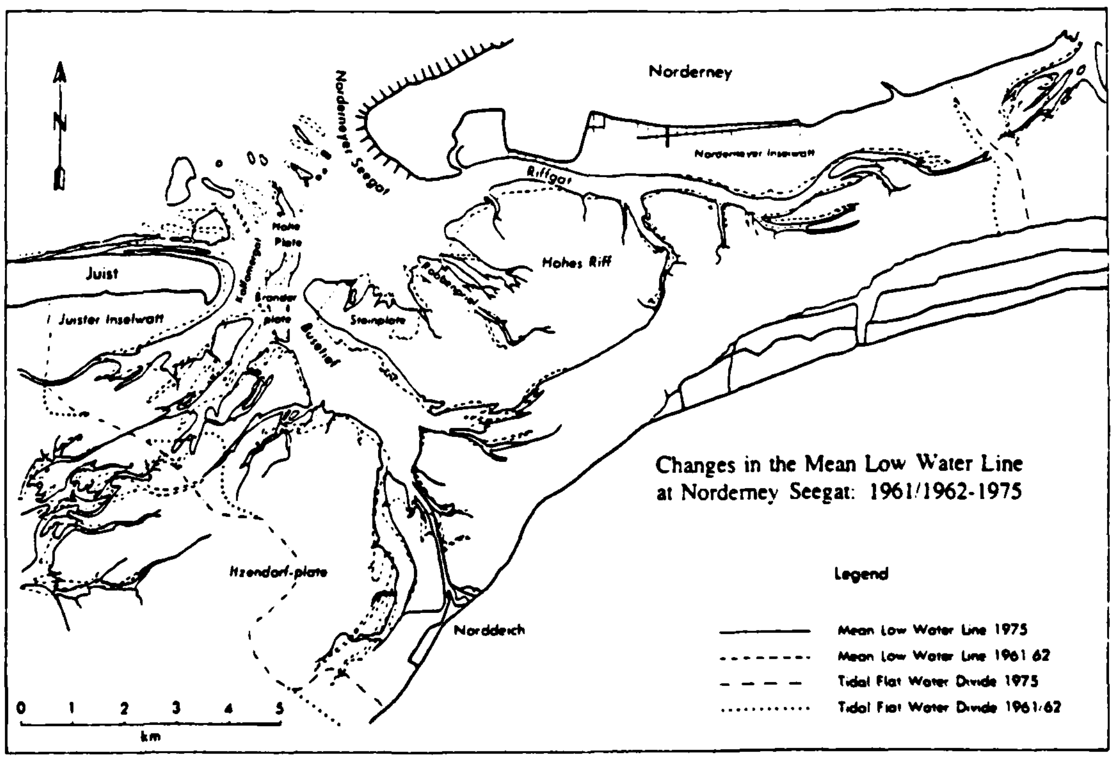

Fig. 25. Historical changes in location of the main channels and shoals within the Norderneyer Seegat system. The map is made from controlled vertical airphoto mosaics obtained in 1961/62 and 1975 (from Ragutzkie, 1978).

the net result of these pathways is that sediment originally derived from the shoreface at Juist will be delivered to the ebb-dominated main channel of Norderneyer Seegat. As the expanding ebb jet decelerates north of the gorge at Norderneyer Seegat, the load is deposited at Nordwestgründe and Nordergründe.

The sediment dispersal pattern here presented correlates quite well with the temporal growth and migration of inlet sand bodies depicted in Ragutzkie's (1978) map (fig. 25).

DISCUSSION

Most tidal inlets are found to be "offset", i.e. the shoreline on the downdrift barrier island is either further seaward (downdrift offset) or further landward (updrift offset) than the updrift shoreline. All the East Friesian inlets are distinctly downdrift offset (fig. 2). Such an offset is explained to be a consequence of wave refraction around the margin of the ebb-tidal delta platform causing bar migration and preferential shoreline accretion at the downdrift shore (Hayes et al, 1970). It has been demonstrated that in certain circumstances inlets may change in a cyclic fashion from downdrift to updrift offset, and back (FitzGerald, 1976).

