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Seabed Morphology and Sediment Dynamics

Die Küste

Seabed Morphology and Sediment Dynamics

By Manfred Zeiler, Klaus Schwarzer, Alexander Bartholomä and Klaus Ricklefs

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1. Introduction

The German coasts extend along two different seas, the tide-dominated North Sea and the intra-continental non-tidal Baltic Sea. While the North Sea has an open transition to the Atlantic Ocean, the Baltic Sea has its only connection to the world's oceans through the North Sea and the shallow and narrow Danish straits and sounds (Fig. 1). Both shelf seas are not only different in their hydrographic characteristics, but also in their geological development (Schwarzer et al., 2008, this volume), their sediment conditions and their geo-morphological features.

Although the seafloor in the German sectors of North and Baltic Sea is built up mainly of loose Quarternary deposits, the driving forces leading to environmental changes are quite different. While in the North Sea the sedimentological and geomorphological development (morphodynamics) is ruled by tides and waves, waves and wind driven currents are relevant for the seafloor conditions and sediment dynamics in the Baltic Sea. In both seas, however, phases of storm-induced high water levels often lead to severe changes of the coastal geomorphological environment. For the German North Sea coast this holds especially for storms from (north-)westerly directions, which can induce water levels of up to five meters above mean sea level usually for the duration of one or two tidal cyles. For the western Baltic Sea coast, storms from north-easterly directions have the strongest influence on coastal changes. Here, high water levels and therefore hydrodynamic extremes can last for days (Schwarzer, 2003).

2. North Sea

The German Bight is a meso-tidal to low macro-tidal environment with a tidal range between two and four meters. According to geo-morphological features and sedimentological environments, the German sector of the North Sea can be divided into the three zones: the offshore waters, the tidal flats of the Wadden Sea and the funnel-shaped estuarine river mouths (Fig. 2). In the meso-tidal environment, the barrier island chain of the East Frisian as
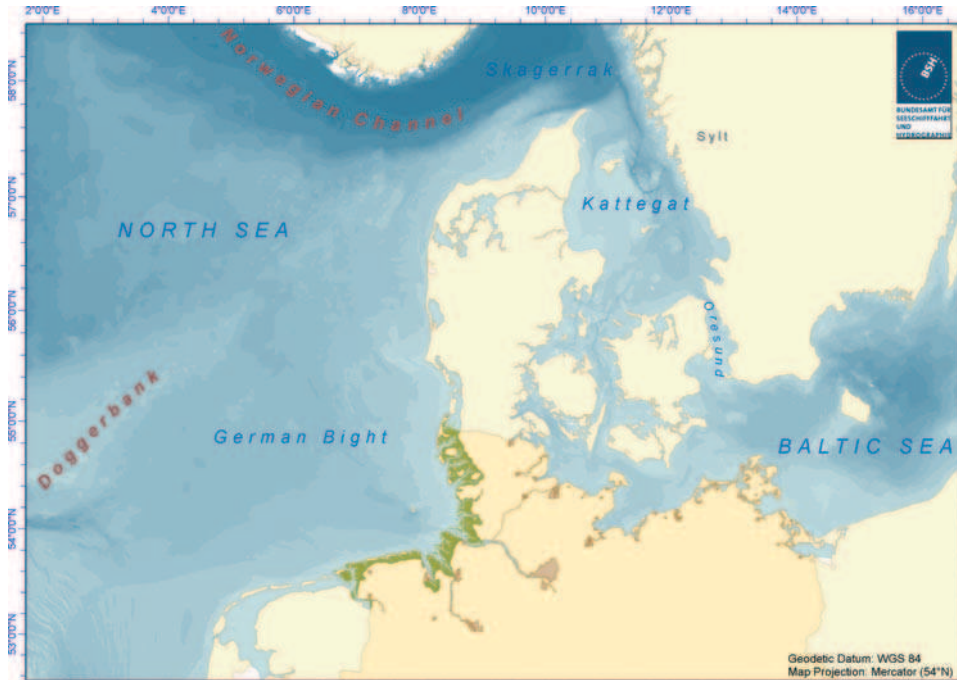
Fig. 1: Seabed Morphology of the North Sea and South-western Baltic Sea.
(Data source for water depths: dhi Water Environment Health)

well as the North Frisian Islands separate the tidal flats from the deeper offshore waters, while in front of the low macro-tidal estuaries of the Elbe and Weser Rivers barrier islands are not developed.

