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Ricklefs, Klaus; Asp Neto, Nils E.

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Die Küste, 69 PROMORPH (2005), 93-127

Geology and Morphodynamics of a Tidal Flat Area along the German North Sea Coast

By KLAUS RICKLEFS and NILS EDVIN ASP NETO

Summary

It is the aim of the study is to give an overview about the geology and the morphodynamics of the Dithmarschen Wadden Sea area, a low macrotidal section of the German North Sea coast. The environment is composed of mainly fine-sandy and silty sediments, which show a typical gradation from hydrodynamically exposed areas with coarser sands to sheltered regions with finer deposits. This sequence is not only true for the surface sediments but also for the deposits of the upper few metres. The overall thickness of the young tidal flat sediments is up to 20 m. Also of Holocene age are consolidated, clay rich silt layers, which exhibit a pronounced resistance against erosion and scouring. They widely form a kind of erosion basis above which most of the morphodynamic processes occur.

The most obvious morphological evolution recognised in the area is the landward migration of the most seaward located sandbanks. Probably active since longer periods this process is clearly visible and always orientated in the same direction since the last three to five decades. Another still ongoing process is the morphological adaptation to the land reclamation of the inner Meldorf Bay in the 70th of the last century. However, there are indications that this evolution, mainly visible as an infilling of channels, at least in some compartments approaches stages of a dynamic equilibrium. Beside these long and medium term evolutions there are pronounced morphological processes being active on a seasonal scale. One of these cycles is the scouring of the channel beds in winter and the infilling in the subsequent calm season.

In spite of the fairly good data basis and the variety of discussed aspects no comprehensive conceptional model of the morphodynamics of the domain could be developed. To realize such tasks, new methods, which go beyond classic morphological research approaches, are needed.

Zusammenfassung

Ziel dieser Studie ist es, einen Überblick über den geologischen Aufbau und die morphologischen Abläufe im Dithmarscher Wattenmeer, einem niedrig makrotidalen Abschnitt der deutschen Nordseeküste, zu geben. Das Gebiet wird von feinsandig, schluffigen Sedimenten aufgebaut, die eine typische Abfolge von gröberen Sanden in den hydrodynamisch exponierten Gebieten hin zu feinkörnigen Ablagerungen in geschützten Bereichen zeigen. Diese Sequenz umfasst nicht nur die eigentlichen Oberflächensedimente, sondern auch die obersten Meter der Wattablagerungen. Die rezenten Wattsedimente erreichen eine Mächtigkeit von bis zu 20 m. Ebenfalls holozänen Alters sind tonreiche Schluffschichten, die aufgrund ihres Konsolidierungsgrades einen erheblichen Widerstand gegenüber Erosions- und Auswaschungsprozessen zeigen. Diese Schichten bilden weithin eine Art Erosionsbasis, oberhalb derer die meisten der morphologischen Umgestaltungsvorgänge ablaufen.

Die offensichtlichste der im Gebiet erkannten morphologischen Entwicklungen ist die landwärtige Verlagerung der seewärtigsten Sandbänke. Vermutlich schon sehr viel länger aktiv, ist dieser Prozess innerhalb der letzten drei bis fünf Jahrzehnte deutlich sichtbar und immer gleich gerichtet gewesen. Eine ebenfalls noch andauernde Entwicklung ist die morphologische Anpassung an die Eindeichung der inneren Meldorfer Bucht in den 70er-Jahren des letzten Jahrhunderts. Es gibt allerdings Hinweise darauf, dass diese Anpassung, die hauptsächlich als Auffüllung von Gezeitenrinnen sichtbar wird, zumindest in einigen Teilbereichen eine Art dynamisches Gleichgewicht erreicht hat.

Neben lang- und mittelfristigen Entwicklungen kommen auch ausgeprägte morphologische Prozesse auf jahreszeitlichen Skalen vor. Eine dieser zyklischen Erscheinungen ist die festgestellte

Ausräumung der Prielbetten im Winter, die von Wiederauffüllung in der nachfolgenden ruhigeren Jahreszeit abgelöst wird.

Trotz der recht guten Datenlage und ungeachtet der Vielzahl von diskutierten Aspekten konnte kein umfassendes konzeptionelles Modell der morphologischen Evolution des Arbeitsgebietes entwickelt werden. Um eine derartige Aufgabe zu realisieren, bedarf es neuerer Methoden, die über die klassischen Ansätze morphologischer Forschung hinausgehen.

Keywords

German North Sea Coast, Tidal Flat, Low Macrotidal, Geological Setting, Holocene Evolution, Short-Term and Long-Term Morphodynamics.

Contents

1. Introduction

The coastal deposits of the German North Sea coast consist of geologically young soft sediments. Especially the wide tidal flats between the mainland and the open sea are characterised by intensive sediment turnover which results in pronounced morphological changes. The aim of this paper is to give an overview of the geological architecture, the distribution of recent sediments, and the type, scale and magnitude of morphodynamic processes of an exposed and very dynamic part of the German Wadden Sea. The individual studies were carried out within the framework of the joint research project PROMORPH (Prognosis of Medium Scale Morphological Changes), which was funded by the German Federal Ministry of Education and Research.

1.1 Investigation Area

The study area is located in the south-eastern part of the German Bight. Stretching from the mouth of the Elbe estuary in the south to the Eiderstedt peninsula in the north it approximately covers the entire Dithmarschen Wadden Sea (Fig. 1), which forms the southern compartment of the Wadden Sea of the federal state of Schleswig-Holstein. The domain is bordered by the mainland coast in the east and the 008° 25' E meridian in the west, which approximates the 10 m isobath of the open North Sea. This paper focuses on an area comprising the tidal channel system of the "Piep" with its adjacent intertidal flats (Fig. 1). Most results presented in this study are thus confined to this region.

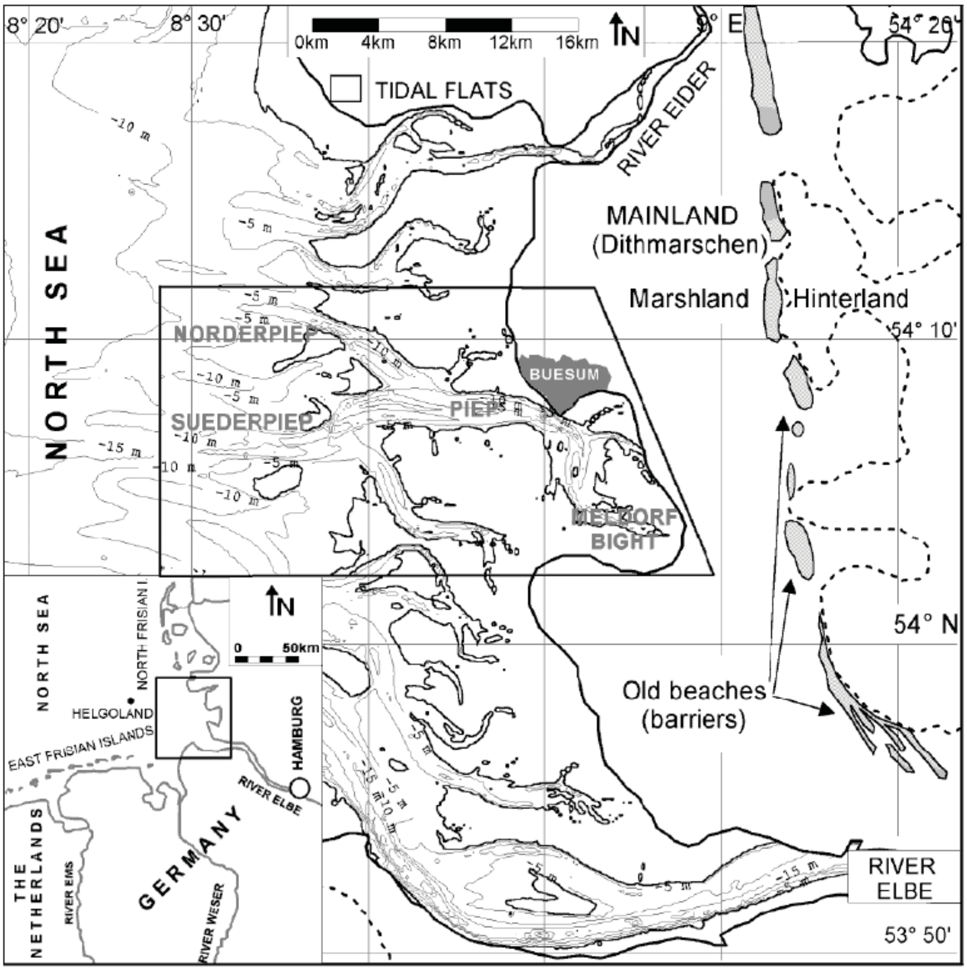


Fig. 1: Map of the investigation area

1.2 Holocene Geological Evolution

The Holocene evolution of the south-east coast of the North Sea has been controlled by the post-glacial sea-level rise. The deposits of the study area are almost exclusively characterised by silty and sandy siliciclastic sediments. Although a number of investigations on the geological structure have been carried out in the past, the level of knowledge about the temporal evolution of the area is considerably lower than that of adjacent areas to the west north. This is due to the lithological composition, intensive redeposition processes, and the lack of datable organic material.

The earliest and most comprehensive investigations were carried out by DITTMER (1938, 1952). Based on numerous core samples, the Holocene deposits were described and the principal (litho)-stratigraphic structure was identified. According to him as well as to Ruck (1969), Menke (1976), Linke (1979) and Tietze (1983), the pre-Holocene landscape was bordered by the melt-water valleys of the river Elbe in the south and river Eider in the north. In addition Dittmer (1938, 1952) was able to show that the surface of the Pleistocene sediments dips down from east to west (more rapidly in the south) to a depth of approximately 30 m below present sea-level. The higher parts of the Pleistocene surface are often composed of till whereas, the deeper parts consist of glacio-fluvial sands. On these sandy plains generated by glacier run-off the history of the post-Pleistocene deposition commences with a thin peat layer. Due to a rapid sea-level rise at the beginning of the Holocene transgression, the peat was partly eroded and is almost completely missing on the more elevated till areas. In the lower parts of the area, the initial brackish and marine deposits are composed of a succession of clayey and sandy silt layers reaching an overall thickness of up to 10 m. The infauna of this widely distributed consolidated mud deposit (Fig. 2), the "Dithmarscher Klei", indicates that the sedimentation of the upper clay-rich beds occurred under permanent submarine conditions.

In a later phase, this early Holocene clayey silt was overlain by partly discordant and partly concordant sandy sediment sequences with some interlayered cohesive, muddy deposits. The facies-change from clay deposition to more and more sandy accretion indicates a change from deep water to intertidal shallow water conditions (Dittmer, 1952; Streif and Köster, 1978). At the beginning of this period (approx. 7000 BP) the sea level rise has reached a level where intensive erosional and depositional processes started to alter the ancient coastline. Around 5000 BP these processes lead to the formation of narrow coast parallel forms similar to beach ridges or barrier islands (Fig. 1, Hummel and Cordes, 1969; Schmidt, 1976). Today these accumulations of coarse sand and gravel can be found some 10 km inland and are still visible as elongated, higher elevated areas partly covered with dunes. The first organic rich deposits formed in the shelter of these barrier-like structures are dated from the period from 4000 to 3500 BP (Hummel and Cordes, 1969). At this time, the process of shore line grading became less important and was replaced by a final and still ongoing phase of deposition of mainly fine sandy, partly silty material which builds up the marshes and tidal flats of today (Hoffman, 1998). These deposits, which account for the bulk of the

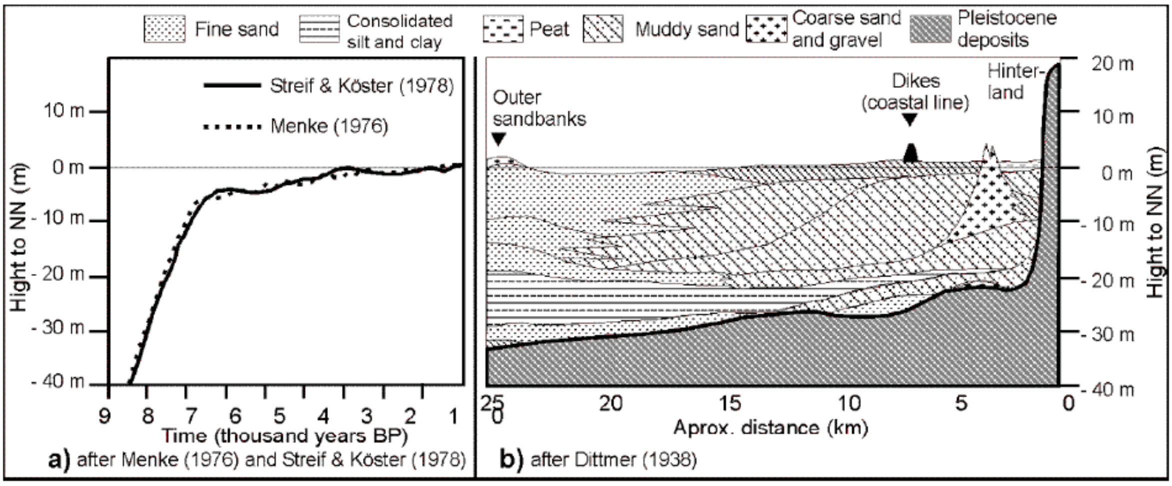


Fig. 2: Mean sea level evolution and a schematic profile of the Holocene sedimentary sequence (after Dittmer, 1952). From east (right) to west (left), the surface profile displays Pleistocene deposits of Saalian age, supratidal marshes, and tidal flats

Holocene sequence, can reach a thickness of around 20 m (Fig. 2). A possible reconstruction of the morphological evolution of the marshes and the coastline over the last 7000 years is given by WIELAND (1990), who compiled information from several authors.

1.3 History of Settlement and Land Reclamation

The first relicts of human settlement in the coastal area of Dithmarschen can be found on the elevated barrier-like sand accumulations close to the Pleistocene hinterland (Fig. 1). The artefacts have been dated as pre-Roman (2500–2000 BP). From there, the people migrated into the adjacent marshes which at that time were still rather narrow. This first wave of colonisation occurred in the Roman period of the first four centuries AD. During the following "migration period" there is no evidence of human occupation in the marshlands. A new phase of colonisation commenced in early mediaeval times (7th century) (MEIER, 2000). People now settled on the younger and more elevated marshes which were formed to the west of the old settlement belt of the Roman period. Since the 11–12th century, the marsh colonists started to change the coastline by protecting their land against the forces of the sea through the construction of dikes (KÜHN, 1992). In the following centuries, more and more land was diked (PRANGE, 1986) to ensure freshwater drainage of the marshes, and for general coastal protection. The last two considerations lead to the embankment of the inner part of the Meldorf Bay (Meldorfer Bucht) between 1972 and 1978 what marks the last phase of the land reclamation history in Dithmarschen. Detailed maps of the reclaimed coastal areas are presented in WIELAND (1984) and KÜHN (1992).

