Deutsche Hydrographische Zeitschrift
German Journal of Hydrography
Volume 49 (1997) Number 2/3

ISSN 0012-0308

Response of the Wadden Sea to a Rising Sea Level: a Predictive Empirical Model

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Summary

A clue to the stratigraphic evolution in the case of a barrier island migrating up against a landward obstruction has recently been obtained from a detailed analysis of sediment patterns in the mesotidal backbarrier environment of the Wadden Sea (southern North Sea). Here the landward boundary is man-made and comprises a continuous dike line constructed in the wake of extensive land reclamation over the past 1000 years. Sea-level rise currently amounts to 25 cm/century. The system is further characterized by a lack of external sediment supply and a pronounced cross-shore energy gradient resulting in progressive landward fining of the backbarrier sediments. Adjacent to the dike the depositional system today is dominated by mixed flats with mud contents rarely exceeding 30%. Land reclamation has thus truncated the natural succession of sediment facies by eliminating mud flats and salt marshes. Contrary to expectations, the re-establishment of a complete but compressed facies sequence incorporating mud flats and salt marshes has not materialized. This would suggest that energy levels at the foot of the dike today are considerably higher than was previously the case along the undiked shoreline. A quantitative relative measure of backbarrier energy levels is the mean settling velocity of the sediment. In extreme cases the system has reached the stage where the finest sands with settling velocities below 0.3 cm s^{-1} (mean grain sizes <0.1 mm) are being eliminated. It is postulated that, in the wake of continued sea-level rise and associated landward migration of the barrier island system, the sediment elimination process adjacent to the dike will continue and involve progressively coarser sediments. In the case of the Wadden Sea, the settling-lag and scour-lag mechanism by which fine-grained sediments are carried shoreward must be modified to incorporate an export loop for those particle sizes which have settling velocities below the local elimination threshold.

The sediment elimination process outlined above is triggered by the rigid man-made boundary which prevents landward displacement of the depositional system onto the adjacent coastal plain. This model may be applicable to natural systems migrating towards a coastal cliff or a steeply rising hinterland in the course of transgression. It is postulated that in such cases an analogous loss of intertidal facies belts adjacent to the shoreline will occur and that this should be revealed in the stratigraphic record by upward coarsening, onlapping sequences.

Veränderungen im Wattenmeer durch Anstieg des Meeresspiegels: ein empirisches Vorhersagemodell (Zusammenfassung)

Eine neuere ausführliche Analyse der Sedimentmuster im mesotidalen landseitigen Watt der südlichen Nordsee gibt Aufschluß über die stratigraphische Evolution im Fall einer sich landwärts verlagernden Barriereinsel. Die landseitige Begrenzung ist hier eine im Zuge der Landgewinnung der vergangenen 1000 Jahre künstlich geschaffene durchgehende Deichlinie. Der Meeresspiegelanstieg beträgt zur Zeit 25 cm in 100 Jahren. Kennzeichnend für das Gebiet ist die fehlende Sedimentzufuhr von außen und ein ausgeprägter küstennormaler Energiegradient, aufgrunddessen die Ablagerungen landwärts zunehmend feiner werden. Angrenzend an den Deich herrscht im Ablagerungssystem Mischwatt vor, dessen Schlickgehalt selten über 30% liegt. Im Zuge der Landgewinnung ist demnach durch das Verschwinden von Schlickwattflächen und Salzmarschen die natürliche Abfolge der Sedimentfazies gekappt worden. Entgegen den Erwartungen hat es keine Neubildung einer vollständigen, jedoch komprimierten Faziesfolge mit Schlickwatten und Salzmarschen gegeben. Das deutet darauf hin, daß die Energieeinwirkung am Deichfuß heute erheblich höher ist als früher an der nicht eingedeichten Küstenlinie. Ein quantitatives relatives Maß für die Energieeinwirkung ist die mittlere Partikelsinkgeschwindigkeit. Das vorliegende System hat im Extremfall das Stadium erreicht, in dem die feinsten Sände mit Sinkgeschwindigkeiten unter 0,3 cm s^{-1} (mittlere Korngrößen <0,1 mm) verschwunden sind. Es wird postuliert, daß sich im Zuge des Meeresspiegelanstiegs und der damit verbundenen landwärtigen Verlagerung der Barriereinseln der Abtransport des feinkörnigen Materials am Deichfuß fortsetzen wird unter Einschluß zunehmend gröberer Partikel. Im Fall des Wattenmeers muß der Sedimentations- und Auskolkungsmechanismus, der feine Partikel zur Küste hin transportiert, durch eine Abtransportschleife für die Korngrößen ergänzt werden, deren Sinkgeschwindigkeit unterhalb der lokal gültigen Schwelle liegt.

Der beschriebene Prozeß wird durch die künstlich geschaffene Grenze ausgelöst, die die landwärtige Verlagerung des Ablagerungssystems in Richtung auf die angrenzende Küstenebene verhindert. Das Modell kann bei natürlichen Systemen Anwendung finden, die sich transgressionsbedingt auf ein Küstenkliff oder auf steil ansteigendes Hinterland zubewegen. Es wird angenommen, daß es in solchen Fällen analog zum Verlust von küstennahen Faziesgürteln im intertidalen Gezeitenbereich kommt, was im stratigraphischen Signal durch gröbere, übergreifende Sequenzen zu erkennen sein müßte.