The offset of Norderneyer Seegat appears to conform to the above explanation, because all bar accretion does take place at the downdrift (Norderney) flank of the tidal delta. In addition, there is a historical element to be considered. Luck (1970) traced the origin of Norderneyer Seegat to an initial breach of the earlier island of Buise (fig. 6). The offset was originally imparted to the system at that time. The sediment dispersal pattern outlined in this paper has contributed to its persistence through time. The large-scale plan form asymmetry of the Norderneyer Seegat ebb-tidal delta (fig. 9) clearly distinguishes it from the low-wave energy inlets of the central Georgia Bight (Oertel, 1975; Nummedal et al. 1977). The asymmetry reflects the strong longshore direction of the wave power combined with an eastward residual tidal current on the inner shelf. The western margin (updrift side) of the ebb-tidal delta is oriented nearly perpendicular to the dominant waves; an orientation which both facilitates lateral offshore movement of sediment through the Osterriff spillover lobe complex and landward sediment transport by wave pumping through Schluchter.

Earlier ebb-tidal delta sediment dispersal models assign varying degrees of significance to the wave-current interaction. For example, Dean and Walton (1975) propose transport of water (and implicitely sediment) towards the inlet throat through the marginal flood channels as a consequence of eddies thought to develop along the sides of the expanding ebb jet. Byrne et al. (1974) present a sand-circulation model for Parramore Inlet essentially in accord with this concept. Fisher et al. (1975) also appear to imply that such a circulation is operating at the ebb deltas of inlets on the northern Texas coast.

In contrast to this, Hine (1975), Hubbard (1975) and FitzGerald et al. (1976) argue that the landward return of sediment from the terminal lobe of the main ebb channel is a function of shoaling waves and flood tidal currents. The dispersal of sediment at Norderneyer Seegat clearly supports the latter view. In fact it emphasizes the role of waves even more, both to account for the overall tidal delta asymmetry and to explain the difference in stability and degree of development of the updrift and downdrift marginal flood channels.

CONCLUSIONS

Historical data extending about 600 years back in time, extensive annual mapping of bar locations carried out by the staff at Forschungsstelle Norderney, long-term current velocity data, bedform profiles, and tracer experiments provide comprehensive data sets for the determination of sediment dispersal in Norderneyer Seegat. These data sets have revealed the following pathways of sand movement in the inlet.

Sand is supplied from the shoreface at Juist and sources further west. It travels through Osterriff through alternating flood and ebb-dominated channels and is thence delivered either to the flood-dominated Schluchter or to the margin of bars flanking the west side of the ebb-dominated channels of Norderneyer Seegat or Busetief. The expanding ebb jet delivers the material to Nordwestgründe or Nordergründe. Transport further to the east, onto the beach of Norderney, takes place through the combined action of wave swash and the eastward directed residual inner shelf tidal current.

The strong longshore orientation of the momentum flux of the breaking waves impart an overall asymmetry to this, and indeed, to all the other inlets in the East Friesian island chain.

Wave pumping is proposed to be an important mechanism in maintaining the effective landward mass flux through updrift marginal flood channels of ebb-tidal deltas situated in a high-wave energy environment.

The overall development of an ebb-tidal delta can only be understood by means of a proper coupling of the effects of waves and tidal currents.

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13. ABSTRACT

The paper presents a sediment dispersal model for a high-wave-energy, mesotidal inlet on the southern coast of the North Sea. The model has been derived through the integrated analysis of historical-morphological data, sub- and intertidal bedform distributions, aerial photography, intertidal fluorescent tracer dispersal studies and long-term current velocity time series.

Long term historical-morhpological data permit the reconstruction of Norderney and environs since the year 1350. Over the last 300 years the island has been subject to sustained growth. Annual inlet maps over about three decades demonstrate that this growth is related to the steady migration of bars around the arcuate margin of the ebb-tidal delta from the island of Juist eastward to Norderney.

The pattern of sediment bypassing is not simple. Sand is delivered to the inlet by wave-induced longshore transport from the shoreface at Juist and sources further west. As it enters the inlet system, sediment is moved offshore and eastward through a complex set of alternating ebb- and flood-dominated channels. It is delivered to the strongly ebb-dominated main channel through a major marginal flood channel and across the large bars (ebb-shields) which form the landward termini of many of the smaller flood ramps. The expanding ebb jet delivers this sediment to two major terminal lobe bar complexes. Once deposited at the terminal lobe the sediment is subject to further eastward movement in the form of large bars. The morphology of the bars demonstrates that they are subject to significant tidal current influence near the updrift (western) margin of the terminal lobe. Tidal influence decreases eastward and the bars become shore-parallel 'swash bars' before they weld to the island shore about 5 km east of the west end of Norderney.