1.4 Morphological Evolution

Detailed information about the morphological evolution of the tidal flats and tidal channels over past centuries is quite sparse and inaccurate. According to LANG (1975), the first reference to the "Piep", which is the main tidal channel in the area dates back to a sailing instruction from 1558. The supratidal sandbanks of Trischen and Blauort were also first mentioned in the 16th and 17th century. A sailing instruction from 1701 described the northern inlet "Norderpiep" as a straight, narrow and deep approach to the harbour of Büsum, whereas the southern inlet "Süderpiep" was depicted as a more braided channel system.

The coastal zone of Dithmarschen was completely surveyed for the first time in 1838 using standard hydrographic techniques. This resulted in the publication of the first "scientifically measured chart" of the area in 1846. A comparison of this chart with topographic information dating from the 16th and 17th century reveals an intensive morphodynamic activity. In this context, WIELAND (1984) mentions a general tendency of the channel to shift from a south-north to a more east-west orientation. Beside this change, the comparison of the 1846 chart with more recent ones and those of today reveals further tendencies in the morphological evolution. Thus, the Piep system with its two inlets has migrated northwards, whereas the sandbank Tertiussand, which separates the two channel branches, as well as the supratidal banks of Blauort and Trischen, have been displaced landwards by several kilometres. Under the influence of a continuing sea-level rise this landward migration of morphological features is still an ongoing process in the German tidal flats (WIELAND, 1972, 1984, 2000; EHLERS, 1988; SPIEGEL, 1997; HOFSTEDE 1999a, b; RICKLEFS et al., this volume). For the supratidal bank of Blauortsand in the centre of the area, WIELAND (1972) calculated a mean migration rate of 32 m/year for the period from 1932 to 1969, whereas KESPER (1992) observed that the rates increased from 40 to 80 m/year between 1970 and 1988.

With the diking of the Meldorf Bay in 1972 and 1978 approximately 480 km^2 of former intertidal flats were reclaimed. This massive encroachment on the natural environment resulted in several morphological adjustments and adaptations in adjacent areas. A detailed analysis of the morphological impact of land reclamation is given by WITEZ (2002). This study, and that of HIRSCHHÄUSER and ZANKE (2001), revealed that the main morphological adaptation in the inner Meldorf Bay concerned channel migration and a reduction of the subtidal channel volume. For the outer parts of the Piep channel system WITEZ (2002) detected a trend towards slightly deeper channels with steeper embankments. This, however, was considered a reaction to the rising sea level (SPIEGEL, 1997; WITEZ, 2002).

In summary, the Dithmarschen Wadden Sea is a typical example of an open tidal flat system exposed to the forces of the open sea, resulting in strong sediment displacement associated with rapid channel and shoal migration. Taking into account the morphological processes and tendencies outlined above one can conclude that in this area, which is caught between coastal defences and rising sea levels, the natural features of the Wadden Sea could be lost or drowned, a process which is known as coastal squeeze.

1.5 Modern Topography

The topography of the inner or central investigation area is dominated by the Piep tidal channel and its adjacent tidal flats. The channel has the shape of a lying Y, in which the northern and southern inlet (Norderpiep and Süderpiep) form the transition zone to the open North Sea. From the point of intersection of the two sub channels the actual Piep stretches in a more or less straight line eastward towards the city of Büsum. The mean water depth along the channel axis is 10 m on an average with maximum values of 26 m. Southeast of Büsum, the Piep splits up into three second-order channels and finally into several tidal creeks which are scattered across the tidal flat area of the Meldorf Bay. The south-western border of the area is characterised by the Bielshövener Loch tidal channel. It separates from the Süderpiep, runs southwards as a bifurcated channel, bends to the east in the vicinity of Trischen island, and finally splits up into a number of gullies (Fig. 3).

The ratio of intertidal to subtidal areas is approximately 60 by 40. The intertidal flats comprise a 15 km wide belt of sandbanks and shoals along the coast. The most seaward banks are relatively complex sand bodies with finger-shaped inter- and supratidal extensions stretching some kilometres westwards. At the transition from these sands to more sheltered areas, a number of isolated horseshoe-shaped supratidal banks such as “Blauortsand” and the incomplete barrier island of “Trischen” can be found. Compared to the seaward banks, the tidal flats in the inner parts consist of relatively large, successional units. Although their outer margins are clearly defined by the main channels, they are often subdivided into smaller units by gullies and tidal creeks.

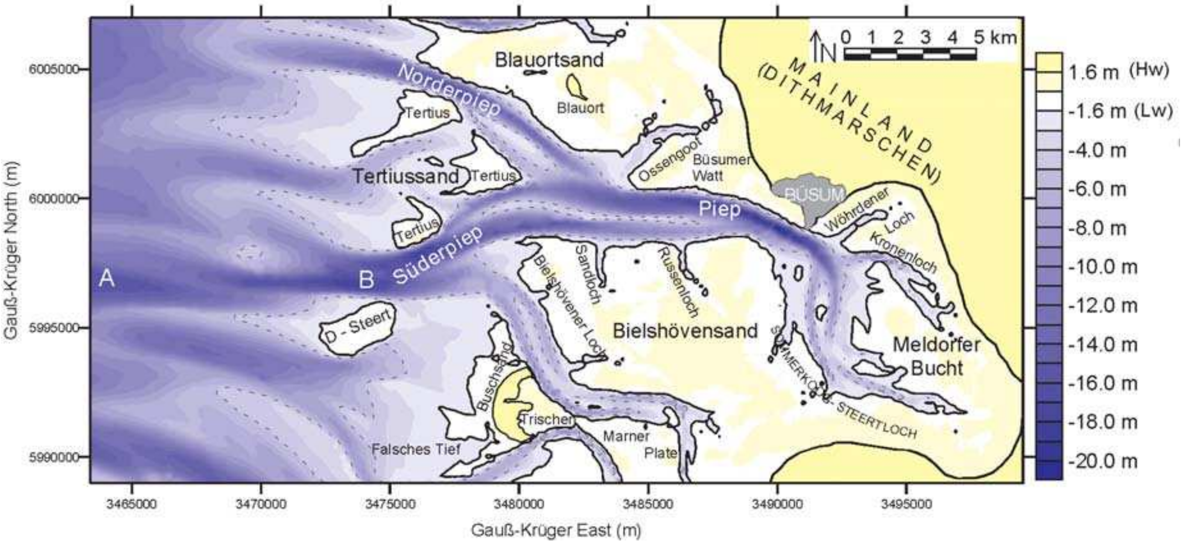


Fig. 3: Topography of the study area. A and B mark own wave gauge stations

1.6 Hydrodynamics

From the mouth of the Elbe Estuary to the Eiderstedt peninsula the mean tidal range varies from 3.1 to 3.4 m. Relative to the German topographic chart datum (NN), the mean high water at Büsum is +1.6 m NN and the mean low water is around –1.7 m NN. The difference between the neap and spring tidal ranges amounts to approximately 0.9 m. Storm surges can result in water level setups of more than +5 m NN (EHLERS, 1988). According to WITEZ (2002), the tidal prism of the embayment east of a line connecting the supratidal sands of Blauortsand and Trischen and the mainland of is of the order of 577 × 10^6 m^3.

The hydrodynamic conditions in the study area are dominated by strong currents associated with the semidiurnal tides. Current measurements carried out with acoustic Doppler current profilers revealed peak current velocities of up to 1.8 m/s in the main channels, whereas maximum ebb and flood currents typically range between 1 to 1.2 m/s. On the tidal flats currents are much weaker, within a typical range from 20 to 30 cm/s. However, velocities exceeding 80 cm/s were measured, near exposed channel margins. Additional information about tides and currents is given in SIEFERT et al. (1980, 1983), and WIELAND et al. (1984).

Whereas in the German Bight storm wave heights of several meters are common, wave heights strongly diminish when entering the shallow Wadden Sea waters. A good example of this attenuation is illustrated in Fig. 4. It shows that from the approach to the Süderpiep shipping lane to the still relatively exposed D-Steert sandbank, the significant wave height is already reduced by at least 50 %.

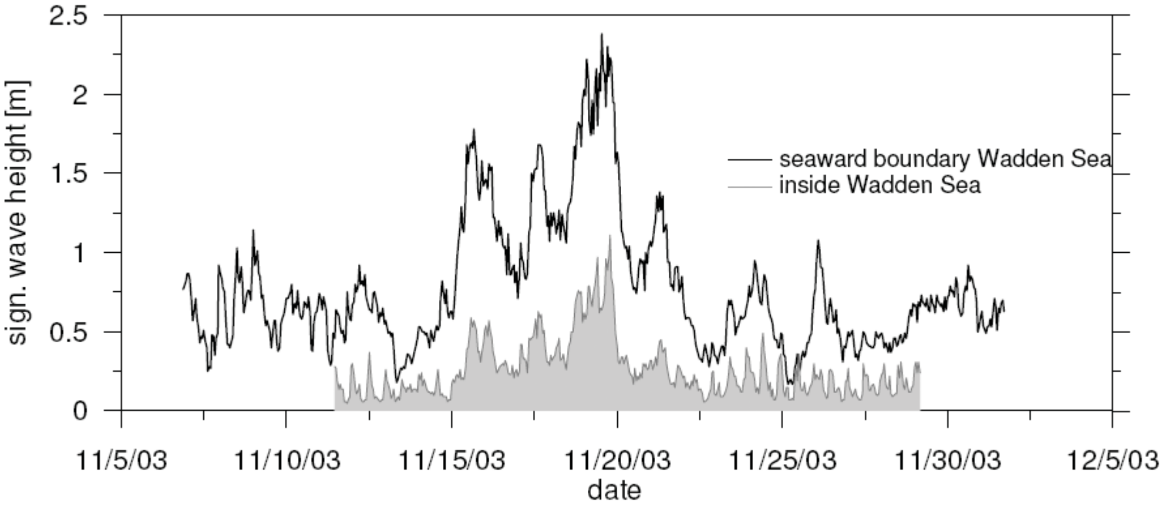


Fig. 4: Time series of significant wave heights recorded at the approach to the Süderpiep shipping lane and north of the D-Steert sandbank (see position A and B in Fig. 3). Measurements were made with an RDI 1200 kHz acoustic Doppler current profiler

Within the tidal flat areas, mainly locally generated waves are observed which are strongly dependent on factors such as water depth (NIEMEYER et al., 1996), wind direction and tidal currents (visible in the lower curve of Fig. 4).

2. Materials and Methods

2.1 Data Base

Bathymetric data of the central study area covering about 600 km^2 were made available by the German Federal Agency for Navigation and Hydrography (BSH). The different digital data sets cover a time span of 27 years (1974 to 2001) on a mainly annual but sometimes also monthly basis.

For the reconstruction of the Pleistocene surface and the interpretation of seismic records, all accessible data of previous studies were evaluated. Due to the generous support of the Landesamt für Natur und Umwelt, Schleswig-Holstein, the logs of more than 30 core samples collected in the area between 1936 and 1987 and reaching down to the Pleistocene, were made available for this study. The positions of some selected cores are shown in Fig. 5.

For the setup of a pre-Holocene surface elevation model, geological information on the Dithmarschen area available in DITTMER (1938, 1952), FISCHER (1955), HUMMEL and CORDES (1969), SCHMIDT (1976), MENKE (1976), HOFFMANN (1998) and MEIER (2000) was used. For the river Eider mouth region, data were taken from RUCK (1969), TIETZE (1983) and RUPRECHT (1999) and for the outer Elbe estuary from LINKE (1979). In the region of the East Friesian Islands and the river Weser, the investigations of GWINNER (1954), LANG (1959), and especially of STREIF (1990) were used to reconstruct the paleo-topography. To obtain information about the most probable former land surface in the open German Bight, data published in FIGGE et al. (1980) and ZEILER et al. (2000) were consulted. Beside these records, useful information was also gleaned from the sedimentological chart of the German Bight (FIGGE, 1981) and modern bathymetric charts.

2.2 Field Measurements

To evaluate the middle- to short-term morphological changes in the Piep channel system, several additional measurements were carried out. These mainly included bathymetric (morphological) and geological surveys.

For a more detailed investigation of the morphological variability of the Piep channel system, several bathymetric cross-sections were repeatedly surveyed (Fig. 5). For this, we used our own research boats equipped with 200 kHz echo sounders and Differential GPS positioning systems. All data were corrected for sound velocity variations in the water column (measured by CTD during the survey) and referenced to the German topographic chart datum (NN) using water level data from the Büsum gauge station. Table 1 gives an overview of the spatial-temporal resolution of the measurement program.

Assessing the quality of the echo-sounder measurements and data processing, four main error sources were identified: a) the precision of the survey equipment (echo-sounder and positioning system); b) water level corrections (tides); c) variations of the speed of sound in the water due to changes in salinity and temperature; and d) data interpolation when generating digital elevation models. The maximum cumulative error was estimated to be of the order of 0.3 m. For the purpose of this paper, variations under 0.5 m were thus not considered in the analysis of morphological changes.

Table 1: Repeated measurements of different cross-sections (see Fig. 6 for location)

	2000			2001			2002							2003			
Fieldwork areas	6	9	12	5	7	12	3	6	8	9	10	11	12	3	4	5	8
Norderpiep (A)	X	X	X		X	X								X			X
Süderpiep (B)		X	X	X	X				X			X		X			
Piep (C)	X	X	X	X	X	X						X		X			
Büsum						X	X	X		X		X					
Sommerkoog-Steertloch						X		X	X		X		X		X	X	

Since the stratigraphic architecture of the Holocene sediments has a substantial influence on the morphological evolution of the study area, and the history of the morphological evolution in turn can, to some extent, be extracted from stratigraphic records, the three-dimensional distribution of the sediments was investigated using hydro-acoustic methods such as side-scan sonar and reflection seismic profiling (Boomer; LURTON, 2002) in addition to conventional coring.

Repeated sonographic surveys of seabed features were performed using a KLEIN-595, 100/500 kHz dual frequency side-scan sonar. Measuring campaigns were carried out in July 2000, September 2000, July 2001 and March 2002. The sub-bottom profiling was mainly carried out with a "Boomer" system. This device sends out pulses at energy levels ranging from 100 to 300 joules and frequencies of 0.5 to 15 kHz. During the measuring campaigns in July and September 2000, shallow seismic profiling was also done with a 3.5 kHz sub-bottom profiler. The operation principles of sub-bottom profilers are described in D'OLIER (1979).