1 Introduction

Stratigraphic models of barrier island depositional systems have mostly dealt with the effects of transgressions and regressions on facies successions and architecture under different sediment supply regimes (e.g. KRAFT [1971]; KRAFT et al. [1973]; SWIFT [1976]; KRAFT AND JOHN [1979]; GALLOWAY AND HOBDAY [1983]; SWIFT et al. [1991]; ROY et al. [1994]). Much less attention has been paid to the effects of different slope angles of the basal surface across which such systems migrate (e.g. ROY et al. [1994]) and even less is known about the stratigraphic imprint produced by a barrier island system migrating against a progressively steepening hinterland or a landward obstruction, e.g. a coastal cliff, especially in its terminal phase.

In this paper, it will be shown that along the Wadden Sea coast of the southern North Sea the process of land reclamation and dike construction has created a situation which is comparable to a natural setting in which a barrier island system migrates against a coastal cliff. In the course of land reclamation the area of the former backbarrier depositional environments of the Wadden Sea has been reduced by as much as 75%, and the once irregular mainland shoreline has been replaced by an essentially straight and rigid dike. The geological impact of this human interference along the Wadden Sea coast has hitherto been greatly underestimated, having had profound effects on backbarrier sediment distribution patterns and the available accommodation space for different sediment types, effects that are likely to amplify in the wake of the predicted acceleration in sea-level rise over the next century or so. It may be expected that under analogous natural conditions sedimentological responses resembling those documented for the Wadden Sea are likely to occur.

2 Physical setting

This study is based on detailed sedimentological and morphodynamic observations made in the vicinity of Spiekeroog Island, one of seven barrier islands situated along the mesotidal East Frisian sector of the German North Sea coast (Fig. 1). The tides are semidiurnal, with a mean tidal range of 2.6 m in the Otzum inlet. The catchment area of the associated tidal basin covers 74.3 km^2, the width between the island beach and the dike is about 9 km, and the mean tidal prism is roughly 131 x 106 m^3 (e.g. WALTHER [1972]; FERK [1995]). Water temperatures range from <5°C in winter to >20°C in summer, while salinities vary between 2.6% and 3.2%.

The weather pattern is strongly seasonal (FACH [1995]), 85% of winds >10 Bft blowing during the winter months, 30% of these in November. Most of the storm fronts approach from the northwest (47%), followed by westerlies (30%) and southwesterlies (19%). Taking winds, wind-induced wave action and tides together, most of the relevant energy flux is oriented NW-SE or slightly oblique to the coast for most of the year (ANTIA [1993]).

The sediments are composed mainly of terrigenous quartz, both in the sand and silt fractions, heavy minerals forming a minor component. Bioclastic material locally contributes substantial amounts, especially in coarse channel lag deposits

(Flemming et al. [1992]) and in the mud fraction which may also comprise up to 20% clay minerals (van Straaten [1954]). The main source of the sediments is local glacial outwash deposits and hitherto unquantified amounts of fine-grained material from remote sources (e. g. Eisma [1968]; Streif [1990]).

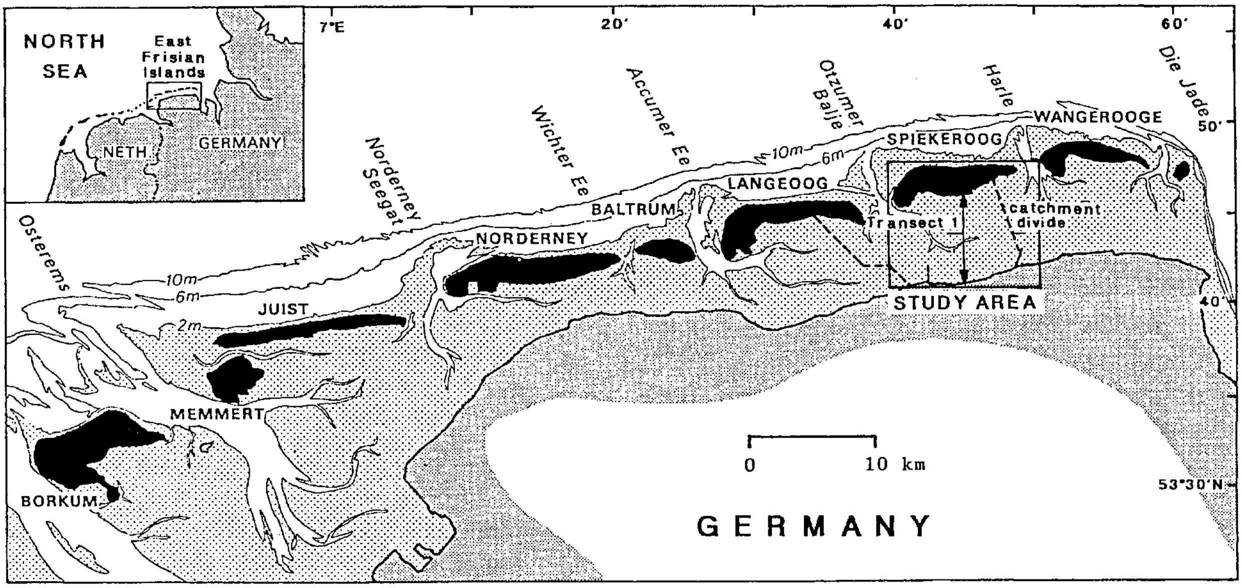

Fig. 1: Location of the study area along the East Frisian sector of the Wadden Sea coast (southern North Sea)