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Louisiana State University
Baton Rouge, LA 70803

Abstracts

Enclosed are five abstracts relating to sediment dispersal in the East Friesian tidal inlets, West Germany.

Abstract No. 1
Tidal Inlet Sediment Dispersal along the German North Sea Coast.
Dag Nummedal

Abstract No. 2
Tidal Inlet Sediment Dispersal.
Dag Nummedal

Abstract No. 3
Patterns of Shoreline Change in the German Bight.
Dag Nummedal

Abstract No. 4
Sand Dispersal at Norderneyer Seegat, West Germany.
Dag Nummedal, P. Shea Penland, and Amy Maynard

Abstract No. 5
Tidal Inlet Sediment Dispersal.
Dag Nummedal

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TIDAL INLET SEDIMENT DISPERSAL ALONG THE GERMAN NORTH SEA COAST

DAG NUMMEDAL

Department of Geology, Louisiana State University,
Baton Rouge, LA, 70803, USA

Sediment dispersal in tidal inlets and estuaries within the German Bight are found to be controlled by three major environmental factors: (1) the tide range, (2) the nearshore wave energy, and (3) the geometry of the back-barrier bay. The German Bight is characterized by high wave energy and low tide range of its flanks and lower wave energy and high tide range in the center (Nummedal and Fischer, 1978). The spatial variability in inlet morphology, therefore, contains information on the relative role of tides and waves in inlet sediment dispersal.

Six inlet morphologic types have been recognized within the German Bight. These are illustrated in figure 1 where they are arranged in a sequence of increasing tidal influence.

Wave dominated inlets (frame 1, figure 1) typically have the majority of the shoals on the landward side of the inlet gorge because the net direction of wave-induced sand transport will be towards the lagoon. Furthermore, the existence of an open-water lagoon rather than a marsh or tidal flat behind the barrier might produce hydraulic flood-dominance in some inlets (Nummedal and Humphries, 1978).

The mixed-energy inlets within the German Bight (frames 2, 3 and 4, figure 1) all appear to be hydraulically ebb dominated, probably because of extensive back-barrier tidal flats. The seaward extent of the swash platform must reflect an equilibrium between the capacity for seaward transport of sand by the tidal currents and landward transport by shoaling and breaking waves on the swash platform. Consequently, the primary change in the ebb-tidal delta with an increase in the ratio of tidal range to breaker energy will be its seaward growth. Secondly, the inlet gorge will become better defined and less subject to changes due to bar migration because wave-induced bar development will take place on platform margins further away from the inlet.

Barrier islands cease to exist along depositional shorelines of high tide range because the longshore sediment movement due to wave action becomes completely subordinate compared to the on-offshore movement of sediment by the tides (frames 5 and 6, figure 1). For the wave energy of the German coast, the critical tide range appears to be about 3 meters. The development of sigmoidal shoals in these high-tide range estuaries is an expected consequence of the deflection of a current around the leading face of any sedimentary deposit formed by a current flowing in the opposite direction. This produces strongly segregated channels for ebb and flood flow, hence the sigmoidal shape of the bar crest.

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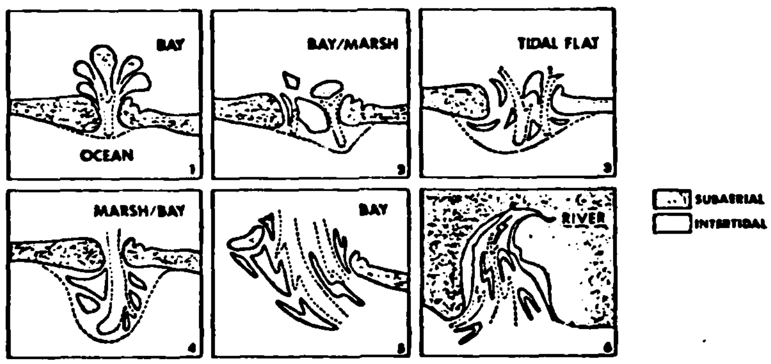

Figure 1. Tidal inlet morphological models. Frames 1 through 6 reflect an increasing role of tidal currents in inlet sediment dispersal.