To complement the study of short- to medium-term morphological changes, several sediment cores were taken in the Dithmarschen tidal flats in September and November 2001. These cores were 1.8 to 5.5 m long and were taken in intertidal or shallow subtidal areas using a specially designed coring boat. The principles of vibrocoring techniques are described in LANESKY et al. (1979). The sampling locations were chosen on the basis of the results of previous morphological analyses. Of particular interest were those areas in the inner, central and outer part of the study area, where substantial deposition over many years had taken place. Figure 6 shows the coring locations.

Surface sediment samples in the channels were taken with a medium sized van Veen grab and on the intertidal areas by small coring tubes 10 cm in length and 4 cm in diameter. A schematic overview of the locations and coverage of the field measurements mentioned above can be seen in Fig. 5.

2.3 Digital Elevation Models (DEM)

The available bathymetric data were used to generate digital elevation models (DEM). These DEMs permit a numerical comparison between different morphological model stages and thereby, a quantification of erosional or accretional tendencies. On the basis of the data density and coverage, grid spacing between 50 and 200 m was used for the interpolation of the BSH data sets. For the more detailed bathymetric measurements carried out in this investigation a grid resolution of 10 to 15 m was chosen. In both cases, the applied interpolation method was based on triangulation. Interpolation, visualisation and volume computations were carried out with the software package SURFER TM (Golden Software).

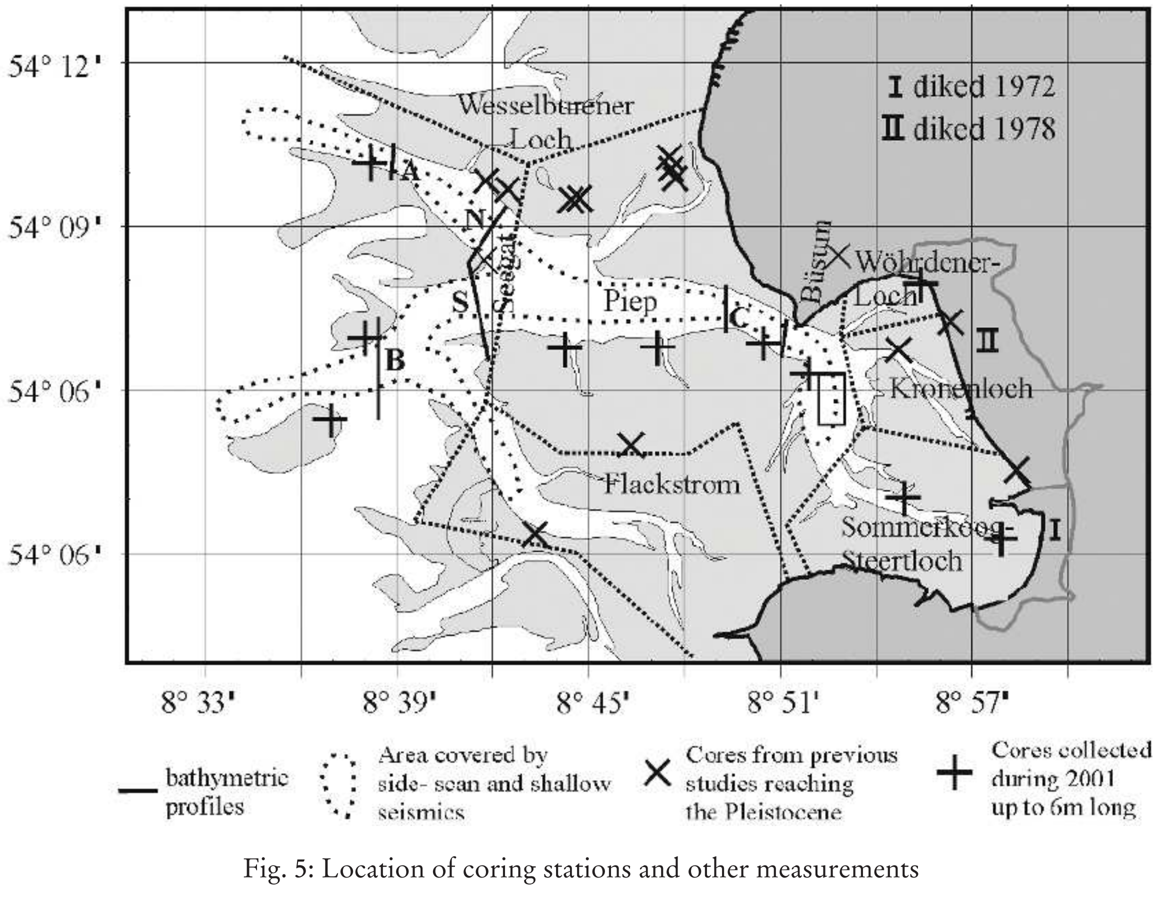


Fig. 5: Location of coring stations and other measurements

3. Results

3.1 Geology

Data from the literature, archived core logs, own core drillings, and shallow seismic records were compiled to set up a digital elevation model of the pre-Holocene surface of the innermost German Bight (Fig. 6) with special focus on the Dithmarschen area (ASP et al., 2003). The simulated Holocene-Pleistocene boundary is based on a 600 by 600 m grid.

The most prominent element in this DEM is the wide NW-SE striking melt water valley of the river Elbe. Other distinct features are the Pleistocene valleys of the river Weser in the SW and the Eider in the NE (Fig. 6). Along the Dithmarschen coast the mainland shore is evidently shaped by relatively wide and shallow embayments. To the west of these bays, the area can be divided in two parts. In a zone extending roughly from the latitude of Büsum southward to the Elbe melt water valley, the Pleistocene surface rapidly dips down to the west and southwest to depths of more than 30 m below the present surface. North of Büsum the westerly dip slope is gentler. However, this surface is dissected by the melt water valley of the Eider. Although the depth of the Holocene base in the region of the modern estuary (RUCK, 1969) and further offshore (FIGGE, 1980) is relatively well known, the course of the former valley along or below the Eiderstedt peninsula has still not been completely reconstructed.

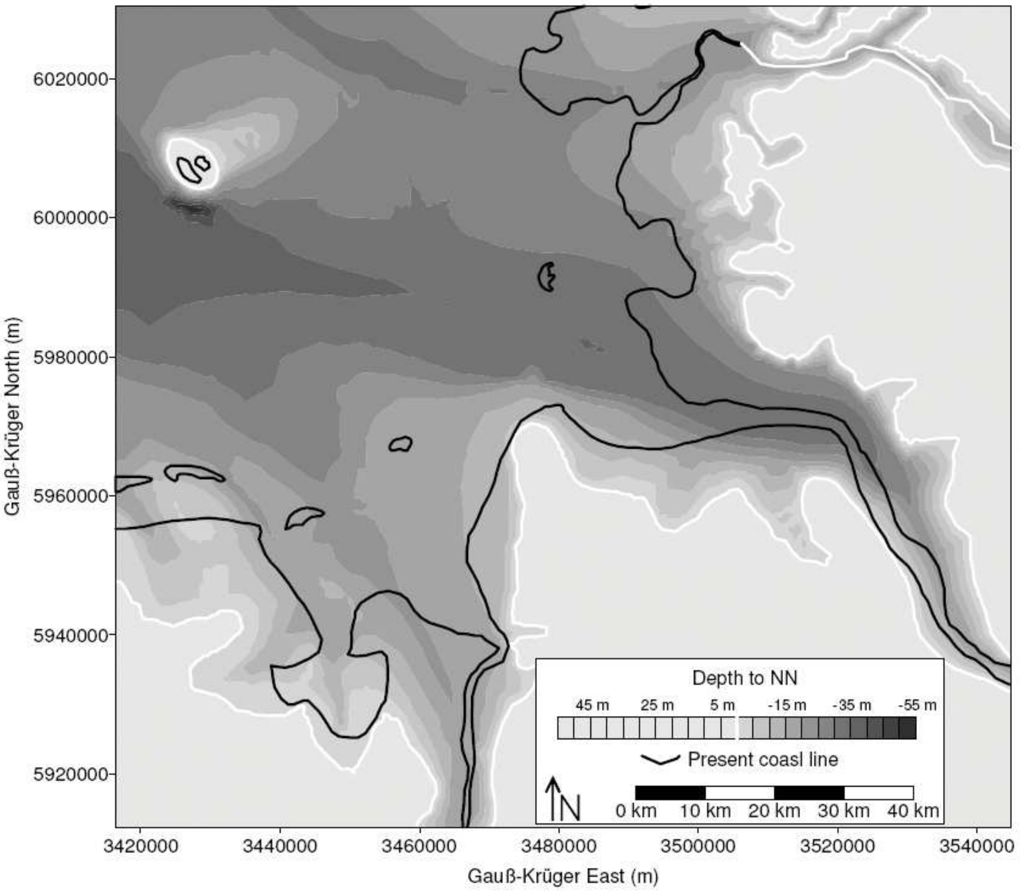


Fig. 6: Reconstructed Pleistocene surface (DEM)

In the central study area, a second major stratigraphic unit has been identified. It is the clayey and sandy silt bed called "Dithmarscher Klei". This consolidated mud deposit directly overlies mostly thin layers of different composition which mark the beginning of the Holocene transgression (Fig. 7). The very cohesive sediment was deposited between 5000 and 7000 years BP (DITTMER, 1938) and has a thickness of up to 10 m (average: 5 m). On the basis of side-scan sonar records it was possible to identify several outcrops in the deeper channels. The depth of contact to the water varies between –15 and –24 m NN. In addition to this unit, a second cohesive mud deposit was detected in the vicinity of the Tertius sandbank. Here, this "Upper Klei" typically reaches depths of up to –12 m NN (Fig. 9). Its thickness is of the order of 1–2 m.

Since both mud beds are very resistant to erosion and scouring, they form a certain discontinuity layer for morphodynamic processes affecting the overlying recent, mainly fine sandy tidal sediments. Under the assumption that the consolidated layers prevent or delay scouring and are therefore important for the "draught" of morhodynamic processes, we developed an elevation model of the surface defining the top of the "Lower Klei" and the top of the "Upper Klei" on the basis of core samples and hydro-acoustic data (Fig. 8). Since this horizon forms the basis of the modern tidal deposits, the DEM also quantifies the thickness and volume of the potentially more erodible sediments.

Based on these results Fig. 8a shows a certain dichotomy. While the eastern part is characterised by the top of the "Lower Klei" sloping down in westerly direction, the western part shows the extent of the overlying "Upper Klei". The top elevation of this layer is highest in the north and lowest in the south. Consequently the thickness of modern sediments

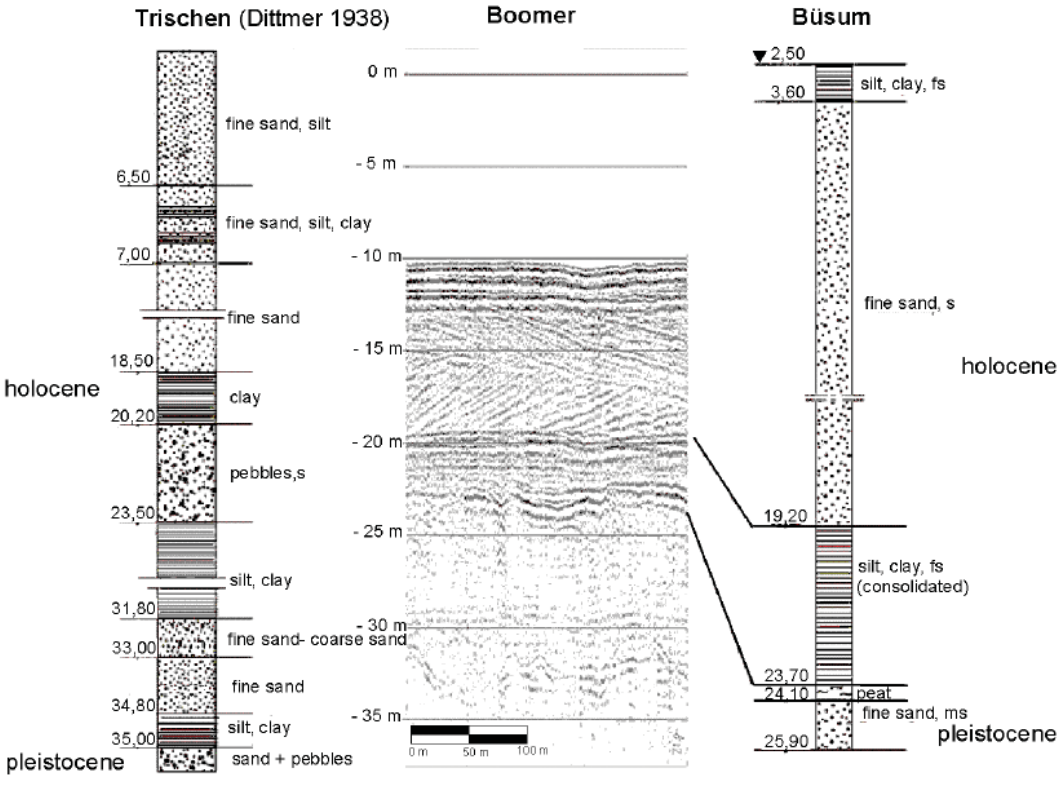
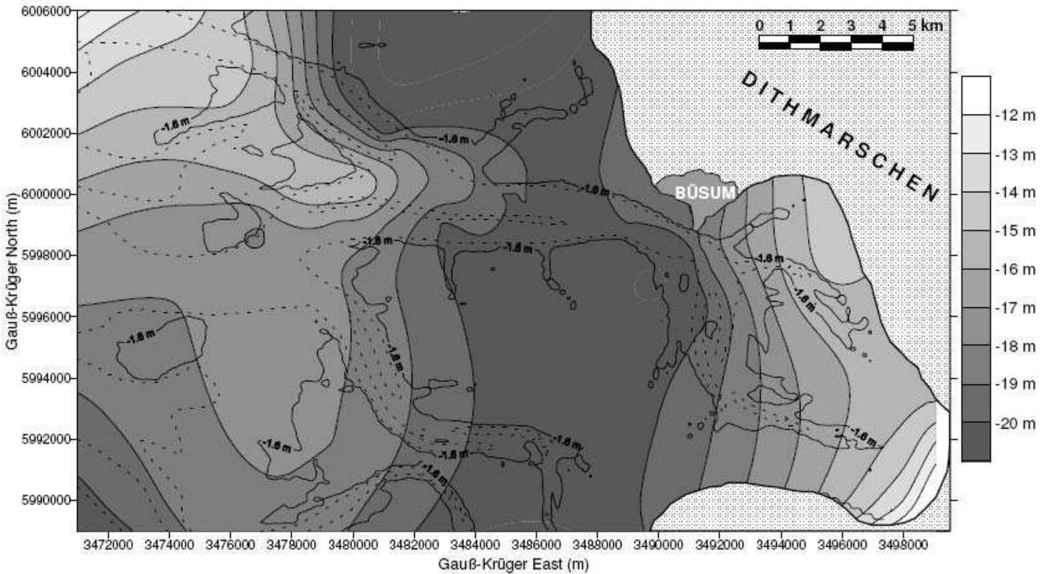
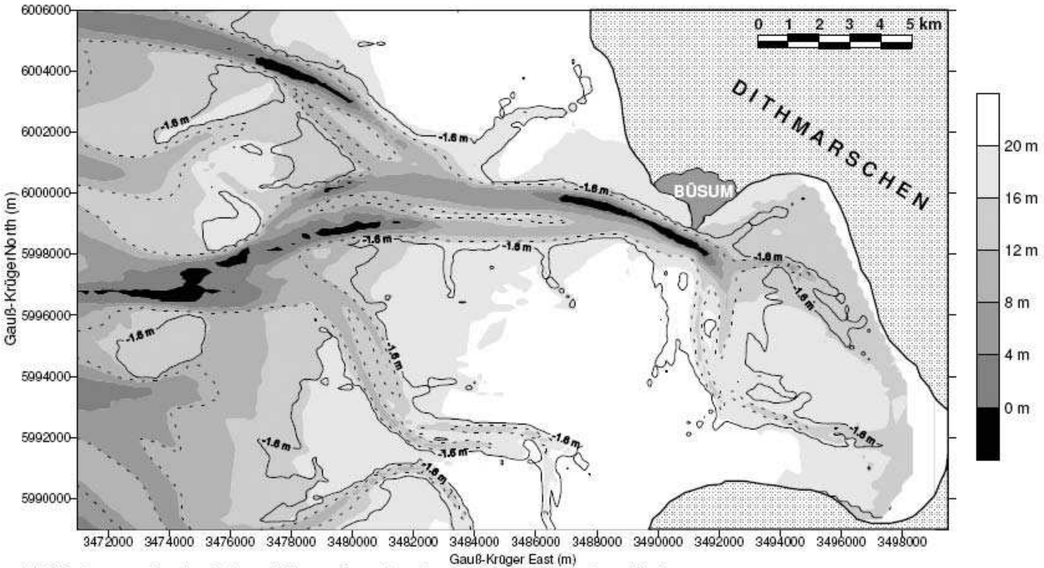


