CHAPTER TWO HUNDRED THREE

SEDIMENTATION PROCESSES ALONG THE EAST FRIESIAN ISLANDS, WEST GERMANY

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ABSTRACT

The East Friesian Islands are located on a high energy shoreline. The average deepwater significant wave height exceeds 1.0 m and the spring tidal range varies from 2.7 to 2.9 m. A large easterly net longshore transport rate has caused eastward growth of the barrier islands. Reclamation of tidal flats has significantly reduced the backbarrier area and has resulted in a decrease in the ratio of inlet width to barrier island length from 42% to 16% during the past 300 years.

The headwaters of the major channel dissecting the tidal flats erode in an eastward direction in response to tidal and wave driven currents, wave suspension, and eastward barrier island elongation. Consequently, the drainage systems of most of the inlets are highly asymmetric with 70-80% of the tidal prism coming from the east. This pattern results in a hooked main channel. The location of the channel at the inlet throat is controlled by the westward ebb flow in the main channel, the inertia of ebb flow in the tributary creeks, eastward longshore sediment transport, and the regional stratigraphy.

The position and orientation of the main ebb channel controls the symmetry of the ebb-tidal delta about the inlet shoreline. This, in turn, affects the location of swash bar attachment to the beach and overall trends of erosion and deposition along the downdrift barrier.

INTRODUCTION

The East Friesian Islands are a barrier chain that has

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undergone a great amount of change during the past 300 years. These changes are the result of natural processes and man's influences. It is the objective of this paper to report the historical changes that have occurred to these barriers and to show that these changes can be explained in terms of the regional stratigraphy and the sedimentation processes active in this area.

This paper represents a summary of several papers published by the authors dealing with the morphodynamics of the East Friesian Islands. These works include a discussion of sediment transport patterns at Norderneyer Seegat (Nummedal and Penland, 1981), control of barrier island morphology by inlet sediment bypassing processes (FitzGerald et al, 1984A), and the correlation that exists between inlet narrowing and backbarrier filling(FitzGerald et al, 1984B).

PHYSICAL ENVIRONMENT

The East Friesian Islands consist of six barriers and five tidal inlets, spanning a 90 km stretch of shoreline along the West German North Sea coast (Fig. 1). The barriers are separated from the mainland by a 4-12 km wide tidal flat and creek system. The tidal flats are comprised of medium-fine sand near the inlets fining to muds toward the drainage divides (Fig. 2).

The winds in this area blow out of the westerly quadrant during the entire year with an average velocity of 8-15 kt (Luck, 1976A). This produces a net eastward long-

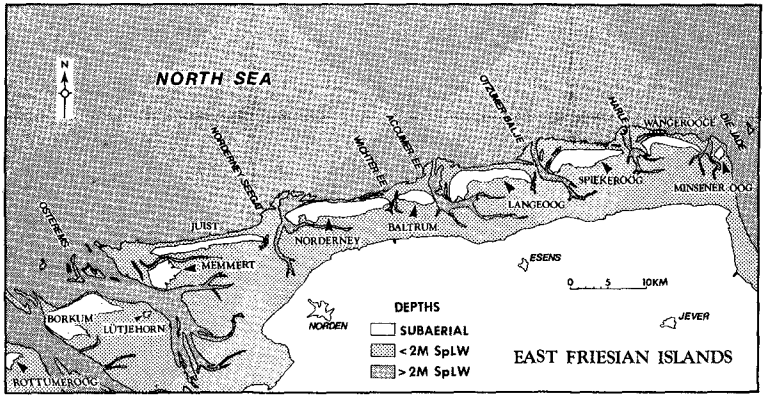

Figure 1. Location map of the East Friesian Islands.

Figure 2. Aerial photograph of Baltrum and Langeoog looking east. Note the coastal structures on the western ends of the islands.

shore power component of $4.44X10^{3}$ $W\text{-}m^{-1}$ (azimuth=101°) (Fig. 3) (Nummedal and Penland, 1981). It has been estimated, using morphological data, that a minimum of 2.7 x 10^{5} m^{3} of sand is transported to east yearly (FitzGerald et al, 1984A.