As no coarse-grained sediment is supplied by remote sources, the entire barrier island depositional succession along the southern North Sea is being continually recycled by erosional shoreface retreat, most of the eroded sediment being subsequently redeposited in the backbarrier environment. Since the onset of land reclamation almost 1000 years ago, the backbarrier sediment deficit created by the sea level rise has decreased progressively in proportion to the reduction of the tidal prisms and catchment areas (Fig. 2). This human intervention has triggered large-scale morphodynamic adaptation processes which in the past have not always been correctly distinguished from other natural processes (e.g. Fitzgerald et al. [1984]; Flemming and Davis [1994]; Biegel and Hoekstra [1995]; Oost [1995]).

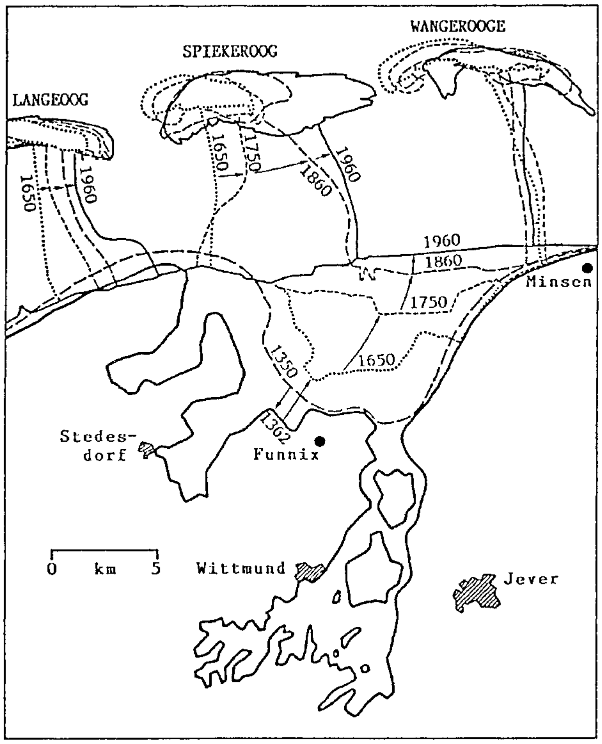

Fig. 2: Morphodynamic responses in the vicinity of Spiekeroog Island as illustrated by changes in island shape and position and the displacement of watersheds between adjacent tidal basins as a result of land reclamation in historical times (after Flemming and Davis [1994])

3 Study Methods

Surficial sediments were collected in the backbarrier tidal basin draining through the Otzum tidal inlet which is situated between the barrier islands of Langeoog and Spiekeroog. The sampling grid was generally spaced at 0.15' Latitude and 0.25' Longitude (approx. 275 x 275 m at 53° 40' N), resulting in some 1,600 samples. In each case at least 4 small random samples of 30–40 g were mixed to obtain a composite sample of 120–160 g. In this way, the probable sampling error was reduced by at least 50% (Krumbein [1934]; Krumbein and Pettijohn [1938]). Positions were fixed by means of a portable DECCA navigator, the typical accuracy after calibration being 25–50 m. The samples were processed in the laboratory following standard procedures (e.g. Carver [1971]), specific aspects being described in greater detail by Flemming and Ziegler [1995].

After separating and drying the mud and sand fractions, the latter were split to an appropriate mass (in this case 0.5–1.0 g) for grain size analysis using an automated, high-resolution settling tube system (Brezina [1979, 1986]). The settling velocity distributions are routinely standardized to a water temperature of 24°C (US engineering standard) before being converted into equivalent settling diameters using a shape factor of SF = 1.18 (glass sphere standard) and a particle density of = 2.65 g cm^{-3} (Gibbs et al. [1971]; Brezina [1979]). Textural parameters were calculated on the basis of moment and percentile statistical procedures. For more details about the philosophy and application of settling tubes and settling velocity distributions the reader is referred to Reed et al. [1975], Middleton [1976], Flemming and Thum [1978], Brezina [1979], and Flemming and Ziegler [1995].

Conversion of mean settling diameters into site-specific temperature- and salinity-adjusted settling velocities was accomplished using the newly-developed software package SedVar 6.2 CTM (Brezina [1996]). Volumetric calculations are based on the evaluation of digitized topographic maps of the study area and include both the backbarrier tidal catchment and the upper shoreface along the open coast of the adjacent barrier island (Spiekeroog). Typical cross-shore grain size and settling velocity trends are illustrated by a transect whose topographic nature is shown in Fig. 3 (position shown in Fig. 1).