Fig. 7: Shallow seismic record from a location close to Büsum.
Note the good correlation with core data



a) Approximate depth of the top of the Dithmarscher Klei



b)Thickness of potential mobile sediments above the Dithmarscher Klei

Fig. 8: Depth of the "Dithmarscher Klei" and thickness of modern tidal flat sediments.

is highest in those areas where no "Upper Klei" could be found and the top of the "Lower Klei" is low lying.

As pointed out earlier, the modern tidal flat and channel sediments were mapped using side-scan sonar, seismics, sediment samples and cores. The survey of the channel deposits reveals that these sediments consist mainly of fine-to medium-grained sands, interrupted by outcrops of the consolidated, fine-grained "Dithmarscher Klei" (Fig. 9). This pattern reflects the high-energy hydrodynamic regime in the main channels. Local occurrences of sandy mud either represent a mixture of partially eroded consolidated silty-clays and mobile sands or they may be associated with rapid local sediment deposition. In contrast to the channel deposits, whose distribution is strongly influenced by the local hydrodynamics, the intertidal sediments show a clear gradual decrease in mean grain size from the outer to the inner parts of the study area. This tendency is particularly well displayed by the distribution pattern of mud contents (Fig. 10). As in the case of the channels, the mud distribution pattern reflects the hydrodynamic regime from exposed and more dynamic depositional environments close

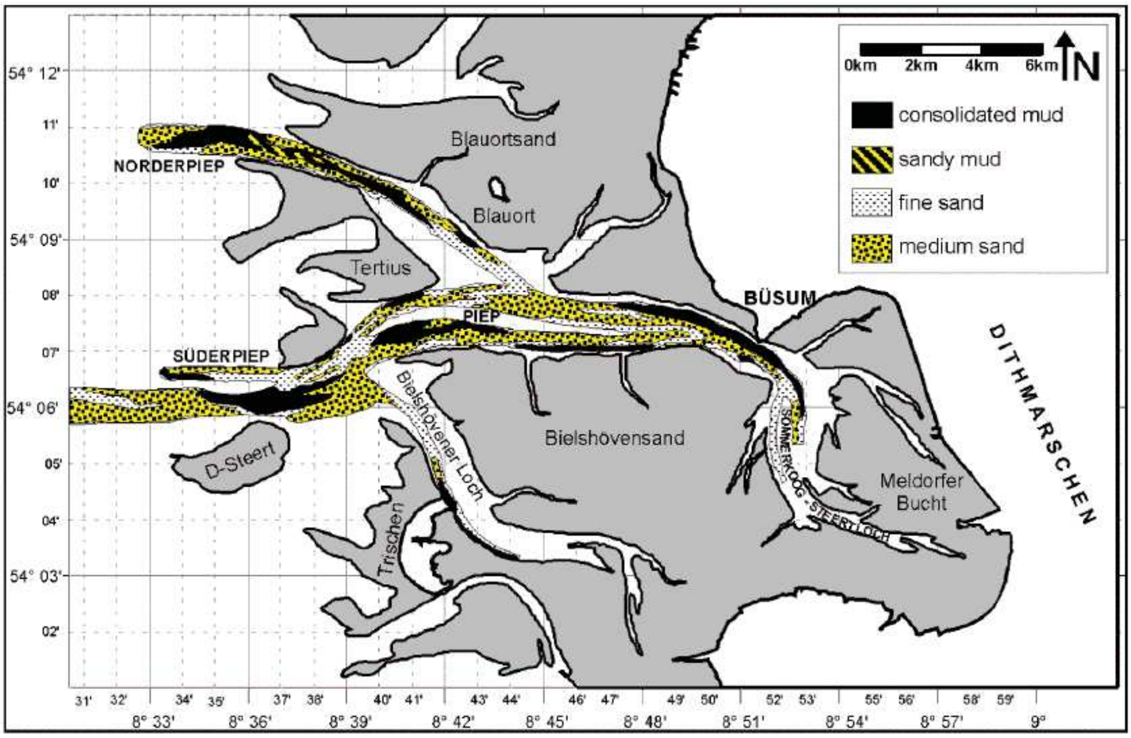


Fig. 9: Sediment distribution in the tidal channels

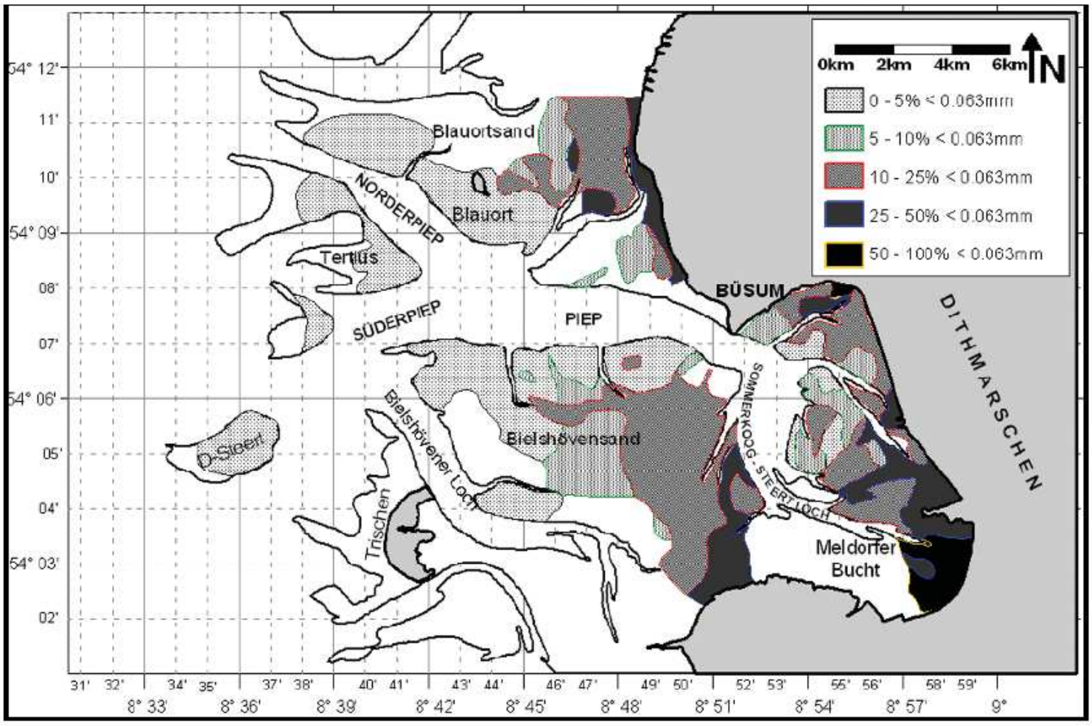


Fig. 10: Sediment distribution on the tidal flats. (after REIMERS, 2003)

to the open sea to more sheltered and generally more elevated accretional areas close to the coastline. In Fig. 11 a number of grain-size distribution curves are presented which characterize the sediments in depositional areas. Thus, the medium-sized type "A" sands can only be found on very high intertidal or partly supratidal sites of energetically exposed sandbanks close to the open sea (mainly Tertiussand, D-Steert and Blauortsand, Fig. 3). Type "B" sediments basically characterize the widespread sand flat facies (REINECK and SINGH, 1980). Here the mud content is less than 10 %. In the mixed flats with 10–50 % fines, bimodal sediments similar to type "C" are often observed. They are typical of depositional environments where frequent mixing of coarser and finer sediment fractions takes place. Type "D" distribution curves represent samples from areas with soft, fine-grained sediments (mud). The shapes of the grain-size distribution curves also indicate that some sediments are composed of differently sorted grain-size populations. However, it is evident that the study area is dominated by very fine sands and silts.

Besides sampling surface sediments, a series of cores was taken to study the structure of the upper metres of the deposits in more detail. The drilling sites are located along a transect from the inner Meldorf Bay to the outermost sandbanks in the west (Fig. 12).

Without going into a detailed discussion, it is obvious that the western sandbanks are almost completely composed of compact sand layers (Ke 1 to Ke 3 in Fig.12). The different bedding types show that the sands are transported by currents as well as by wave action. The upper metres of the sediment body in the central part of the study area, i. e. along the Bielshöfensand, are again primarily composed of sandy layers. However, here thin strata of silt and clay (mud) are now intercalated. Further towards the mainland and the inner parts of the Meldorf Bay muddy layers become more and more frequent. Here the sediments are typically composed of tidal rhytmites with alternately bedded thin strata of fine sand and mud. The only exception in this sequence from sandy to more and more muddy deposits shows core KE 6, which is located in a very dynamic channel meander belt south of Büsum (Fig. 12). Here, sediment transport is dominated by the migration of large bedforms generated by strong tidal currents. As a result, the composition of the sediments more closely resembles that of the outer regions.

In summary, it can be concluded that both the upper meters of the recent intertidal deposits as well as the surface sediments basically show the same well known gradual decrease in grain-size from exposed to sheltered tidal flat areas.

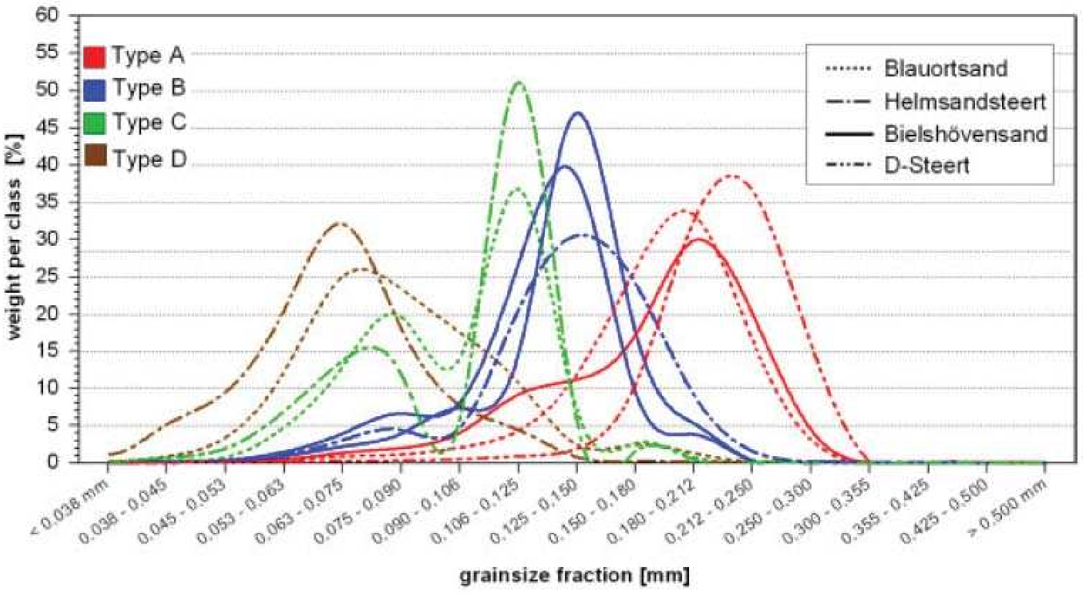


Fig. 11: Grain-size distribution curves of typical intertidal sediments (after REIMERS, 2003)