The tides in the North Sea are semi-diurnal and propagate in an easterly direction along the coast. The tidal lag between the islands of Juist and Wangerooge is approximately one hour. Spring tidal range varies from 2.5 m at the mouth of Osterems to 2.9 m at Die Jade.

HISTORICAL ANALYSIS

Historical changes of the East Friesian Islands were determined from sequential maps compiled by Homeier and Luck (1969). One of the overlays that were constructed from these maps is shown in Figure 4. During the 310 year period of record the Island of Norderney prograded 12 km to the east. Note, however, that the eastward growth of Norderney was accommodated not only through inlet migration but also by the narrowing of Wichter Ee. This same trait is apparent at Accumer Ee and repeated along the rest of the barrier island chain.

During the past 310 years an abundant sediment supply has led to an 80% increase in aerial extent of the barrier islands (Fig. 4). Of this increase, 45% was due to land reclamation along the backsides of the barrier (Fig. 2), while the rest of the growth (35%) was caused by natural

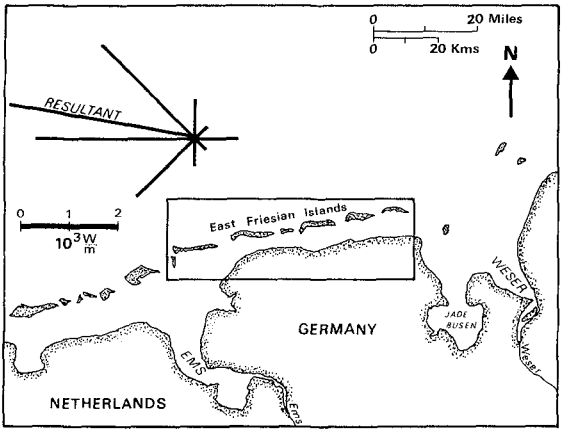

Figure 3. Deep-water wave power distributions for the Bremerhaven data square as determined from the Summary of Synoptic Meteorologic Observations. The northwesterly resultant component of wave energy produces a large easterly longshore transport rate (from Nummedal and Penland, 1981).

processes including spit accretion and beach progradation. During this same time span empoldering was also occurring along the mainland shoreline (Fig. 4). Since 1650 the backbarrier drainage area has been reduced by 30%. As discussed by FitzGerald et al (1984B), the decrease in bay area has caused a reduction in the inlet tidal prisms. This, in turn, has resulted in smaller equilibrium inlet cross sectional areas (O'Brien, 1931, 1969). One reflection of this has been a continued decrease in total inlet width from 20.4 km in 1650 to 9.4 in 1960. One other consequence of the smaller tidal prisms has been a decrease in the size of the ebb-tidal deltas (Walton and Adams, 1976; FitzGerald et al, 1984B).

BACKBARRIER PROCESSES

From the historical analysis it is known that most of the East Friesian barrier islands and some of the tidal inlets have migrated in an easterly direction. Therefore, it would be expected that if the backbarrier channels had remained relatively static then through time they would have become hook-shaped and oriented toward the west. However, just the opposite pattern has developed. As seen in Figure 5, the channels are indeed hook-shaped, but they are oriented west, not east. The reason for this is that

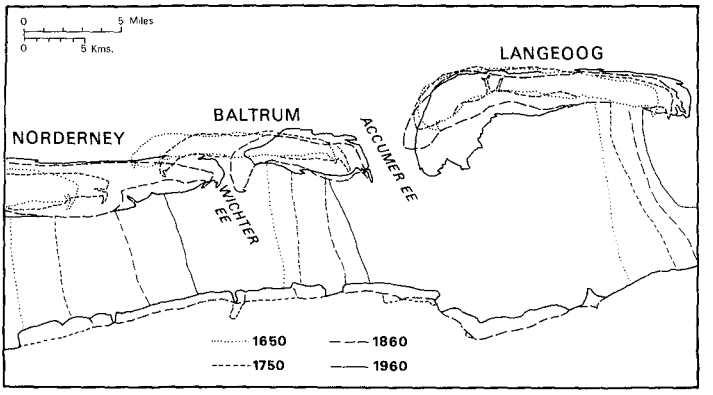

Figure 4. Historical changes for a portion of the East Friesian barrier island chain. Constructed from maps produced by Homeier and Luck (1969).