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Sand body geometry						

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NUMMEDAL, DAG, Louisiana State Univ., Baton Rouge, La

Tidal-Inlet Sediment Dispersal

Tidal inlets along the southeastern coast of the United States from Cape Hatteras to Cape Canaveral (the Georgia Bight) and along the North Sea coast from the Netherlands to Denmark (the German Bight) reflect a range in physical processes from wave dominance (at the flanks of the two bights) to tide dominance (at the center of the German Bight). Studies of the hydraulics, sediment dispersal, and historic morphologic changes of several inlets within the two bights have led to the identification of a continuum of inlet types from microtidal wave-dominated inlets at one end to macrotidal tide-dominated inlets at the other. The factors controlling the inlet types are: (a) the longshore sediment-transport rate caused by the momentum flux of the breaking waves, (b) the onshore-offshore sediment-transport rate resulting from tidal currents, and (c) the flood-ebb asymmetry in tidal-current velocities. This last factor is determined by the hydraulic geometry of the back-barrier bay.

The wave-dominated inlets have all their shoals on the bay side of the inlet throat. The mixed-energy inlets have shoals landward of, in, and seaward of the throat, and there is a distinct increase in the volume of the seaward shoals (ebb-tidal deltas) with increasing tide range. The tide-dominated inlets reflect situations where the longshore sediment-transport rate is completely subordinate to the onshore-offshore transport. In these situations, barrier islands cease to exist and tidally controlled lunate, sigmoidal, and linear sand bodies occur throughout the estuary entrance

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Patterns of Shoreline Change in the German Bight.

Dag Nummedal, Department of Geology, Louisiana State University,
Baton Rouge, LA, 70803.

Introduction.

Work accomplished under contract no. N00014-78-C-0612 since its initiation on July 1, 1978, has consisted of the following:

1. Aerial reconnaissance of the shoreline of the German bight in preparation of a morphological classification of a tide dominated shoreline.
2. Acquisition of historical maps and data for analysis of the long-term stability of intertidal and shallow subtidal bathymetry.
3. Collection and analysis of tidal hydraulic data in Norderneyer Seegat and Vortrapptief and their adjoining tidal drainage basins.

This abstract will present a preliminary review of the regional coastal morphology and discuss the sediment transport dynamics in qualitative terms.

The Schleswig-Holstein Coast.

Tide range increases to the south from about 1.5 meters at List on Sylt, to about 2.5 at the southern end of the North Friesian island chain. The wave energy is high and generally directed normal to the coast.

The northern part of this coast, as well as the adjacent Danish coastline is characterized by typical "drumstick" - shaped barrier islands with wide tidal flats behind. These isalnds formed in response to seaward transport of sand by ebbing tides and downdrift dispersal of the material by wave-induced longshore currents. In the short term (decades) these islands appear relatively stable; most shoreline change is associated with movements of the swash bars at the seaward margins of the ebb-tidal deltas.

Islands further south have a more random distribution of shapes as well as locations. Their origins are multiple and complex, most are segments of the mainland coastal plain, separated from shore by large storm tides in historic time. Many are flanked on their seaward side by large accretionary sandy tidal flats. The accretionary forms vary from recurved spits through ridge-and-runnel topography to enechelon bars.

The Central German Bight

This macrotidal embayment has no barrier islands because the on-offshore movement of sand by tidal currents exceeds the longshore transport by currents generated by obliquely breaking waves. As a consequence, the sand is accumulated in large linear, lunate and sigmoidal shoals which occupy the estuary entrances. Their long-axes are parallel to the main axis of the estuary. Sediment appears to by-pass the estuary mouth through a zig-zag movement on adjacent flood and ebb dominated shoal ramps (Barthel, 1976). The large shoals are also subject to form movement. A typical replacement period for a major sigmoidal shoal is about a century. Shoals located on the major interchannel divides may become supratidal and partly stabilized by vegetation. Alte Mellum, Grosser Knechtsand and Scharhorn are examples of such supratidal shoals. These shoals grow by bar accretion at their seaward side during storm tides. The final location of the supratidal shoal appears to depend on the profile of the underlying platform. Landward bar migration rates are reduced and ultimately cease in very shallow water. During extreme storm tides even supratidal shoals move by washover processes and spit growth at the shoal margins.

The East Friesian Islands.