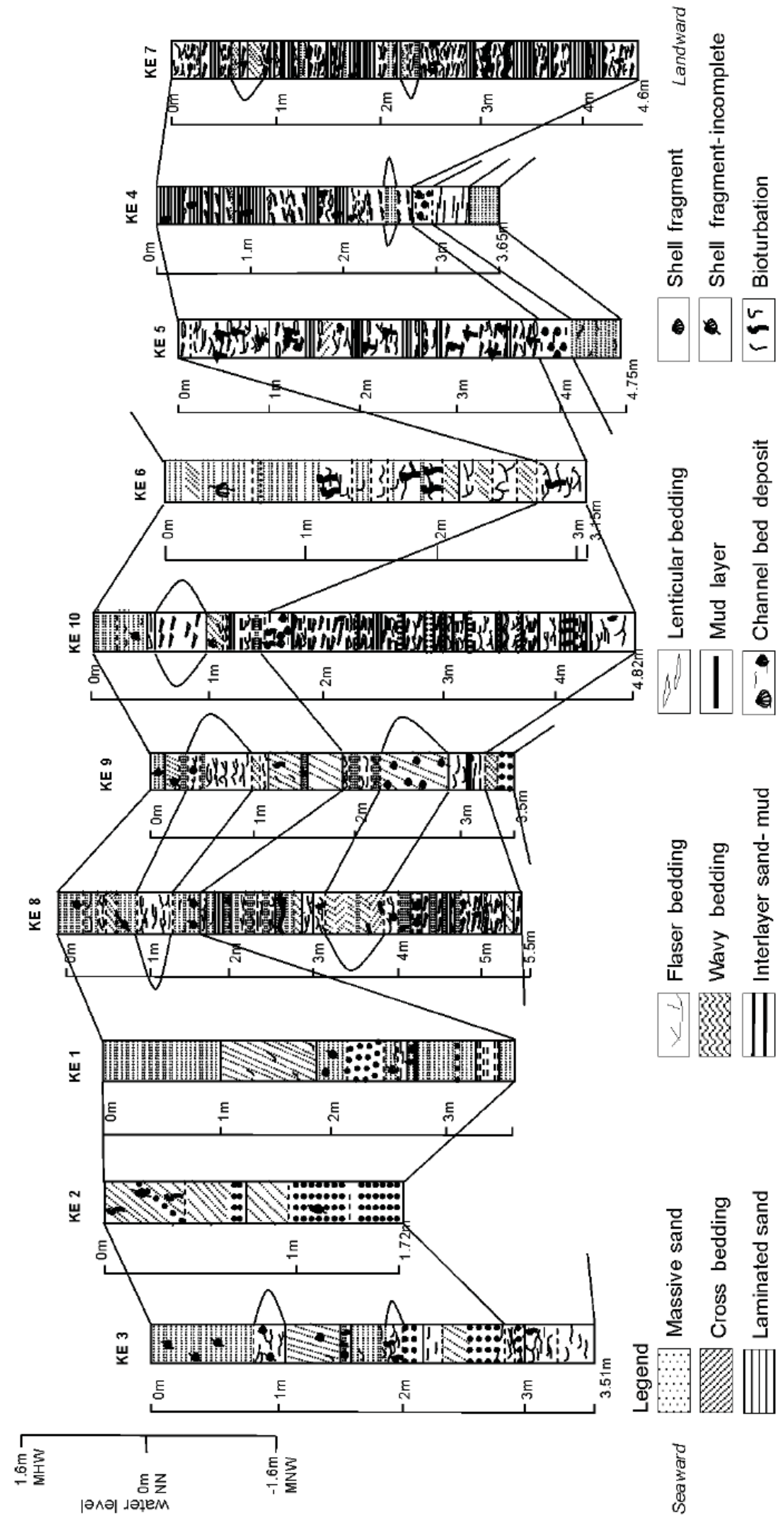


Fig. 12: Stratigraphic cross-section through the study area as revealed in cores. See locations in Fig. 5 marked by "+"

3.2 Long-Term Morphological Changes on Temporal Scales of Years and Decades

The morphological analysis is mainly based on bathymetric data collected by the German Federal Agency for Navigation and Hydrography in the course of annual surveys over a period of almost 30 years. For morphological comparisons and particularly for trend analyses, digital elevation models were run for almost all the available data sets. The visual and numerical analysis of the various simulated topographies reveals both minor short term and major long-term trends. The latter trends cover periods of several years to decades. To give an integrative overview and a rudimentary quantification of the longer-period morphodynamic evolution, the numerical elevation difference between the 1977 and 1996 bathymetries is illustrated graphically in Fig 13.

For the Meldorf Bay the figure shows that in the time span from 1977 to 1996 some smaller tidal channels silted up. This can be understood as a response to the reclamation of the inner Meldorf Bay, which took place in the 1970s. This artificial reduction of the tidal prism also resulted in adaptations of the Sommerkoog Steertloch tidal drainage system. Together with intensified meandering and lateral channel migration in an easterly direction, a decrease of the subtidal volume can be observed. This trend to stronger meandering is most pronounced in the main channel opposite the harbour entrance of Büsum (Fig. 14) where relatively strong accretion can be observed along the southern flank and erosion along the channel slope in front of the Büsum waterfront. A more detailed analysis of the progressive channel displacement suggests that the breakwaters of Büsum port and other coastal defence structures counteract erosion along the channel's stoss-side. Whereas the shrinkage of the subtidal volume in the inner bay caused by siltation is directly related to the reduced water masses passing through the channels, migration and meandering seem to be controlled by other factors, considering that an increasing meandering tendency was already detectable prior to the diking (WIELAND, 1984).

Following the Piep channel further towards the west, a significant departure in the depositional trends on either side of the mid channel shoal can be observed. While erosion prevails south of the shoal, a tendency towards accretion is observed along the northern slope and on the shoal itself. However, despite this internal reshaping, the reach and position of the central Piep channel remain relatively stable. An even stronger growth of the mid-channel shoal can be found in the southern channel of the Bielshövener Loch. Again, the general position of the tidal stream seems to be relatively stable. In contrast to the Piep, however, the stronger vertical accretion of the central shoal confines the channels an either side, causing these to deepen and producing some erosion along the northern and southern banks. In the field this is revealed by steep slopes and some shell accumulations. East of the island of Trischen the erosion of the southern channel bank becomes more pronounced. This is due to continued southward migration of the meander belt in this area.

On the other hand, the extensive intertidal flat of the Bielshövensand, located between the Piep and the Bielshövener Loch tidal streams, has remained relatively stable, at least within the limits of the vertical resolution of the DEM. Only very local sedimentation or erosion can be recognized together with a more pronounced change being restricted to the western tip of the sandbank which has expanded towards the north-west.

In contrast to the relatively stable situation on the Bielshövensand, the Blauortsand, a tidal flat north of the Piep channel shows more substantial changes. Here, data analysis reveals a deepening of gullies and a slight decrease in tidal flat elevation between 1977 and 1996.

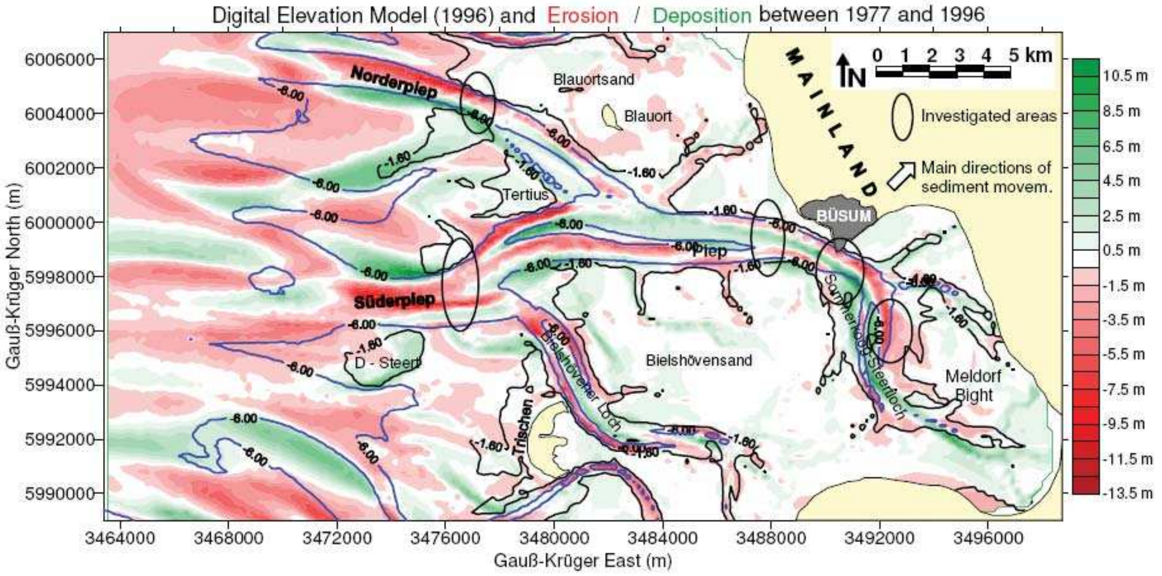


Fig. 13: Overview of long-term morphological changes in the study area

Compared to the relatively stable central part of the study area, the more westerly and most exposed regions are characterised by intense erosion and re-deposition processes. Hydrodynamic forces have driven the outer sandbanks such as Tertiussand and the D-Steert landwards. In the case of the Tertiussand, the migration has produced a compressed morphology. The reason for this is that the sandbank is trapped like a wedge between the two bordering inlets of the Süder- and Norderpiep. The morphological response is revealed by erosion in the seaward parts and accretion in the more easterly regions, especially along the channel banks. This wedge-like advance also forces the inlet of the Norderpiep to the north, as clearly recorded by erosion along the northern and accretion along the southern bank (Figs. 13 and 14).

In contrast to the evolution of the northern channel, the situation in the Süderpiep is more complex. Here, the channel is bifurcated (cross-section B-Süderpiep and Seegatt–S in Fig. 14) over wide stretches. At the section Seegatt-S the stronger morphodynamic response of the southern, flood-dominated channel is associated with increased meandering. In both cases a northward migration of the mid-channel shoal and the northern channel section is observed. This northward migration in combination with the ebb-domination of the northern channel, results in erosion along the flanks of the Tertius sandbank (stoss-side for the ebb current). Comparable but weaker bank erosion can be observed at the more westerly B- Süderpiep profile (Fig. 14). However, here the most affected area is the mid-channel shoal. During the observation period from 1977 to 1996, the shoal initially accretes up to the end of 1979 the trend reversing from the early 1980s onwards until it almost disappears by 1996. Still further west, a strong downward erosion of the channel is evident (Fig. 14). This deepening might again reflect the evolution from a bifurcated to a single channel as seen in the previous profile. However, it may also be related to the landward migration of the Tertius and D-Steert sandbanks. As a consequence, the channel would get more and more compressed, resulting in stronger incision by the tidal stream. Since this latter process could also explain the disappearance of the mid-channel shoal, a reliable interpretation of the erosion pattern in this area can not be given at the present stage of the investigation. However, we think that

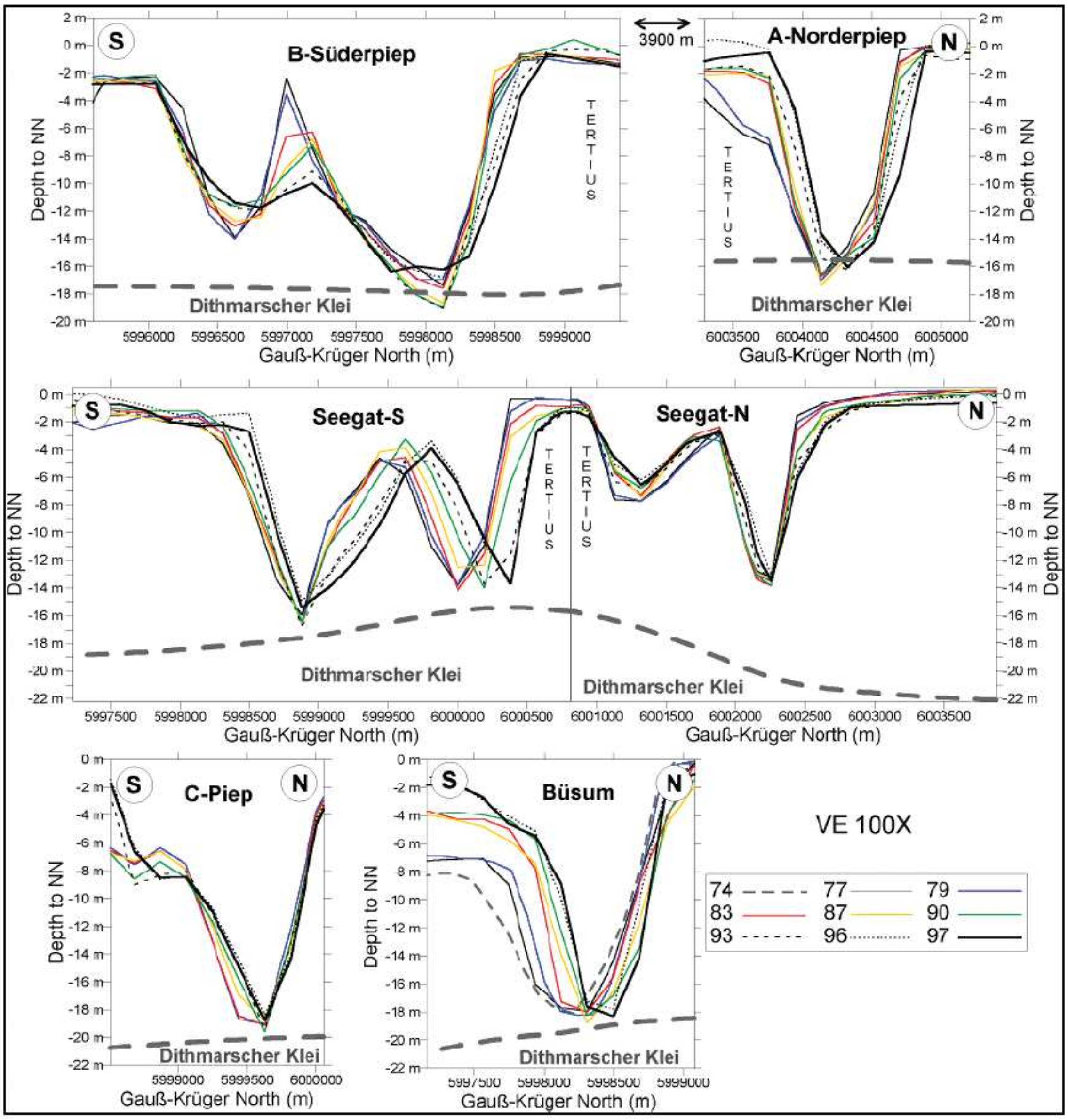


Fig. 14: Annual to decadal morphological evolution along several channel cross-sections relative to the depth of the Dithmarscher Klei. Locations of cross-sections see Fig. 5

the downward erosion will be limited due to the consolidated layer of "Dithmarscher Klei". From Fig. 14 and other fieldwork it is evident that the maximum channel depth often matches the elevation of the "Dithmarscher Klei".

In summary, the study area can be divided into three regions. In the innermost part represented by the Meldorf Bay, the change in hydrodynamic conditions caused by land reclamation in the 1970s has controlled the morphodynamic evolution. The central part of the study area has remained relatively stable and is characterized by minor internal reshaping processes. The outer region, west of the bifurcation of the Piep channel into the Norder- and Süderpiep, is exposed to intense erosion processes. Landward migration of sandbanks, vertical accretion, especially of those parts of the sandbanks which border the channels and erosion tendencies in the channels are typical for this area. Finally, there is the transition to the open sea where widespread erosion seems to prevail. The question, to what extent this overall loss in sediment volume is real or an artefact of data quality can not be answered reliably at the present stage of the study.