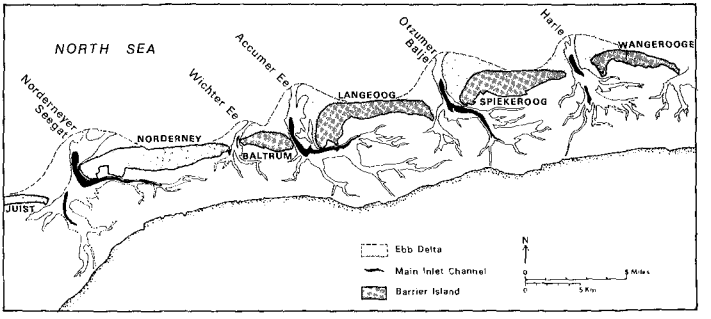

Figure 5. Positions of the main ebb channels and configurations of the ebb-tidal deltas.

through time the drainage divides have also migrated in an easterly direction, keeping pace with the growth of the barrier islands (Fig. 4). The easterly extension of the backbarrier channel systems is a product of headward erosion with a net transport fine-grained material to the east across the drainage divides.

The processes affecting sedimentation in the backbarrier include tidal current 1) time asymmetry and 2) velocity asymmetry. Time asymmetry, as first put forth

by Van Straaten and Kuenen (1957), Postma (1961, 1967), Groen (1967), Reineck (1967) and others, refers to the condition when maximum current velocities do not take place at mid-tide but rather occur early or late in the tidal cycle. This condition was used by the above workers to develop the concepts of scour and settling lags to explain the net landward movement of fine-grained sediment on Dutch and German tidal flats. Velocity asymmetry occurs when the maximum current velocities are unequal during the flood and ebb cycles. In the East Friesian Island back-barrier flood tidal currents predominate. This velocity asymmetry is attributed primarily to: 1) a steepening of the tidal wave and 2) wind effects.

Redfield (1978) has shown that as the tidal wave propagates across a wide shallow shelf it steepens in a manner similar to a wind generated wave along a beach. This steepening produces a shorter period in the rise of the tide than its fall. In the main inlet channels of the East Friesian Islands this difference in tidal duration amounts to approximately one half hour. Because the water has a shorter time to enter the inlet than to exit the currents must move more swiftly, hence, the stronger flood tidal currents.

As mentioned earlier, the winds along this portion of the North Sea blow out of the westerly quadrant during the entire year. This direction coincides with the longest fetch length of the backbarrier region (E-W). Consequently, superimposed on the tidal regime is an easterly movement of water driven by wind stresses. Winds of 15-30 kph are capable of producing current velocities of 10-20 cm/sec. The effect of the winds on the backbarrier water circulation, if tidal currents were symmetrical, would be to cause stronger flood currents in the eastern portion of the inlet drainage and to increase ebb flow in the western part of the drainage system.

Current velocities recorded by Koch and Luck (1974) behind the island of Juist show the effects of the factors that have been discussed above (Fig. 6). Stations #7 and 8 on the western side of the drainage divide have stronger flood than ebb tidal currents. On the opposite side of the divide stations #9 and 10 are clearly dominated by ebb currents.

Thus it is proposed that the easterly migration of the drainage divides is the result of net sediment transport to the east. This is caused primarily by wind-generated currents augmenting and retarding the tidal currents.