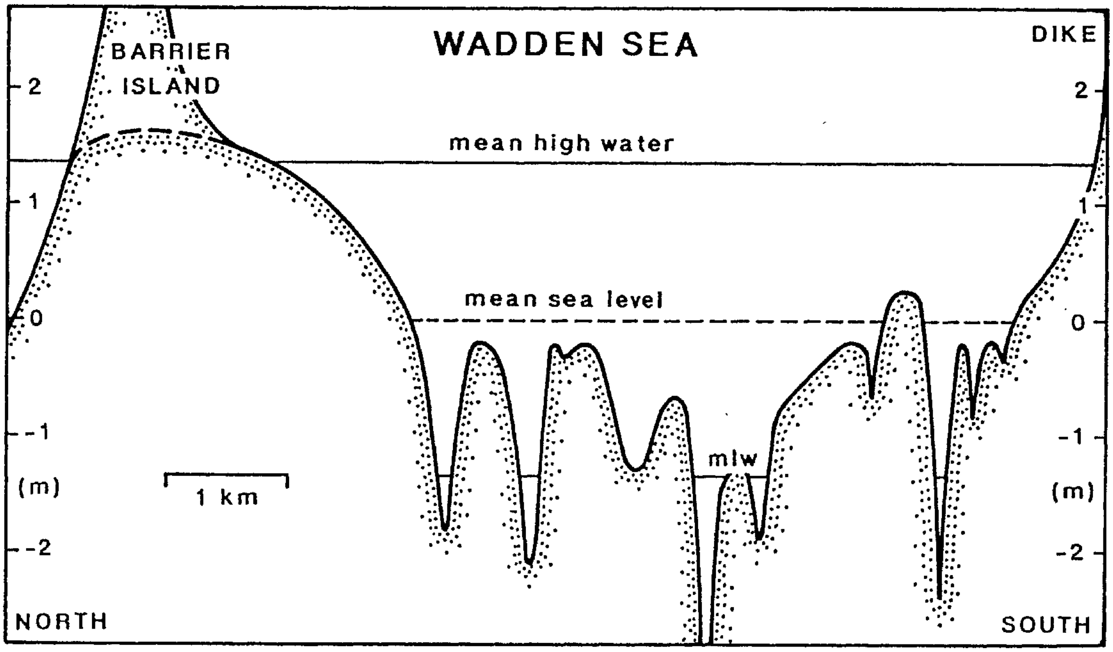

Fig. 3: Topography of a typical transect across the Otzum tidal basin. For position of transect see Fig. 1

4 Results

The grain size data show a progressive cross-shore fining trend producing a shore-parallel arrangement of facies belts. This is illustrated by the sediment facies map in Fig. 4 which is based on a composite view of dominant grain sizes, i. e. all 0.5-phi size fractions that contribute 50% or more to the local sediment. The spatial nature of this grain size gradient has been discussed in greater detail by Flemming and Ziegler [1995]. When resolving individual 0.5-phi size fractions along a cross-shore profile (Transect 1), the shoreward fining trend is highlighted in the form of overlapping, irregular bell-shaped concentration profiles (Fig. 5), the sediment at any particular location along the transect being composed of the sum of all proportional size fractions found at that point. As illustrated by the 2.5–3.0 phi size fraction, the total cross-shore spread of each fraction amounts to at least 9 km, while the portion >50% covers 4–5 km.