3.3 Short-Term Morphological Changes on Temporal Scales of Weeks to Months

Beside the analysis of long-term (years to decades) morphological changes, the investigation also included an analysis of short-term morphological changes at temporal scales of months or weeks. The aim was to identify seasonal effects and effects of singular events. The data for this purpose were collected in the course of repeated bathymetric surveys. These soundings mainly concentrated on the same cross-sections discussed in the previous chapter (Fig. 14).

Cross-section "A"-Norderpiep:

Old nautical charts of the 19th and beginning of the 20th century show a much wider northern inlet of the bifurcated Piep channel system and the presence of a well developed mid-channel shoal. (LANG, 1975). Since that time the Norderpiep shows a progressive decrease in width and a gradual reduction of the mid-channel-shoal. Today the central reach is relatively narrow and shows a simple U-shaped profile (Fig. 14). The results of bathymetric measurements (Fig. 15), carried out between summer 2000 and summer 2003, confirm the tendency for a general northward migration of the channel. Although depth variations of up to 4 m can be recognised in the process of this relocation, the cross-sectional area of the tidal stream stays relatively stable. However, Fig. 15 also reveals localized accretional and erosional phases. A temporal analysis of these variations shows that deposition prevails from winter to summer, and erosion from summer to winter. This is most obvious in the centre of the channel but also holds true for the flanks. Along the northern channel bank, by contrast, erosion mainly occurs in autumn and winter. This increase in cross-sectional area is compensated by the deposition of a comparable sediment volume along the southern bank in the subsequent calmer late spring and summer period. It is noteworthy that, especially in the region of the surveyed profile, lateral deposition as well as lateral erosion produces remarkably steep channel slopes. As a result, the occurrence of submarine slides due to either erosional or depositional processes is quite common.

In summary, the channel in this region can be considered to be in dynamic stability with seasonal variations and the superposition of a tendency towards northward migration in the longer-term.

Cross-section "B" – Süderpiep:

The bathymetric profile at cross-section "B-Süderpiep" (Fig. 16) is much more complex than cross-section "A-Norderpiep". Here the passage to the Bielshövener Loch channel branches out from the Süderpiep tidal stream to produce two channels separated by an elongated sill which increases in height from west to east (Fig. 16). A short distance landward of the bathymetric profile, the Süderpiep splits up again into a flood dominated southern and an ebb dominated northern branch. The cross-sectional area of this profile is about three times larger than that of the Norderpiep. As a consequence, the discharge should be correspondingly higher. This has in fact been confirmed by current measurements, which suggest a 2 to 2.5 times larger water volume passing through the Süderpiep.

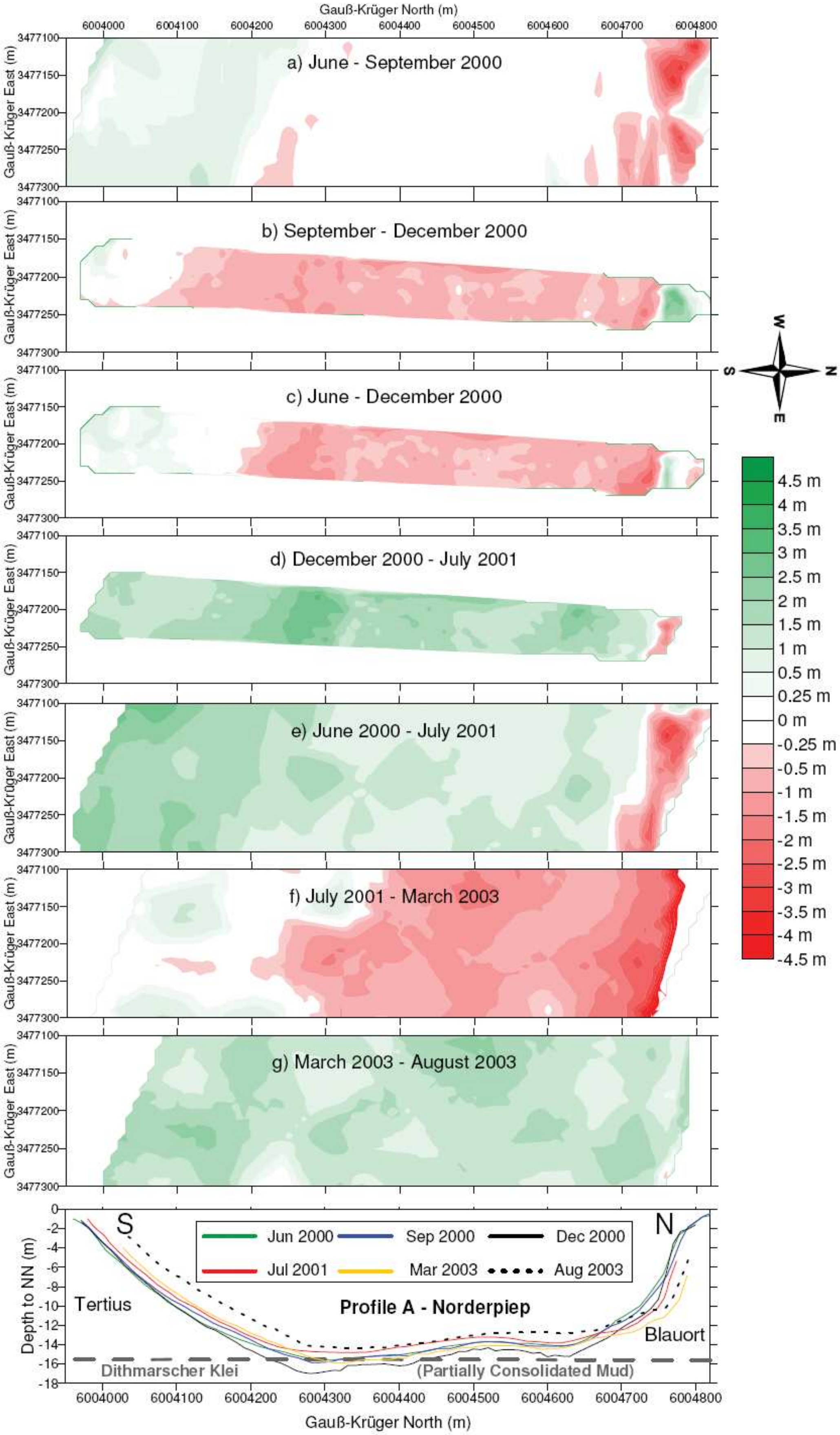


Fig. 15: Comparison of bathymetric data and quantification of elevation changes (red: erosion /green: deposition) at cross-section A – Norderpiep

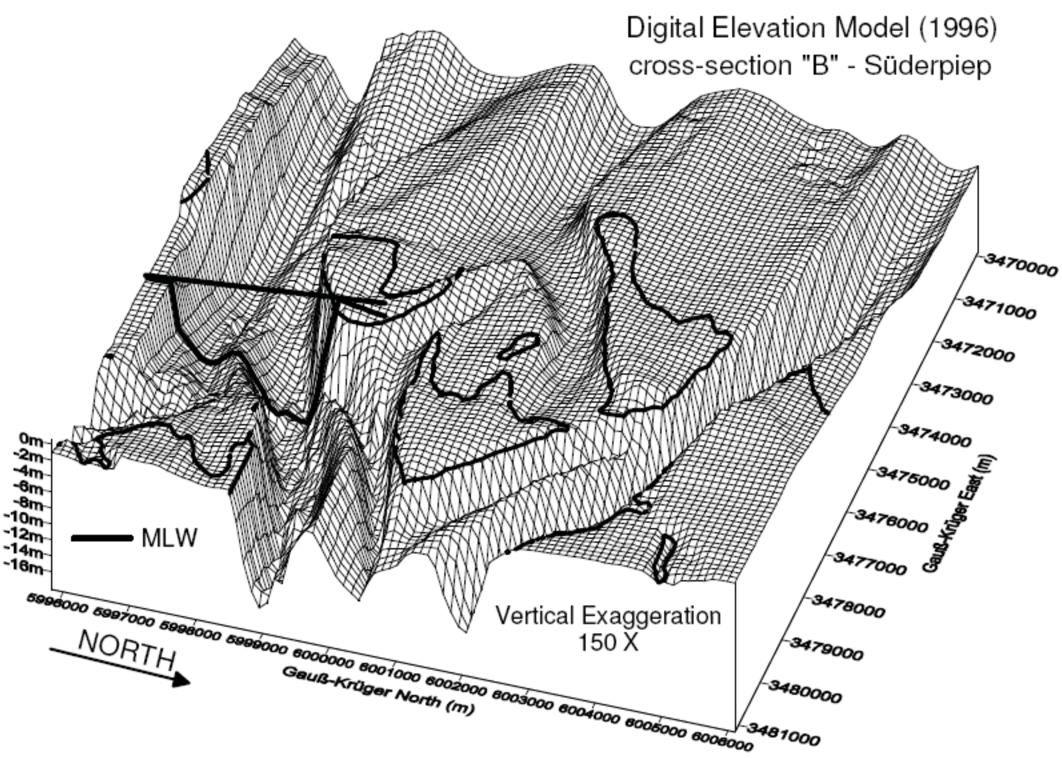


Fig. 16: 3-D view of the Tertius Sand with marked position of the cross-section B – Süderpiep

In the course of six surveys between late summer 2000 and spring 2003, depth variations of one to two meters were observed along the deeper parts of profile (Fig. 17).

Higher values were measured only on the northern side where erosion seems to prevail. Here the ongoing attack of especially the ebb current has sculptured a very steep slope along the Tertius sandbank. In this context, the existence of an underwater ledge in the lower slope of the bank is noteworthy. Results of different hydro-acoustic measurements show that this ledge is associated with a cuesta-like outcrop of cohesive sediment beds (Upper Klei). In our opinion the formation of this inconsistency in the slope indicates that the consolidated layers prevent an even stronger displacement of the slope. The obvious question, whether this bank erosion results from a widening or from a northward migration of the channel, can not be answered on the basis of the available data. Thus, the interpretation of Fig. 17 does not permit any statement concerning a net deposition on the southern side of the cross-section which would be an argument in favour of channel migration. However, the morphological setting in that area is so complex that nearby deposition balancing the erosion due to channel migration can not be excluded. Unfortunately the quality of the digital elevation models to some extent suffers from the presence of megaripples (dunes) in this area. Due to the high natural variability of these bedforms, the uncertainty imparted by the bedforms on successive DEMs can add up to produce a purely numerical patchiness in erosional and depositional trends. This could mask any real bathymetric trends. Despite these uncertainties and considering the complexity of the morphological evolution of this cross-section, we are nevertheless confident that we can recognize a pattern suggesting erosion in autumn / winter and deposition in spring / summer. However, in some cases, e. g. between August and November 2002, the observed morphological changes do not match this seasonal cycle.

In summary, the cross-section B-Süderpiep can be considered to be relatively stable in the period from summer 2000 to spring 2003. Depth variations of 1-2 m were monitored

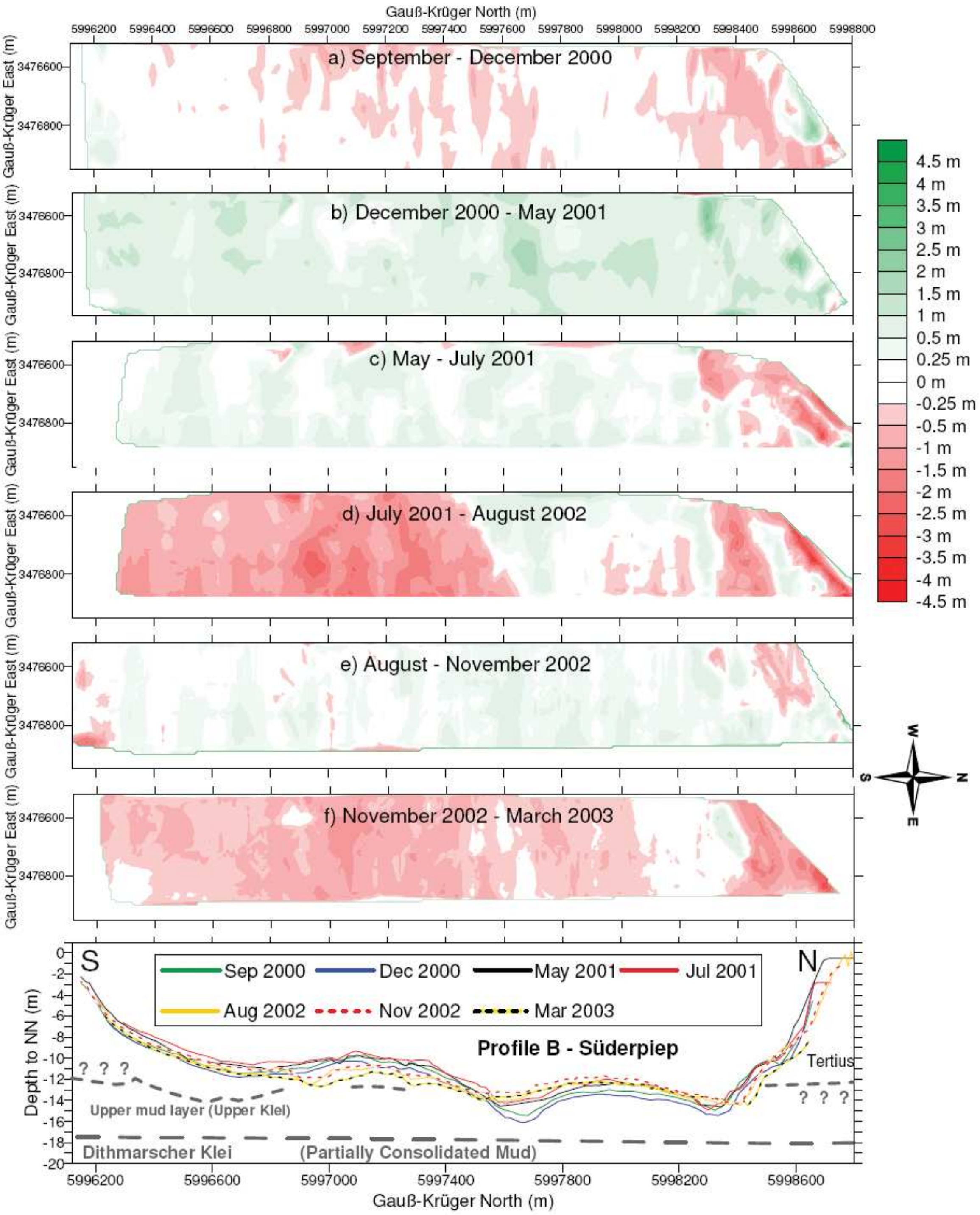


Fig. 17: Comparison of the various bathymetric measurements along cross-section B – Süderpiep

without showing any clear evolutionary trend. Persistent erosion was only observed along the northern embankment of the Tertius sandbank.