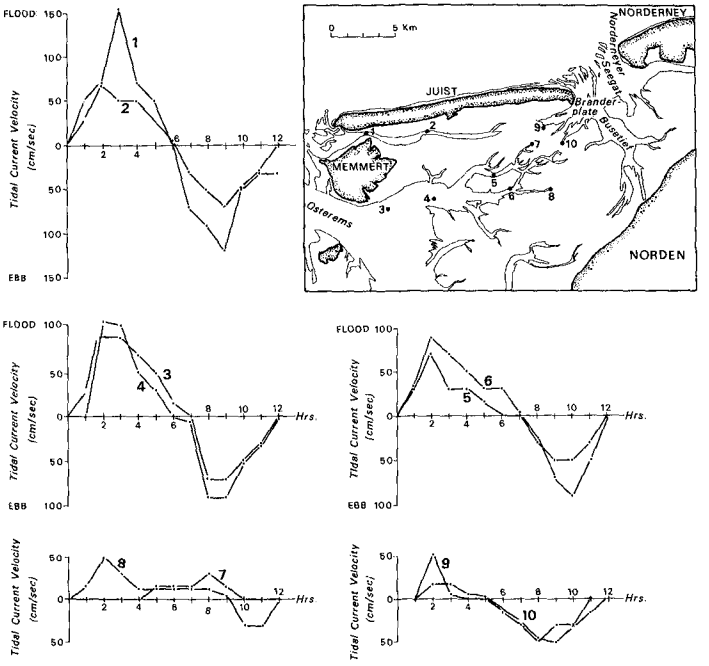

Figure 6. Velocity curves in the tidal channels behind the island of Juist. Note the flood dominance of stations #7 and 8 and the ebb dominance of stations #9 and 10. Velocity data from Koch and Luck (1974).

TIDAL INLETS

Morphology

Tidal inlets along the East Friesian Islands are classified in Hayes' (1979) and Nummedal and Fischer's (1978) mixed energy (tide-dominated) coastal setting. They are fronted by well developed ebb-tidal deltas and have main ebb channels that are dominated by ebb-tidal currents. Inlet throat geometry exhibits a large degree of variability along the island chain. Most often, the channels are highly asymmetric with their thalwegs abutting the updrift or downdrift shoreline (Fig. 5). The factors that control channel morphology include: 1) easterly longshore sediment transport, 2) stratigraphy of the area, 3) backbarrier tidal channel distribution and 4) stabilization projects. Changes in tidal inlet morphology

have been discussed by Luck (1976B).

The strong easterly longshore transport system would seem to dictate that all the Friesian inlets should have channel thalwegs along their eastern downdrift sides. However, this is not the case (Fig. 5). As Sindowski's (1973) stratigraphic study of the barriers has revealed, several of the inlets have scoured into semi-indurated marine clays or glacial tills. The resistance of these sediments to erosion has served to naturally stabilize these inlets and control their geometry. For example, the thalweg at Accumer Ee is anchored along the western side of the inlet, having eroded into glacial tills. While the position of inlet thalweg was stabilizing at Accumer Ee, the backbarrier tidal channels continued to erode in an easterly direction. In this hook-shaped configuration the ebb-tidal flow in the main backbarrier channel is directed toward the western side of the inlet. This further stabilizes the thalweg along the updrift inlet shoreline.

At Nordeneyer Seegat the deepest portion of the inlet channel abuts the island of Norderney (Fig. 5) and has eroded laterally into compacted glacial sediments (Sindowski, 1973). The downdrift location of the channel thalweg is a product of the position and orientation of Buse Tief (a tributary creek with a northwesterly orientation) and the downdrift offset inlet shoreline configuration which affords greater exposure of the inlet channel to the dominant westerly wave energy.

It should be mentioned that during the past 100-150 years many of the inlets have been stabilized with groins and seawalls of various constructions (Fig. 2). A jetty has also been built at Harle Inlet.