Historical documentation of the Friesian Islands demonstrate a rapid eastward migration prior to structural stabilization of the inlet shores. Typically, growth took place through the accretion of large recurved spits at the downdrift (east) end of the islands and rapid erosion along the banks of the main inlet channel at the west end of the island. Sand bypass the inlets through a nearly continuous arc of swash bars (reef-bow) at the seaward margin of the swash platform. Luck (1975) since this arc most commonly reaches the shore at the middle of the next downdrift island, the west ends of the islands are sediment starved; hence the rapid erosion prior to construction of groins and seawalls. In terms of stability of the different environments along the Friesian island chain, the seaward margin of the tidal delta is the most dynamic, the island beach itself is subject to less frequent changes and the back-barrier tidal flats are by far the most stable.

Conclusions.

1. The pattern of variability in tidal inlet sand body geometries within the German bight suggests the existence of a continuum of inlet morphologic types. In this continuum the shoals assume a configuration which directly reflects the relative capacity for sediment transport by waves and tidal currents.
2. The classification of depositional shorelines proposed by Davis (1964) has been found to be inadequate. A morphologically-based classification of wave dominated versus tide-dominated shorelines clearly demonstrates that both tide range and the mean annual wave height are controlling parameters. An increase in one parameter requires an increase in the other to retain a similar pattern of inlet sand body distribucion.

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NUMMEDAL, DAG, P. SHEA PENLAND, and AMY MAYNARD, Louisiana State Univ., Baton Rouge, LA

Sand Dispersal at Norderneyer Seegat, West Germany

Norderneyer Seegat connects the North Sea and the Wattenmeer between the East Friesian Islands of Juist and Norderney. It is a high wave-energy mesotidal inlet. The mean tide range is 2.4 m and the estimated mean breaker height exceeds 1 m. The sediment dispersal pattern and resultant morphology differ significantly from those of mesotidal inlets investigated along the low wave-energy shores of the southeastern United States.

The seaward margin of the ebb-tidal delta consists of a nearly continuous arc of bars, the "reef-bow." These bars have segregated tidal flow; flood dominates a broad ramp facing into the dominant waves (i.e., the west side), ebb dominates the narrow steep leeside margin. The bars migrate eastward through combined tide and wave action at an average rate of 400 m/year. Bar migration appears to be the dominant mode of inlet sediment bypassing.

The gorge section of the main inlet channel is ebb-dominated as a result of (1) water level-dependent inlet efficiency and (2) net water supply to the inlet drainage basin due to prevailing southwest winds.

Flood-dominated intertidal sand shoals abound in, and landward of, the inlet gorge. Ebb-dominated flanks occur on some of the shoals. The degree of flood dominance increases landward, an effect which is attributed to the difference in celerity between the tidal wave trough and crest.

Both the mechanics of ebb-delta sand bypassing, and the occurrence of tidal-flat flood dominance, distinguish the dispersal pattern at Norderneyer Seegat from that at mesotidal inlets with lower wave energy. Stratigraphic models for tidal-inlet sequences must consider both tide range and wave energy.

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Tidal Inlet Sediment Dispersal

D. NUMMEDAL
Department of Geology, Louisiana State University, U.S.A.

1. INTRODUCTION

The primary objective of this paper is to identify the pathways and mechanisms of bed material movement in inlets subject to intermediate wave and tidal energy (mixed-energy inlets of Nummedal and Fischer, 1978). Case studies of inlets along the southeastern coast of the United States and in the Friesian province of West Germany form the basis for these generalizations. The modes of sediment transfer on the ebb-tidal delta, in the inlet gorge, and within the bay subenvironments will be discussed separately.

2. EBB-TIDAL DELTA

The symmetry of the ebb-tidal delta platform depends on two factors: (1) the sediment transport capacity of the inlet currents relative to that of the waves, and (2) the directional distribution of the incoming wave energy flux (Oertel, 1975). For strong tidal currents, and/or fairly symmetrical wave approach, the generalized ebb-delta net sediment dispersal is as outlined by Hayes (1975) and Oertel and Howard (1972): seaward in the main ebb channel, laterally along the margin of the swash platform to the swash bars and marginal flood channels, and back to the inlet gorge. Some sediment may complete this whole cyclic pattern, but a large amount generally bypasses the inlet from the updrift to the downdrift beaches. Four different mechanisms have been identified for sediment bypassing on the ebb-tidal deltas.

1. Spit migration and breaching. This mechanism is operative in spatially unstable inlets. Abundant historical documentation shows that some inlets migrate for kilometers only to have the updrift spit breached by a (storm-induced) inlet which start the cycle anew. (FitzGerald et al. 1978; Langfelder et al. 1974).