Cross-section "C" – Piep:

The cross-section C – Piep is located approximately three nautical miles west of the town of Büsum (Fig. 5, 14). It covers the eastern junction of the main Piep tidal channel and its southern flood dominated branch called Dwarsloch. The data show this profile to be morphologically very stable. Although maximum depth changes of up to three meters were measured, they more commonly remain below 0.5 m (Fig. 18) on short time scales (months). Since the morphological changes along this cross-section are not very large, there is no clear evidence for a directional displacement or a seasonal cyclic behaviour comparable to that discussed earlier. On the contrary, a comparison of data from June, September and December 2000 suggests deposition from summer to winter. This trend, however, reverses in the period from December 2000 to May 2001 when erosion occurred from winter to summer instead.

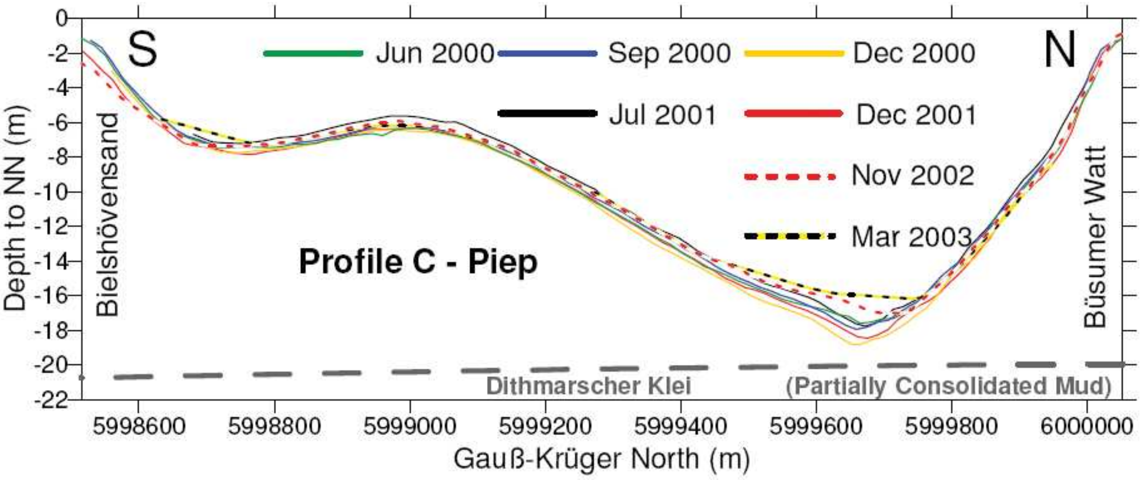


Fig. 18: Bathymetric profiles measured between summer 2000 and spring 2003 at location "C"

Cross-section Sommerkoog Steertloch:

This profile covers the eastern branch of the Piep tidal stream after entering the inner Meldorf Bay (Fig. 15). The large gully is part of the so-called Sommerkoog Steertloch and has a South – North orientation. It reaches depths of about 8 meters, and the cross-section has an intermediary shape between a "V" and a "U". In contrast to the other cross-sections, a 1400 m long channel section was monitored in this case (Fig. 19).

The most obvious morphological change in this area is the pronounced easterly migration of the channel. This progressive displacement was already pointed out in the previous chapter when discussing changes on larger temporal scales since the late 1970s. On the basis of the short-term bathymetric monitoring carried out between December 2001 and September 2003, migration rates of 50 to 75 m/a were calculated (Fig. 19). These data also show that a seasonal depositional cycle is superimposed on the net eastward migration of the gully. The erosion clearly dominates the cold season and affects almost the entire channel. However, the scouring is to a certain extent counter-balanced by accretion in the summer months. Furthermore, erosion during autumn/winter is more intense on the eastern flank of the channel, whereas deposition is more pronounced on the western flank during spring/summer and occurs more seldom in the cold season. Similarly, deposition along erosional eastern bank is reduced to very small quantities even during the net accretional phase in spring/summer. This distribution of net depositional and net erosional areas is responsible for the net easterly migration of the channel.

According to Fig. 19 the channel geometry has not changed significantly in the course of migration, although the pattern of deposition and erosion would suggest that a split-up of the

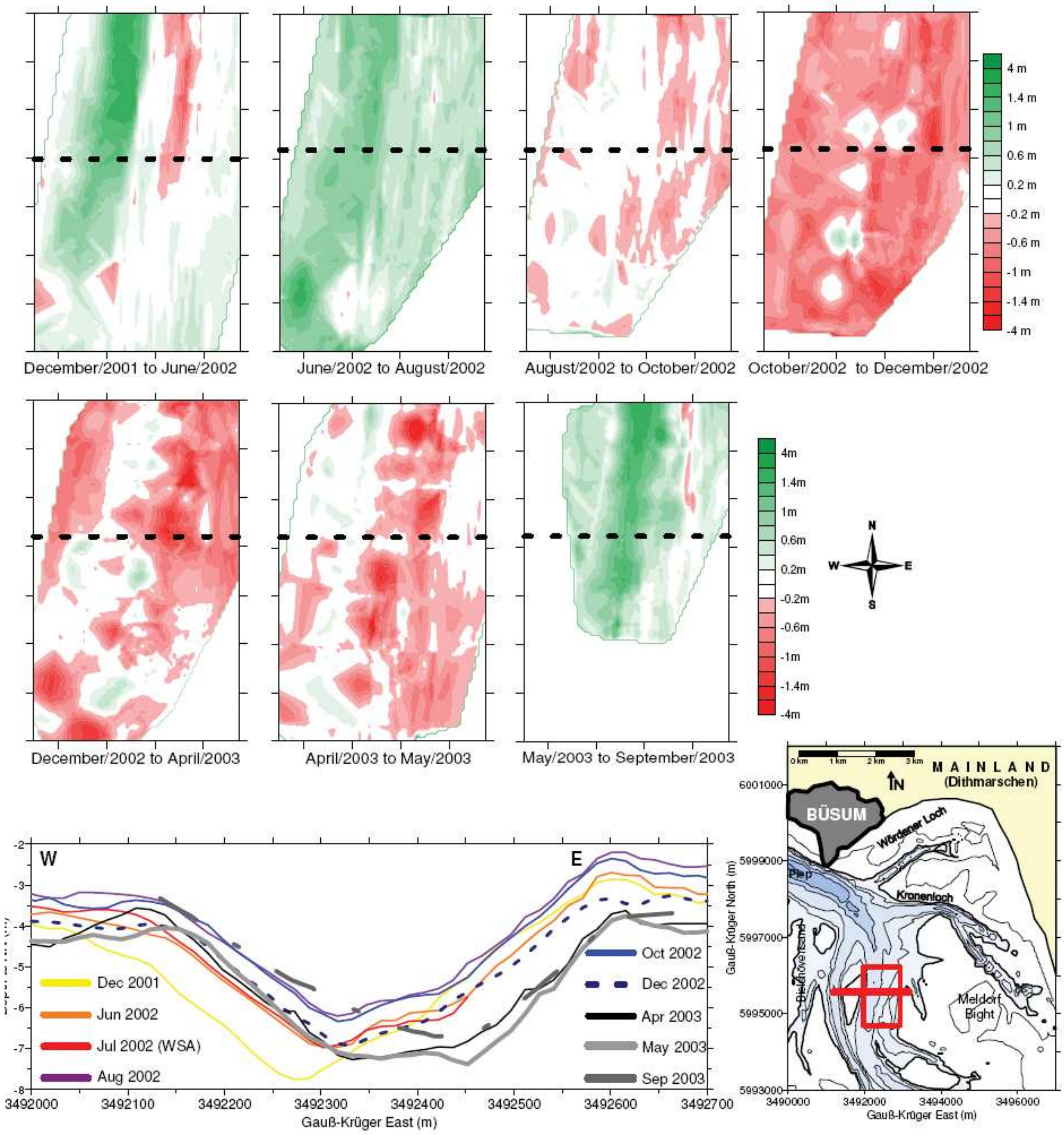


Fig. 19: Morphological changes along the surveyed cross-section in the Sommerkoog-Steertloch

gully into two branches separated by a new elongated mid-channel shoal is imminent. More recent surveys actually demonstrate that this development has become more pronounced since the last measurement carried out in this study.

When integrating all the results, some general aspects of the morphodynamic evolution of the study area can be recognised. Most of the phenomena are visible on both long-term (years and decades) and short-term (weeks to months) time scales. In addition, in most parts of the area directional trends seem to be superimposed by a seasonal cycle, dominated by channel scouring in the cold season and deposition in the warm season.

Substantial morphological changes, especially in the outer regions, result from a landward migration of highly mobile sandbanks such as the Tertius Sand of the D-Steert. In the case of the Tertius sandbank, the migration towards the mainland seems to be combined with a slight displacement of the entire morphological complex to the north. This is particularly well documented by the migration of the northern inlet and, to a lesser extent, the southern inlet.

Significant morphological changes in the channels themselves can be mainly attributed to either lateral migration or to the formation and/or re-formation of mid-channel shoals in areas where a channel splits into flood- and ebb-dominated branches. Especially the latter process leads to pronounced changes in the cross-sectional channel profiles which are often associated with the erosion and redeposition of huge amounts of sediment. However, the present data do not give any reliable indication to what extent the morphodynamic changes cause net increases or decreases in the subtidal volume. This is mainly due to the insufficient quantity and quality of the data but also to the limited resolution of the DEMs applied for this study. This is especially true for the outer and central part of the study area. However, a satisfactory assessment can be given with regard to the changes observed along the cross-sectional profiles. For the period from 1977 to 1996, a decrease in cross-sectional area has been demonstrated for all three of the investigated sites. For profile A – Norderpiep the loss in area is of the order of 28 %, for cross-section B – Süderpiep around 24 %, and for cross-section C – Piep it is approximately 12 %.

Over the time period under consideration, the inner part of the Meldorf Bay proper shows a tendency to a net sediment import. This trend is mainly documented by channel infilling and vertical accretion of shore-connected tidal flats.

Finally, the results show that the recent morphodynamic evolution is to some extent limited by the existence of older consolidated cohesive sediment deposits. In regions where only one deep horizon exists, the channel depth can be 20 m or more, whereas in the north-western part, where a second upper layer is present, the channels are significantly shallower.

4. Discussion

While discussing the results of the geological analysis one has to keep in mind that the quality of the digital elevation model defining the base of the Holocene (Fig. 8) partly suffers from a limited quantity and/or quality of data. This is inevitable because the coverage of stratigraphic control points is rather sparse in many compartments of the study area. The map presented in this study therefore does not claim to reproduce the actual natural situation in every aspect. In fact, it was only compiled to have a model bathymetry as a basis for numerical simulations of tidal action at the beginning of the Holocene transgression (ASP NETO et al., 2003). In the central study area, however, the quality of the DEM is regarded to be relatively good. A variety of different information sources has been used for its compilation. Due to the general limitations and because of the wide grid size of the elevation model, not all natural features can be depicted even in the central area. Thus, small channel structures known to exist in the Pleistocene surface (SCHMIDT, 1976) are not resolved in the map.

Furthermore, the DEM of the top of the early Holocene consolidated cohesive sediment sequence (Lower und Upper Dithmarscher Klei) is based on the same data set as the DEM map of the Holocene base. However, since in this case known outcrop locations have been included, this map is considered more reliable. The importance of these cohesive layers for the morphodynamics of the channels in the area has been demonstrated in Fig. 14 by the fact that in many cases their depth is controlled by outcrops of the erosion-resistant strata. The lower and upper “Klei” deposits thus form a physical barrier which effectively limits depth erosion. This would suggest that in locations where these deposits prevent deeper excavation, the channels must become wider in order to satisfy the rule of hydraulic continuity.

Two cases are known which vividly accentuate the protective function of the "Dithmarscher Klei" against erosion. In both situations the layers were penetrated by depth erosion, as a result of which the seabed was scoured down to depths of more than 30 m. One case was reported by LÜNEBURG (1969). Not far from Büsum he found an oval scour pit in the channel bed of a size of about 500 by 200 m and quite steep flanks. Here the water depth was around 30 m and coarse Pleistocene melt water sands outcropped on the bed. According to LÜNEBURG, the structure discovered in autumn of 1966 was unknown to the local authorities and the fishing community. He concluded that the scour pit must have formed over a rather short period of time. Today this hole in the cohesive beds is silted up, but it is still visible on shallow seismic records as an area of stratigraphic discontinuity.

The second report concerns a location at the Eider estuary storm surge barrier. In this area, an upper and a lower layer of "Dithmarscher Klei" are present (RUCK, 1969). Due to the constriction of the channel cross-section within the flood gates, deep scours formed on either side of the dam. These scours remained relatively stable for several years. Their depth was effectively controlled by the cohesive sediments present in the subsurface. Due to maintenance works in the early 1990s, one of the gate sections had to be closed for several months. Consequently, the concentration and increase of the currents led to scouring of the clayey silt bed and, within a very short time, a huge and deep (40 m) scour pit formed on the seaward side of the construction. Since retrogressive erosion threatened the stability of the dam construction, extensive and expensive measures had to be taken to stabilise the scour. This case not only emphasizes the importance of the geological structure for natural morphological adaptation processes but also for the stability of man-made structures in the coastal zone.

Above the old consolidated beds, late Holocene and modern tidal flat sediments are present. These younger deposits can reach a thickness of more than 20 m (Fig. 9). The composition is dominated by fine sands with variable portions of either finer or coarser components. As pointed out earlier, the intertidal surface sediments show a distinctive sequence from coarser material in the westerly, exposed areas to smaller grain sizes in the sheltered, inner regions. This characteristic grain-size gradient reflects the progressive decrease in hydrodynamic energy from the open sea to the more elevated flats close to the shoreline (REINECK and SINGH, 1980). The close relationship between sediment distribution and hydrodynamics poses the question to what extent the sediments in the study area may have been affected by the diking of the inner Meldorf Bay in the 1970s.

Land reclamation in general has a serious impact on the environment. With the new 15 km dike almost 50 km^2 of tidal flats were reclaimed. This resulted in a decrease of the tidal prism of about 37 x 10^6 m^3 (TARNOW et al., 1978). Compared to that of the entire tidal basin of the Piep channel system (413 x 10^6 m$^{3)}$, as quantified by SPIEGEL (1997), this amounts to a loss of 8 %. The sedimentological response to this environmental impact was studied by REIMERS (2003). Comparing his results with maps of 1978 (GAST et al., 1984) and 1989 (VAN BERNEM, 1994) as well as with those of DIJKEMA (1989), he was able to show that a clear trend towards finer sediments occurred after the diking of the inner Meldorf Bay. Between 1978 and the year 2000 the areas covered with fine-grained (< 63 nm) sediments had increased significantly. However, this tendency was limited to the area of the Meldorf Bay while already the eastern part of the adjacent Bielshövensand sandbank was left almost unaffected by this development.