Inlet Processes

Tidal inlet hydraulics and sediment transport patterns have been studied in detail at Norderneyer Seegat by Nummedal and Penland (1981) and at Harle Inlet by Hanisch (1981). The data base for these investigations consisted of historical information, grain size data, box cores, bedform measurements, velocity profiles and tracer experiments. Although in each of the studies different sediment transport processes were deemed most important similar sediment transport trends were envisioned. Nummedal and Penland's (1981) sediment transport model for Norderneyer Seegat is shown in Figure 7. The bedform data at Wichter Ee (Fig. 8) corroborate these general sand transport patterns.

Sand bypasses tidal inlets along the East Friesian Islands by a combination of wave and tidal processes in a manner first described by Brunn and Gerritsen (1959).

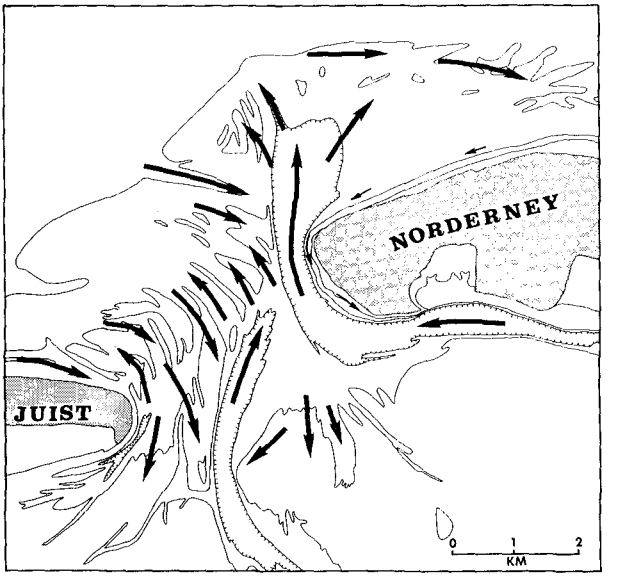

Figure 7. Sediment transport patterns at Norderneyer Seegat (from Nummedal and Penland, 1981).

One of the end products of inlet sediment bypassing process is the attachment of large bar complexes to the downdrift beach. Sand is transported to the inlets by wave action from the west. Once in the vicinity of the ebb-tidal delta sand is moved toward the inlet through marginal flood channels by flood tidal currents and wave-generated currents. Most of the sand that is delivered to the main ebb channel is transported in a net seaward direction by dominant ebb tidal flow. This sand is deposited along an arcuate series of bars (reef bow) that comprise the outer portion of the ebb-tidal delta. These bars migrate in an easterly fashion along the periphery of the delta (Fig. 9) (Homeier and Kramer, 1957). Aerial views of the ebb-tidal delta bars at Norderneyer Seegat and Wichter Ee are shown in Figure 10.

Sand from the ebb-tidal delta is ultimately added to the downdrift beach through the landward migration of large swash bars, which may be more than 1 km in length. Bar complexes in the process of welding to the shoreline of Baltrum are illustrated in Figure 11. It should be emphasized that as much as half of the volume of sand that bypasses the inlet is moved onshore by wave action

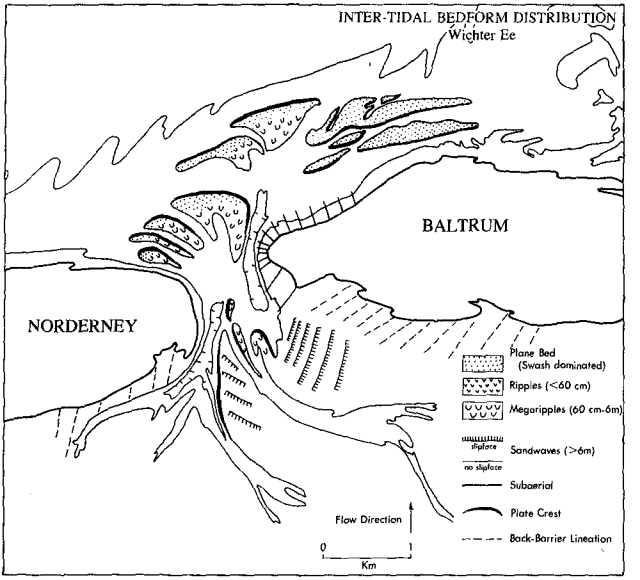

Figure 8. Bedford distribution map for Wichter Eee.

independent of the bar complexes.