2. Ebb-tidal delta breaching. This mechanism, as the previous one, is operative in areas of a strong net longshore sediment transport. The main ebb channel is deflected downdrift in response to strong net transport. As this produces a hydraulically unstable situation for the expanding ebb jet, an ebb spillover lobe takes over as the new main channel (Wojtal, 1977; FitzGerald et al. 1978).

3. Multiple swash bar migration. In inlets subject to high wave energy, or relatively weak tidal currents, multiple swash bars typically outline the swash platform margin. As demonstrated particularly well by Hommeier and Kramer (1956) these swash bars migrate as morphological entities in an arc from the updrift to the downdrift margin of the tidal delta on the time-scale of a decade or two.

4. Tidal current bypassing. In the three previous cases the actual sediment bypassing rate is probably significantly higher than that associated with the described form-movement. A large amount of sediment is introduced to the main ebb channel by wave and current action across the updrift swash platform, carried seaward by the tide and moved from the terminal lobe into the next downdrift beach by further wave-induced current action. This mechanism is always operative, and in the case o. ~~able inlet channels, it is the only bypassing mechanism.

3. INLET GORGE

Whereas the main ebb channel within the ebb-tidal delta is characterized by stronger peak and mean ebb velocities than flood velocities in all the investigated inlets, the current regime in the inlet gorge shows a lot of variability. Ebb dominance characterizes the gorge sections of the South Carolina and Georgia Inlets (Nummedal and Humphries, 1978; Hubbard et al. 1977). Large variability exists in the inlets of the Friesian province of Germany but most appear to have a nearly symmetric gorge current regime (Nummedal, 1979). No mixed energy inlet is known to have definite flood current dominance in the gorge.

Factors which control the current asymmetry of the inlet gorge include:

(a) the relative variability in bay surface area during a tidal cycle,

(b) The relative celerity of the tidal wave trough and crest, and

(c) the hydraulic geometry of the inlet gorge itself.

4. BAY ENVIRONMENTS

The factors listed above as controlling the asymmetry of the flow in the inlet gorge contribute to, and are in turn influenced by, the hydraulic characteristics of the bay. In the Friesian inlets there is a strong flood-dominance in nearly all channels on the landward side of the island. This flood dominance becomes progressively stronger further landward. Its cause appears to be factor (b) above (Nummedal, 1979). This mechanism of landward coarse sediment transport, coupled with near-symmetry at the inlet gorge, produces massive flood-tidal deltas. Morphologically, these flood-tidal deltas consist of multiple sand bodies flanking the seaward margins of large intertidal shoals.

Significant bay sand bodies are absent in the mixed energy inlets of the southeastern United States. This is consistent with current studies by Ward (1978), and Nummedal and Humphries (1978) which document increasing ebb current dominance in a landward direction through two South Carolina salt marsh systems. This difference in bay current regime appears to be caused by the smaller size of the South Carolina systems, which will make factor (b) above of negligible importance compared to factor (a).

5. SUMMARY

An attempt has been made to synthesize the observed patterns of coarse sediment movement within mixed-energy tidal inlets.

All these inlets have an ebb-current dominated main channel on the ebb tidal delta, facilitating sediment bypassing of the inlet either by lateral swash bar migration or tidal current transport.

Sediment dispersal and deposition at the landward side of the inlet depends on the current asymmetry which in turn is a function of bay hypsometry and size. Flood-tidal deltas are significant depositional features in inlets where the current velocity in the gorge is nearly symmetric and where tidal wave shoaling produces rapid flood dominance further landward.

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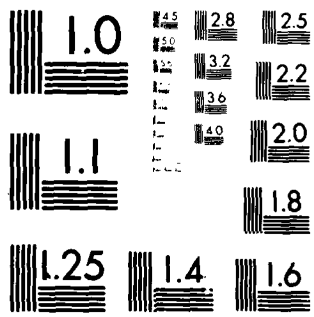

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San Diego, California 92155

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Dr. Donald Swift
Marine Geology and Geophysics Laboratory
AOML-NOAA
15 Rickenbacker Causeway
Miami, Florida 33149

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DMA Aerospace Center
St. Louis, AFS, MO 63118

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DK-2100 Kobenhavn O, DENMARK

Prof. Dr. Rer. Nat. H. G. Gierloff-Emden
Institut F. Geographie
Universitaet Muenchen
Luisenstrasse 37/111
D-800 Muenchen 2, WEST GERMANY