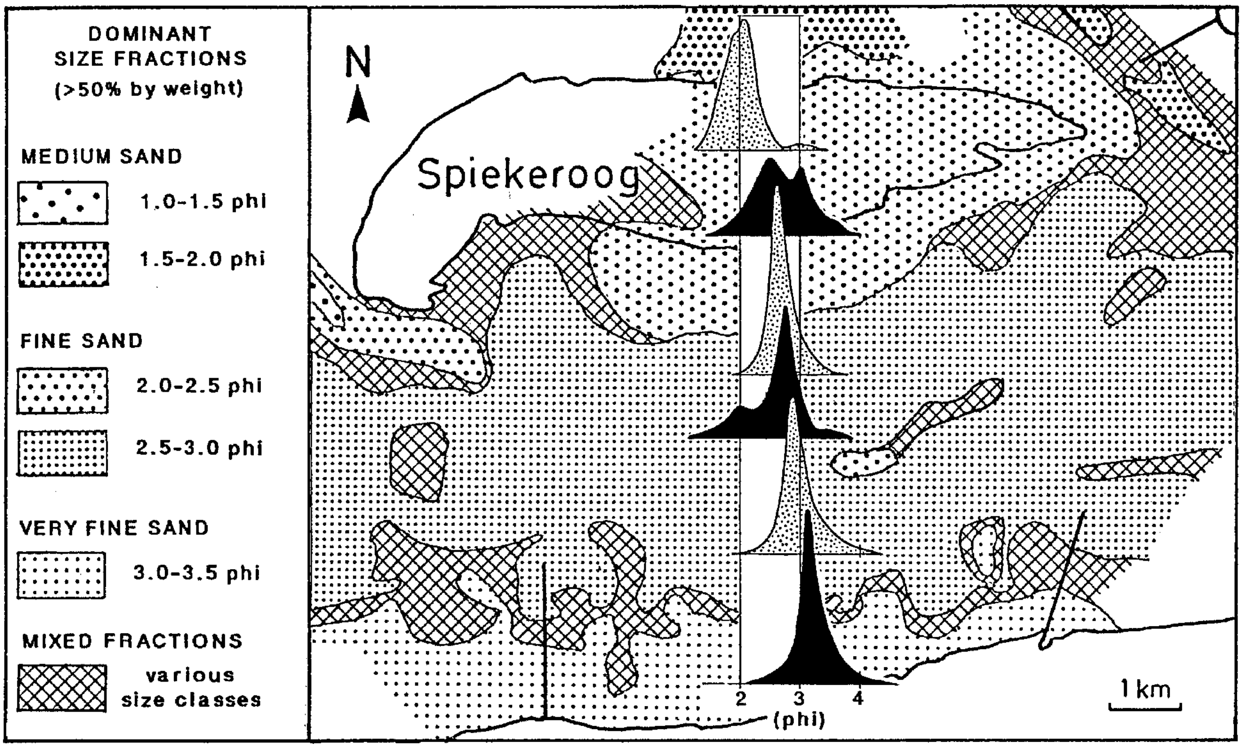

Fig. 4: Map illustrating the landward fining trend and shore-parallel arrangement of successive sediment facies as represented by the dominant 0.5-phi size fractions. Note the missing finest very fine sand facies (3.5–4.0 phi or 0.88–0.063 mm)

In Fig. 5 the coarser size fractions to the left (north) and the finer ones to the right (south) appear truncated along the seaward and landward margins, respectively. However, the work of Antia [1993] has shown that the coarser fractions continue in like manner onto the upper shoreface. Similarly, although the finer size fractions to the south are indeed truncated by the dike along the mainland shore, bore-hole records from the Netherlands (e. g. Zagwijn [1986]) and Germany (e. g. Streif [1989, 1990]) prove that finer-grained intertidal sediments used to continue landwards in the past, i. e. before land reclamation commenced some 1000 years B.P.

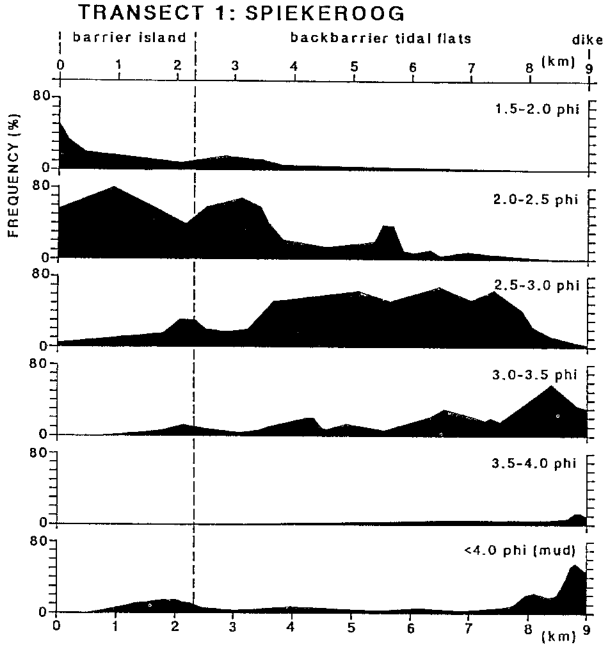

Fig. 5: Transect illustrating the shoreward fining trend by the cross-shore dispersion of individual 0.5-phi size fractions. Note the landward truncation of all facies finer than 3.0 phi

It is important to note that the original fine-grained facies that used to line the undiked shore, i.e. mud flats and lower salt marshes comprising pioneer plants like Salicornia and Spartina, have not re-established themselves to any degree in front of the dike. Instead, the dike foreland today is fringed in most places by upper salt marshes (e.g. Pucinellia meadows) the establishment of which has been actively promoted by man to create an energy buffer between the open tidal flats and the dike. The only natural salt marshes remaining along the mainland coast of the Wadden Sea today occur in the Varde Å estuary in Denmark, an area where tidal flats have not been reclaimed for agricultural purposes (Bartholdy and Pjerup [1994]). On the other hand, there is ample evidence that salt marsh formation will proceed extremely rapidly once suitable conditions prevail, i.e. low energy coupled with less than 3.5 h of submergence per tide on average (e.g. Streif [1990]; see also Flemming and Davis [1994]).