BARRIER ISLAND PROCESSES

Erosional-depositional trends along the East Friesian Islands are discussed in detail by Luck (1975 and 1976B). These trends correlate well with the location where bars weld to the beach and the local longshore transport patterns. If the bars move onshore some distance down-drift of the inlet shoreline then the updrift end of the barrier is likely to be erosional. Conversely, the site where the bars weld to the beach and the shoreline down-drift of this location are normally accretionary (Luck, 1975).

FitzGerald et al (1984) have also shown that the shape of the East Friesian barriers is tied closely to the bar welding process (Fig. 12). If the bars move onshore close to the inlet mouth then a drumstick barrier develops, as would be predicted by Hayes and Kana (1976). However, when the bar complexes attach to the beach some distance away from the inlet a humpbacked or downdrift bulbous barrier is formed (FitzGerald et al, 1984A).

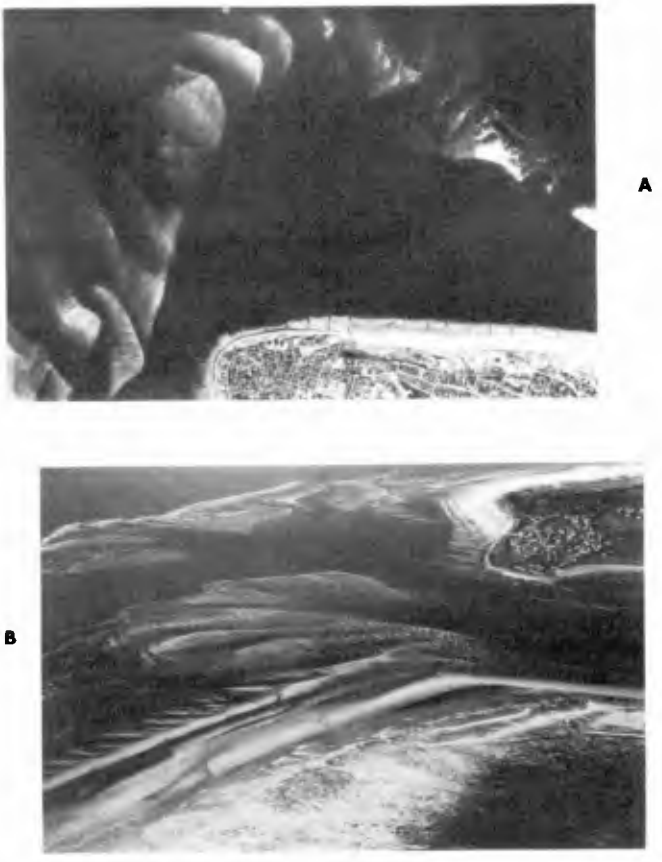

Figure 9. Aerial photographs of A. Norderneyer Seegat and B. Wichter Ee.

The position along the downdrift barrier island shoreline where the bar complexes weld to the beach is a product of the size and symmetry of the ebb-tidal delta. These factors control the amount of overlap of the ebb-tidal delta and therefore the distance from the inlet that the sediment bypassing process is completed. The size of inlet is a function of the backbarrier drainage area. The symmetry of the ebb delta is controlled by the position of the main ebb channel at the inlet throat. The influence of these various factors is demonstrated in Figure 5. Note that the large size of Norderneyer Seegat coupled with the downdrift location of the main channel at the inlet throat have produced a highly asymmetric ebb-tidal delta that