Prof. Dr. Eugen Seibold
Geol.-Palaeontolog. Institut
Universitaet Kiel
Olshausenstrasse 40-60
D-2300 Kiel, WEST GERMANY

Dr. R. Koester
Geol.-Palaeontolog. Institut
Universitaet Kiel
Olshausenstrasse 40-60
D-2300 Kiel, WEST GERMANY

Prof. Dr. Fuehrboeter
Lehrstuhl F. Hydromechanik U. Kuestenwasserbau
Technische Hochschule Braunschweig
Beethovenstrasse 51A
D-3300 Braunschweig
WEST GERMANY

Prof. Dr. Walter Hansen
Direktor D. Instituts f. Meereskunde
Universitaet Hamburg
Heimhuderstrasse 71
D-2000 Hamburg 13
WEST GERMANY

Prof. Dr. Klaus Hasselmann
Institut F. Geophysik
Universitaet Hamburg
Schulterstrasse 22
D-2000 Hamburg 13
WEST GERMANY

Prof. Dr. Nils Jerlov
Institute for Physical Oceanography
Kobenhavns Universitet
Haraldsgade 6
DK-2200 Kobenhavn, DENMARK

Prof. Kiyoshi Horikawa
Dept. of Civil Engineering
University of Tokyo
7-3-1, Hongo, Bunkyo-ku
Tokyo 113, JAPAN

Prof. Yuji Iwagaki
Civil Engineering Department
Kyoto University
9 Shimogamo Zenbucho
Sakyo-ku
Kyoto, JAPAN

Delft Hydraulics Laboratory
P. O. Box 177, 2600 MH
Delft, NETHERLANDS

Ir. M. W. Van Batenberg
Physisch Laboratorium TNO
Oude Waalsdorper Weg 63
Den Haag, NETHERLANDS

Prof. Toshiyuki Shigemura
Civil Engineering Department
National Defense Academy
1-10-20 Hashirimizu
Yokosuka 239, JAPAN

Mr. William T. Whelan
Telecommunication Enterprises Inc.
2430 Industrial Drive
Panama City, Florida 32405

Prof. John D. Isaacs
University of California A-207
Institute of Marine Research
La Jolla, California 92093

Dr. G. D. Hickman
Applied Science Technology, Inc.
19212 Plummer Drive
Germantown, Maryland 20767

Dr. Benno M. Brenninkmeyer, SJ
Department of Geology and Geophysics
Boston College
Chestnut Hill, MA 02167

Dr. Choule J. Sonu
Tek Marine, Inc.
41 West Santa Clara
Arcadia, California 91006

Dr. Richard A. Davis, Jr.
Department of Geology
University of South Florida
Tampa, Florida 33620

Dr. William T. Fox
Department of Geology
Williams College
Williamstown, MA 01267

Dr. Hsiang Wang
Department of Civil Engineering
Dupont Hall
University of Delaware
Newark, Delaware 19711

Dr. John T. Kuo
Henry Krumb School of Mines
Seeley W. Mudd Building
Columbia University
New York, New York 10027

Dr. Edward B. Thornton
Department of Oceanography
Naval Postgraduate School
Monterey, California 93940

Prof. C. A. M. King
Department of Geography
University of Nottingham
Nottingham, ENGLAND

Dr. Douglas L. Inman
Scripps Institution of Oceanography
La Jolla, California 92037

Dr. Omar Shemdin
Jet Propulsion Lab 183-501
4800 Oak Grove Drive
Pasadena, California 91103

Dr. William W. Wood
Department of Geosciences
Purdue University
Lafayette, Indiana 47907

Dr. John B. Southard
Department of Earth and Planetary Sciences
Massachusetts Inst. of Tech.
Cambridge, Massachusetts 02139

Dr. J. Ernest Breeding, Jr.
Department of Oceanography and Ocean Engineering
Florida Inst. of Technology
Melbourne, Florida 32901

Dr. John C. Kraft
Department of Geology
University of Delaware
Newark, Delaware 19711

Dr. Dag Nummedal
Department of Geology
Louisiana State University
Baton Rouge, Louisiana 70803

Mr. Fred Thomson
Environmental Research Institute
P. O. Box 618
Ann Arbor, Michigan 48107

Dr. Thomas K. Peucker
Simon Fraser University
Department of Geography
Burnaby 2, B. C., CANADA

Robert Dolan
Department of Environmental Sciences
University of Virginia
Charlottesville, VA 22903

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