The main aspects of the morphological response of the Meldorf Bay to the artificial reduction in the tidal prism were already dealt with earlier in this paper. From 1977 to 1996 a decrease in the sub-tidal volume was registered. Moreover, intensified deposition especially of fine-grained sediments enhanced the vertical accretion of the intertidal areas. Quantifications of this evolution are given in WITEZ (2002) and HIRSCHHÄUSER and ZANKE (2001). The latter authors also show that the most intense morphological adaptation occurred in the period from 1979 to 1982, i. e. directly after the last reclamation in 1978. These findings support the widely accepted perception that the volume of the tidal prism or the basin size is directly proportional to the cross-sectional area of the inlet (O'BRIEN, 1931; RENGER, 1976; MISDORP et al. 1990). NIEMEYER et al. (1995) developed numerical formulations of the correlation of channel size at its mouth and the tidal volume (approx. twice the tidal prism) for different sub-basins of the Meldorf Bay. For the situation from 1942 to 1969, which is equivalent to the time before the first diking, their equation is loaded with a factor of 6.98. For the period from 1973 to 1990, i. e. mainly after the last diking, this factor is 7.72. This means that after the land reclamation and the related reduction of the tidal water masses, the channel cross-sectional areas increased. At first sight, this finding appears to disagree with the empirical knowledge that a decreased tidal prism should lead to smaller channel cross-sections. Instead, it shows that the process of morphological adaptation after the land reclamation was not completed until 1990. At that time the channel cross-sections were still a bit too wide relative to the tidal volume.

In her work, WITEZ (2002) used the parameter "characteristic elevation" to describe the morphological state of tidal basins. The "characteristic elevation" reflects the ratio of intertidal sediment volume to intertidal area and describes the specific height which a tidal flat area can attain under given boundary conditions (GÖHREN, 1968). WITEZ calculated this parameter for three sub-basins of the Meldorf Bay and for the tidal basin of the Piep channel. Thus, ten morphological states are characterized covering the time span from 1937 to 1991. On the basis of these values we graphically displayed the temporal morphological evolution of the four tidal basins (Fig. 20). The morphological trend before as well as after the diking can be approximated by a simple linear function. The good correlation permits an extrapolation of the best fit line. This reveals the extent to which the morphological adaptation after the final land reclamation of the inner Meldorf Bay in the 1970s has proceeded.

In the four decades before the diking the analysed basins show relatively stable trends. Whilst for the Kronenloch tidal basin the "characteristic elevation" increases over time, the situation in the other three areas is fairly balanced. In all tidal basins the dikings of 1972 (mainly influencing the southern part of the Sommerkoog-Steertloch basin) and of 1978 have caused a drop in the elevation values. The trend lines evaluated for the period following the closure of the basin indicate that the system tends to revert to the initial state. Following the idea of our conceptional model i.e. the trend lines, full morphological adaptation of the small shore-connected basins Wöhrdener Loch and Kronenloch should be completed within the next 40 to 50 years. The data for the more exposed Sommerkoog-Steertloch area, by contrast, suggest that this basin has already returned to the state of 1972. By the same token, the huge and open tidal basin of the Piep (Fig. 20) is not far away from the "characteristic elevation" values prior to 1978.

Besides man-made impacts such as land reclamation the morphodynamics of the area are also driven by natural processes. These processes act on different time scales. There are, for example, short periodical changes due to a single tide or the neap-spring cycle. Although their effects on individual small-scale morphological units like bedforms can clearly be recognised, the implications for complex units like a tidal basin are still obscure. The same is true for single storm events. The shortest time scale at which we were able to quantify morphological

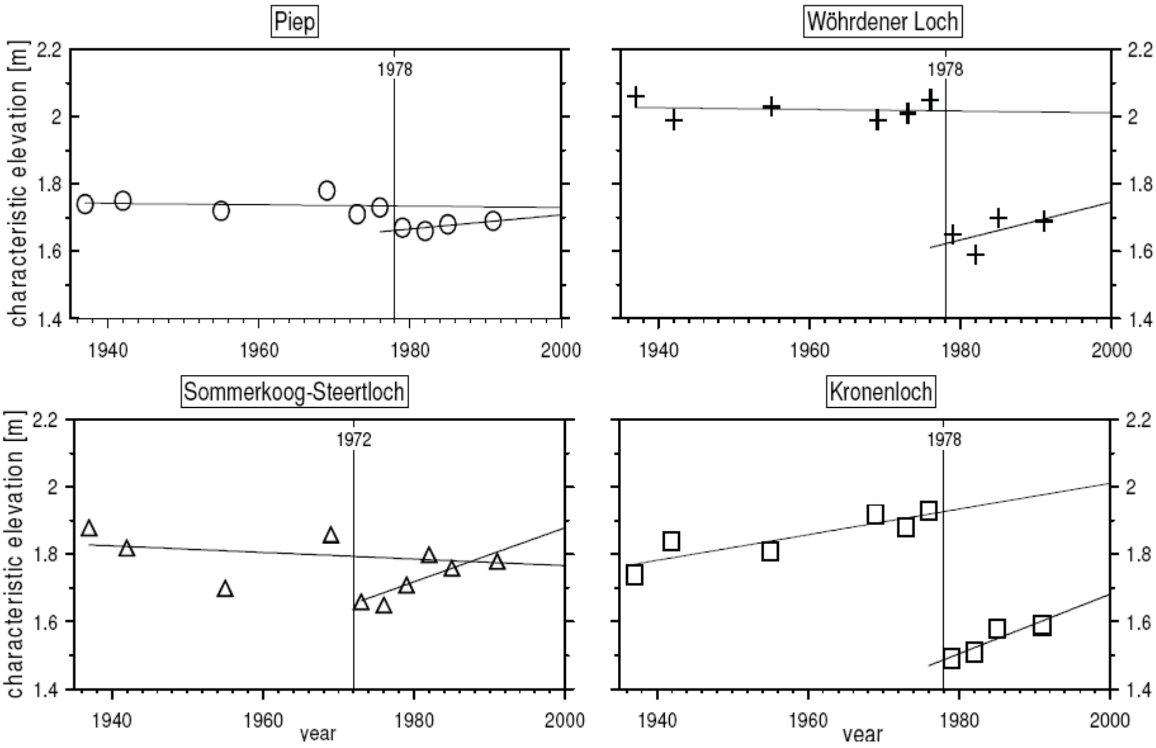


Fig. 20: Temporal evolution of the "characteristic elevation" for four tidal basins. For locations see Fig. 5

changes was the seasonal time scale. Although not all results point in the same direction, it became apparent that in the tidal channels erosion prevails in the cold and deposition in the warm season. Attempts to correlate this variability with seasonal fluctuations of the tides or seasonal meteorological characteristics were not satisfactory (ASP, 2004). FLEMMING and BARTHOLOMÄ (1997) attribute the winterly erosion of fine-grained sediments on the East Frisian tidal flats to a higher kinematic viscosity of the cold water. Higher kinematic viscosity aids the entrainment and favours the suspension of sediments (a decrease in water temperature from 20 to 5 °C results in a reduction of particle settling velocity of around 25 %). This could explain that in the cold season the channel beds are scoured. However, this hypothesis does not explain the whereabouts of the interim storage for the channel deposits, which are present in the warm season and absent in the cold season. In this context an observation of REIMERS (1999) is of importance. He observed that on accreting mudflats of the Meldorf Bay small runnels completely silted up in winter and were cleared again in summer. This means that there must be a transport of sediments towards the shore in winter and an export out of this region during the warm season. Massive shoreward transport and material imported from deeper levels are also visible in the migration of the supratidal Blauortsand sandbank. According to WIELAND (1972), migration rates of 30 m per year, tantamount to the cold season, are typical. Based on numerical model simulations HIRSCHHÄUSER and ZANKE (2001) also postulate an exchange between intertidal and subtidal regions. Based on their findings, they conclude that a transport of sediments from the tidal flats into the channels can be traced back to storm events. Since storms are more frequent in winter this would contradict the field observations made by REIMERS (1999) and our findings that channel scouring is more frequent in the period from late autumn to early spring. Moreover, redeposition of sediments is not only limited to a transport between intertidal and subtidal compartments. It also occurs between the tidal flat system including its channels and the bars and shoals (e.g. ebb-delta) located at the transition to the open sea (NIEMEYER and KAISER, 1994). In this case, seaward transport is often caused by an interaction between storm effects and ebb currents. During ebb-surges following storm-elevated water levels in tidal basins the ebb-current velocities in the deeper channels can be significantly higher (66 %; FLEMMING, 2004) than under average weather conditions. Under extreme conditions this can lead to an irreversible export of intertidal sands into the open sea, traceable as sand layers in the muddy deposits of the open shelf (GADOW and REINECK, 1969).

In the context of seasonal variability, the question arises whether the seasonal changes are a finely balanced back and forth movement or whether there is a net one-directional gain or loss of sediments. One of the most significant morphological trends visible on wider spatio-temporal scales is the lateral migration of the tidal channels. In many cases this is related to meandering which is not only a tidal phenomenon (TRUSHEIM, 1929; REINECK, 1958; AHNERT, 1960; REID and FROSTICK, 1994; GÖNNERT, 1995). In this context the formation of ebb and flood channel systems already described by VAN VEEN (1950) and AHNERT (1960), must be mentioned. A typical example for such a system is the central Piep. Between the flood branch in the south, i. e. on the right hand side of the inflowing flood current, and an ebb branch in the north, i. e. on the right hand side of the outflowing ebb current, intensive sediment reworking takes place (for details, see previous chapter).

Lateral migration of channels, however, is also forced by displacements of sandbanks induced by prevailing meteorological conditions. This is the case for the supratidal Blauortsand sandbank. Mainly due to heavy winter storms from the westerly sector, this sandbank migrates towards the east (WIELAND, 1972; KESPER, 1992). During the last 30 years, wind conditions at Büsum monitoring station have been fairly stable at a relatively high energy level (BENKEL and GROSS, this volume). Therefore, the simultaneous displacements of the Tertius Sand and the D-Steert sandbanks may, to a certain extent, be generated or amplified by storms or frequent strong winds from westerly directions. The study of old nautical charts, however, reveals that the landward progression of these banks is a process which has been active for several centuries (LANG, 1975; WIELAND, 2000). Landward displacement of morphological features is inevitably accompanied by displacements of tidal watersheds which, in turn, results in a progressive decrease in basin size. This development is also known from other compartments along the southern North Sea coast. In the case of the East Frisian barrier-island system, FLEMMING (2004) traces back the basin size reductions primarily to morphological adjustments triggered by land reclamation. He also notes that this influence is often underestimated in morphological analyses. Besides the reaction of tidal basins to land reclamation (DIECKMANN, 1985; EISMA and WOLFF, 1980; FLEMMING, 2002; WIELAND, 1984, 2000; WITEZ, 2002), the effects of a rising sea level are widely discussed (FERK, 1995; FLEMMING and BARTHOLOMÄ, 1997; HOFSTEDE, 1999b; MISDORP et al., 1990; REISE, 1998; SPIEGEL, 1997). Conceptual models (e. g. FLEMMING and DAVIES, 1994) suggest that the elevation of tidal flats and saltmarshes follows a rising sea level, provided that the rate of sediment supply can compensate the rate of sea-level rise (e. g. FLEMMING, 2002). The sediments needed for this accretion can either be derived from external sources or from internal redistribution. In the latter case, the material can stem from a reduction of tidal basin size. This may also be accompanied by stronger gouging of the tidal channels. The sediments eroded here may then bolster intertidal accretion. Modern examples for this kind of morphological response are given in DIECKMANN, (1985), EISMA and WOLFF (1980) or REISE (1998). Especially in the tidal flats north of our study area (North Frisian Wadden Sea), channel gouging is a widespread phenomenon (overview in SPIEGEL, 1997). Forecasts of the morphological adjustment under an increased sea-level rise scenario mainly focus on stronger channel excavation activity (e. g. MISDORP et al., 1990 and SPIEGEL, 1997).

In contrast to frequent examples for channel gouging, our analysis reveals a more stable situation for the Piep channel system or an even slightly reverse tendency. The widely observed correlation between maximum channel depth and the presence of cohesive, erosion-resistant sediment layers in the subsurface suggests that these layers effectively oppose scouring of the channels in this case. This means that the sediment demand for morphological adaptation in the Meldorf Bay after the land reclamation and for adjustments to a rising sea level has to be supplied from other sources. Since the landward dislocation of the outer sandbanks is undisputed, the most obvious sediment source would be the internal redistribution due to a decrease in basin size. However, in a sense, this contradicts the concept that the Dithmarschen Wadden Sea is characterised by a certain surplus of sediments (EHLERS, 1988). In this context DIEKMANN (1985) discusses possible longshore sediment transport pathways. According to him, sediment streams coming from the west and from the north end in this coastal compartment. However, this idea of generalized sediment flows is not based on direct observations but is inferred to be a consequence of large-scale land reclamation in the Dithmarschen area during the last 200 years (WIELAND, 1984, 2000), the strong and rapid siltation of the Eider estuary after construction of the barrier (WIELAND, 1999), or the quantification of the huge amounts of mobile fine-grained deposits present in adjacent offshore areas (ZEILER et al., 2000a, 2000b).

5. Conclusions

The present study has combined a variety of investigations in order to provide an integrated approach for a better understanding of the litho-stratigrafical, sedimentological and morphological setting of the Dithmarschen Wadden Sea. Beside typical characteristics of a low-macrotidal environment, the area exhibits some unique features. Thus, one of the most important outcomes of the study is the insight that morphodynamic erosional processes are depth-limited by the existence of cohesive deposits of early Holocene age in the subsurface (Dithmarscher Klei). The resistance to erosion of these layers is significantly higher than that of the modern tidal flat sediments. This, in turn, changes the way morphological adaptations in the region occur. Channel gouging, which is often observed in other tidal flat environments observed as a response to changed hydrodynamics, seems to play a minor role in the Dithmarschen Wadden Sea. Nevertheless, intensive morphological changes are active on various temporal and spatial scales. In this context, a new process has been identified, namely a seasonal erosion-sedimentation-pattern in the channels. Most of the processes acting on longer time scales can be correlated with the observations of other authors. Although this investigation is based on a variety of information sources, it has not been possible to even generate a simple qualitative conceptional model which would explain the different aspects of the complex morphological processes in the area. Particularly those processes occurring on large spatial scales still require reliable quantification. These present shortcomings signify a major challenge for future numerical simulations.

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