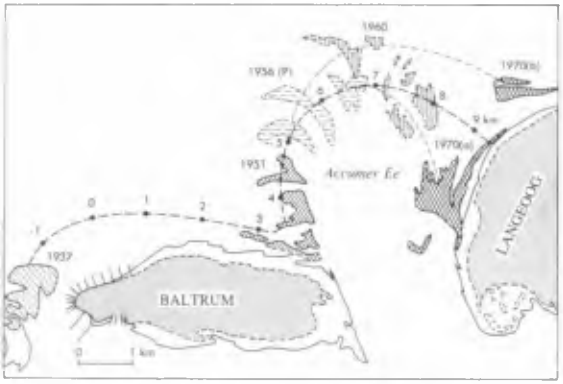

Figure 10. Pathways of bar movement at Wichter Ee and Accumer Ee (from Homeier and Kramer, 1957).

Figure 11. View of swash bars welding to the beach along Baltrum.

greatly overlaps the downdrift beach (5.0 km). This explains the humpbacked development of the island of Norderney. Contrastingly, the western position of the main ebb channel at Accumer Ee has resulted in a symmetrically-shaped delta. Bar welding along Langeoog occurs close to the inlet and thus Langeoog has a drumstick shape.

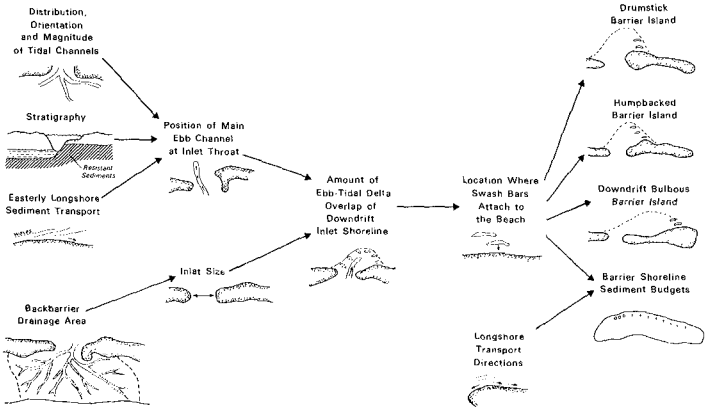

Figure 12. Model of the morphological development of East Friesian barrier islands.

SUMMARY

1) The East Friesian Islands have undergone dramatic changes since 1650. An abundant sediment supply has resulted in a 35% increase in aerial extent of the barrier islands. Coincident with this growth was a 30% decrease in backbarrier drainage area due to land reclamation efforts. This decrease in bay size has caused a reduction in the tidal prisms and smaller equilibrium tidal inlet cross sectional areas.

2) The strong westerly wind regime of this region produces a dominant easterly longshore transport direction. This easterly transport of sediment has caused an easterly extension of the barrier islands. Some of this eastward growth has occurred through an easterly migration of the tidal inlets. However, most of the growth has been accommodated by a narrowing of the inlets.

3) There has been a long-term eastward migration of the backbarrier drainage systems caused by the dominant westerly winds. Wind driven currents augment and retard the tidal currents resulting in a net easterly transport of sediment and headward erosion of the tidal

creeks. This has produced hook-shaped backbarrier channels. The position of the main channel at the inlet throat and the degree of hook-shape of the backbarrier channels are controlled by the stratigraphy of the region. Norderneyer Seegat and Accumer Ee have scoured into resistance sediments and thus have stabilized. At these locations there has been little inlet migration and their main channels are highly hooked. Conversely, Harle Inlet has had a history of easterly migration prior to jetty construction and its main channel is fairly straight.

4) Sediment bypasses the inlets in the form of landward migrating swash bars. Sand is also bypassed independent of the bars along the periphery of the delta. The location where the bars weld to the beach is controlled by the overlap of the ebb-tidal delta which, in turn, is a function of inlet size and position of the main ebb channel at the inlet throat. The site where swash bars move onshore coincides with the bulbous portion of the barriers. This accretionary process is responsible for barriers of various shape.

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