The sedimentological results suggest that the mean grain size of sediment in the vicinity of the dike should be a sensitive indicator of the prevailing energy regime (e.g. van Straaten and Kuenen [1958]; Postma [1961]; Nyandwi and Flemming [1995]). In terms of settling velocity, the energy gradient along the East Frisian coast in the vicinity of Spiekeroog Island can be approximated by the empirical linear regression equations:

$$V_{20\,°C} = 2.968 - 0.255L \text{ or } V_{05\,°C} = 2.219 - 0.196L$$

where $V_{20\,°C}$ and $V_{05\,°C}$ are the respective summer and winter settling velocities in cm s^{-1} at mean water temperatures of 20 °C and 5 °C and L is the distance in km from the island shore (Fig. 6). The landward cut-off point thus can be calculated simply from the measured distance between the mean high water line (MHW) on the island beach, which represents the highest energy zone of the system, and the corresponding line along the foot of the dike which represents the lowest energy zone. The available data clearly show that the shorter this distance, the coarser the sediment or the higher the particle settling velocity along the landward shoreline. Since sediment particles have their lowest settling velocities at low water temperatures due to the higher kinematic viscosities of the fluid, sediment distributions in the Wadden Sea are postulated to be adjusted to a local mean winter water temperature of 5 °C (cf. Krögel and Flemming [in press].

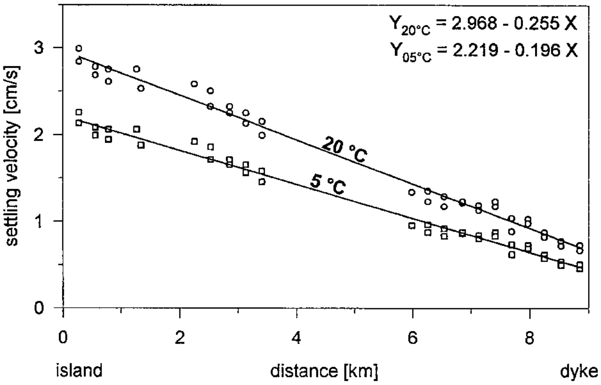

Fig. 6: Settling velocities of surficial sediments along transect 1 across the backbarrier tidal flats for water temperatures of 5 °C (winter) and 20 °C (summer) and a salinity of 3%

5 Discussion and conclusions

Highlighting the effects of land reclamation on sediment distribution, FLEMMING AND NYANDWI [1994] explained the widespread lack of mud flats and natural salt marshes in the Wadden Sea by a substantial increase in the energy gradient along the mainland coast in the course of land reclamation, i. e. in response to the reduction of the catchment area. Since the degree of land reclamation and the remaining width of the backbarrier tidal flats changes along the coast, as does the mean energy flux as a function of coastline orientation to the regional weather pattern, the sediment elimination process has reached different evolutionary stages in different parts of the Wadden Sea. The evolutionary stage which a particular coastal sector has reached is defined by the mean settling velocity of the sediment adjacent to the dike in winter when the water has its highest kinematic viscosities.

Besides the inherently lower settling velocities in winter, the different slopes of the two regressions in Fig. 6 also imply a marked seasonal difference in the dynamic behaviour of backbarrier sediments. Thus, due to the lower settling velocities and the less steeply sloping cross-shore gradient at a mean water temperature of 5 °C, the sediment is clearly more mobile in winter than in summer. As a result, the depositional system can accommodate less fine-grained sediment along its landward boundary in winter than it would in summer. Since the energy flux is actually higher in winter, these effects are further enhanced. This situation is aggravated by a rising sea level because the landward migration of the barrier island depositional system now meets a rigid obstruction in the form of the dike, which inevitably leads to a further elimination of sediment (Fig. 7). In the face of a continued and possibly accelerating sea-level rise (currently 25–30 cm/century along the East Frisian coast), coupled with a further reduction in backbarrier catchment areas, the sediment depletion mechanism along the landward margin of the Wadden Sea will not only continue in the future but obviously involve progressively coarser-grained sediments. This is schematically illustrated in the strongly simplified conceptual model presented in Fig. 8. A closer analysis of this phenomenon revealed that in the present situation the finest sand fractions have already been affected in some places. It has also been assumed that the progressive depletion of fine-grained substrates over the past centuries must have had an effect on the structure of the ecosystem (FLEMMING AND NYANDWI [1994]).

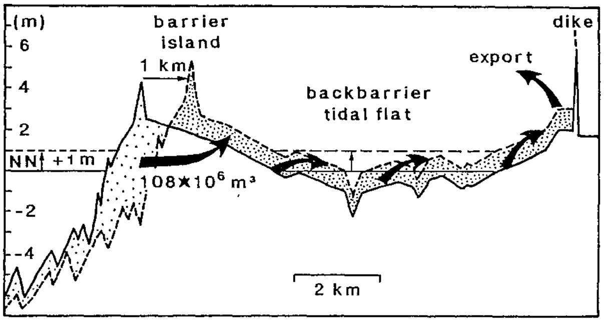

Fig. 7: Schematic diagram illustrating the expected response of the Wadden Sea to a sea level rise of 1 m (modified after FLEMMING AND DAVIS [1994])

Since man-made dikes in the case of the Wadden Sea would correspond to coastal cliffs along natural shorelines, it has been postulated that similar effects are likely to occur when barrier island systems migrate towards a cliffed or steeply rising hinterland in the course of sustained transgression. In the case of a uniformly sloping coastal plain coupled with a lack of external sediment supply the barrier island system is simply displaced landward by erosional shoreface retreat while retaining its entire facies succession (Fig. 9A). When migrating towards a progressively steepening shoreline, the backbarrier facies belts might be expected merely to compress as the tidal basin decreases in width, a situation illustrated in Fig. 9B. Observations along the Wadden Sea coast, however, do not support this model. Instead we observe a progressive elimination of the finer-grained nearshore facies belts, evidently caused by an increase in energy levels along the mainland coast. As illustrated in Fig. 9C, the stratigraphic evolution of the backbarrier basin under such conditions appears to be characterized by an onlapping transgressive facies succession

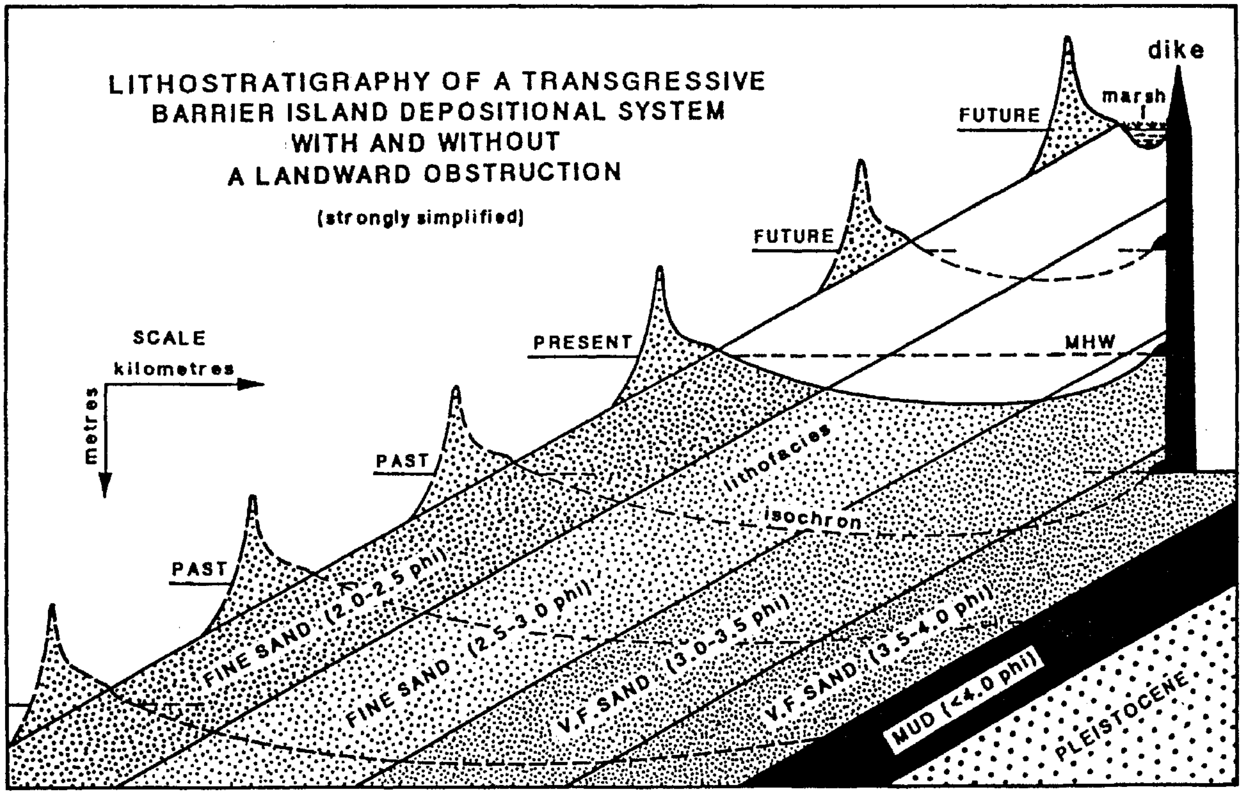

Fig. 8: Simplified lithostratigraphic evolution of a barrier island system in the presence of a landward obstruction, here formed by the dike (modified after Flemming and Nyandwi [1994])

which is produced by progressive elimination of marginal facies belts, a process which should continue until the energy flux begins to diminish in the terminal phase when the inlet is rapidly infilled and wave energy decreases.

It is not clear at this stage whether the situation observed in the Wadden Sea, i. e. the model illustrated in Fig. 9C, reflects the normal course of events or whether it simply reflects circumstances produced by the interference of man. It should be emphasized that thus far no evidence has been found supporting the latter assumption. In order to argue in favour of the model illustrated in Fig. 9B, it would have to be demonstrated that the reduction in the size of tidal catchment areas in the course of transgression against a steeply rising hinterland is inherently linked with a proportional reduction in energy levels. Only then would it be possible to retain the complete facies sequence in compressed form. Unfortunately, most of the available data on barrier island stratigraphy lack the spatial resolution required for an unequivocal recognition of trends comparable to those documented for the Wadden Sea. Nevertheless, although not entirely conclusive, some published data would seem to favour the Wadden Sea model outlined above (e. g. Curray et al. [1969]; Belknap and Kraft [1977]; Kraft et al. [1979]). Moreover, recent and as yet unpublished observations by the first author clearly favour the model in Fig. 9C. Thus, locally along the Danish Wadden Sea coast where the landward shoreline is lined by natural cliffs cut into Pleistocene deposits, salt marshes and mud flats are conspicuously absent.

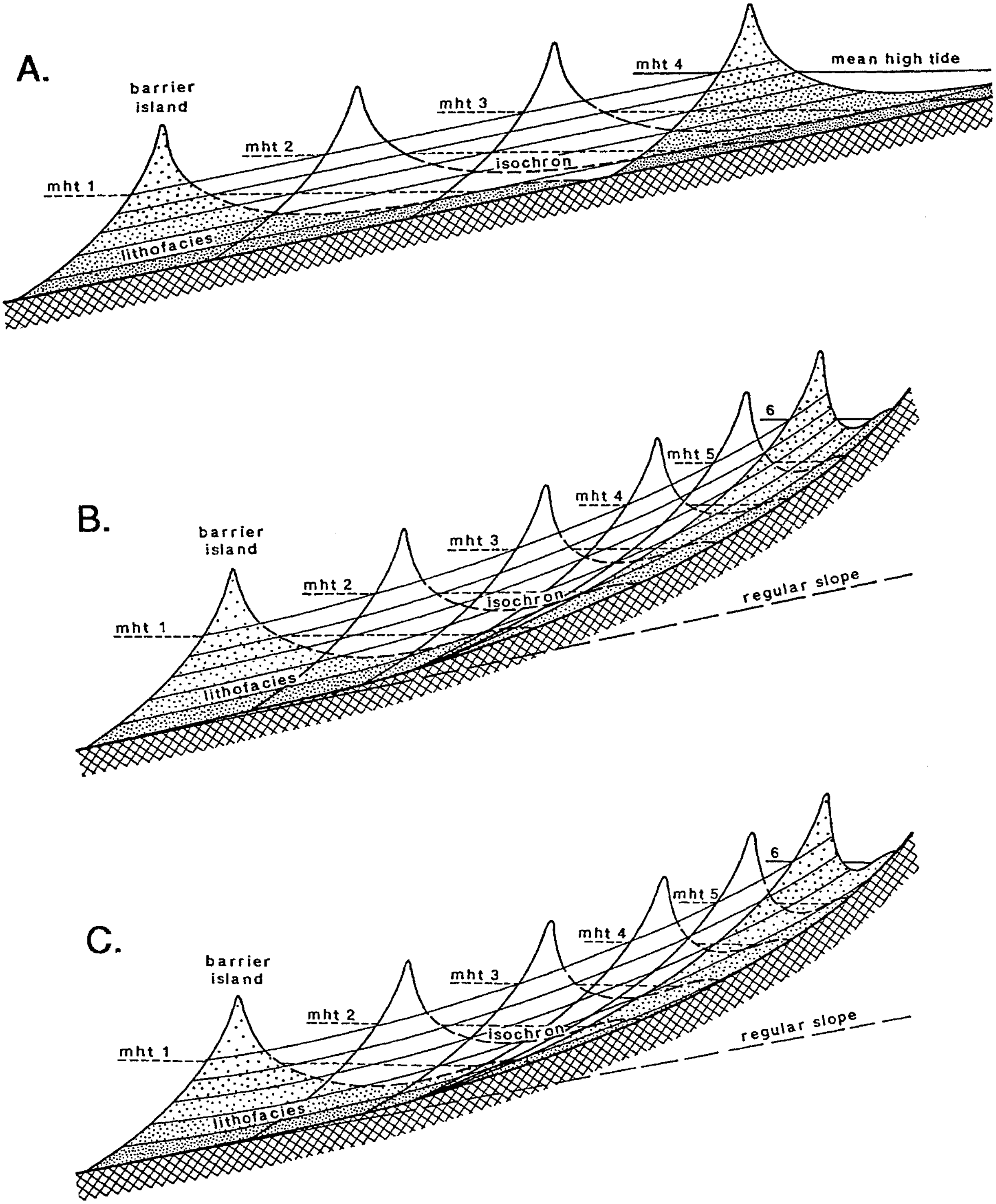

Fig. 9: Comparison of the theoretical stratigraphic evolution of transgressive barrier island systems in the presence of a uniform slope (A), a progressively steepening slope accompanied by a compression of facies belts (B), and a progressively steepening slope accompanied by the gradual elimination of the finer facies belts along the landward margin (C)

Acknowledgements

I wish to thank the captain and crew of the research vessel "Senckenberg" for their unfailing expertise in negotiating shallow ebb tidal deltas and manoeuvering in the tight backbarrier channel systems of the Wadden Sea. Karen Ziegler, Astrid Raschke and numerous students are thanked for various assistance with topographic chart evaluations, sample collections and laboratory analyses. The project was financially supported by the Senckenbergische Naturforschende Gesellschaft, the State of Hessen and the German Federal Government.

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Submitted: 20. 02. 1997
Accepted: 30. 07. 1997

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