2.1 Offshore Waters

The seabed morphology of the eastern German Bight is characterized by a relatively smooth slope and an uneven sea floor. The most prominent morphological features are the shoal Amrum Bank and the island of Helgoland together with the adjacent Steingründe, a submarine lag deposit area. Relict deposits of the Saalian terminal moraines are present towards the NNW oriented slope of the former Elbe glacial spillway, which forms the western boundary of the eastern German Bight. Strips of coarse sand, submarine dunes, sand ribbons and biogenic patches are described as typical bed-form features for this area (KÖSTER, 1974; TABAT, 1979; WERNER, 2004). Other recent morphological elements are the longitudinal sand bars in the nearshore zone of Sylt Island, which are in equilibrium with the present hydrodynamic regime (FIGGE, 1976).

Along the southern coastline of the German Bight, the seabed has a relatively steep slope. In the shallow parts, seawards of the East Frisian barrier islands, long-shore sand bars occur down to water depth of approx. 6 m below MSL (Mean Sea Level). Further offshore, shoreface connected sand ridges are present (REINECK and SINGH, 1973; SWIFT et al., 1978). These
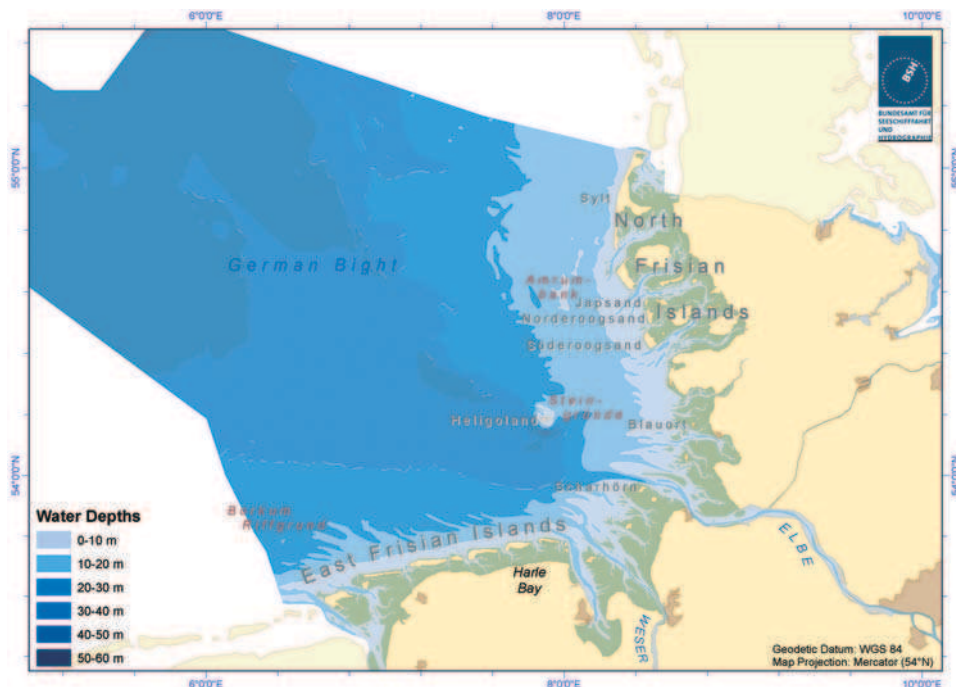
Fig. 2: Seabed Morphology of the German Bight (North Sea) including localities mentioned in the text. (Source: CONTIS [BSH])

sand ridges are 2–5 m in height and occur in water depth between 12–18 m MSL. The core of such ridges is at least of early Atlantic age, i. e. approx. 7,500 years Before Present (LABAN and SCHÜTTENHELM, 1981). These morphological features exhibit a pronounced dynamic behaviour having cross-shore migration rates of between 100 and 200 m a^{-1} at their maximum (ANTIA, 1996).

Borkum Riffgrund extends towards the Dutch offshore waters and represents a relict of a former Pleistocene terminal moraine. Below approx. 20 m MSL, the seafloor of the western German Bight is comparatively flat and smooth except some patchy areas showing current ripples. Dogger Bank (Tail's End) dominates the seabed morphology at the north-western end of the German North Sea sector.

Because the North Sea was not covered by ice during the last glacial period, the seafloor underwent one regressional and two transgressional phases which shaped and levelled the sediment surface (FIGGE, 1981). Accordingly, the sediment distribution pattern in the German Bight (Fig. 3) to a high degree reflects reworking processes acting since the retreat of the Saalian ice shield. On one hand, relict sediments ranging from fractions of coarse sand to boulders usually cover glacial till and protect the sea floor against further abrasion. On the other hand, fractions of fine to medium sand are almost permanently reworked by wave-induced and tidal currents.

The thickness of the mobile sediment cover along the German North Sea coast down to a depth of 20 m below MSL shows three distinct zones which are running more or less parallel to the coastline (Fig. 4). Seaward of the Wadden Sea in shallow water depths between
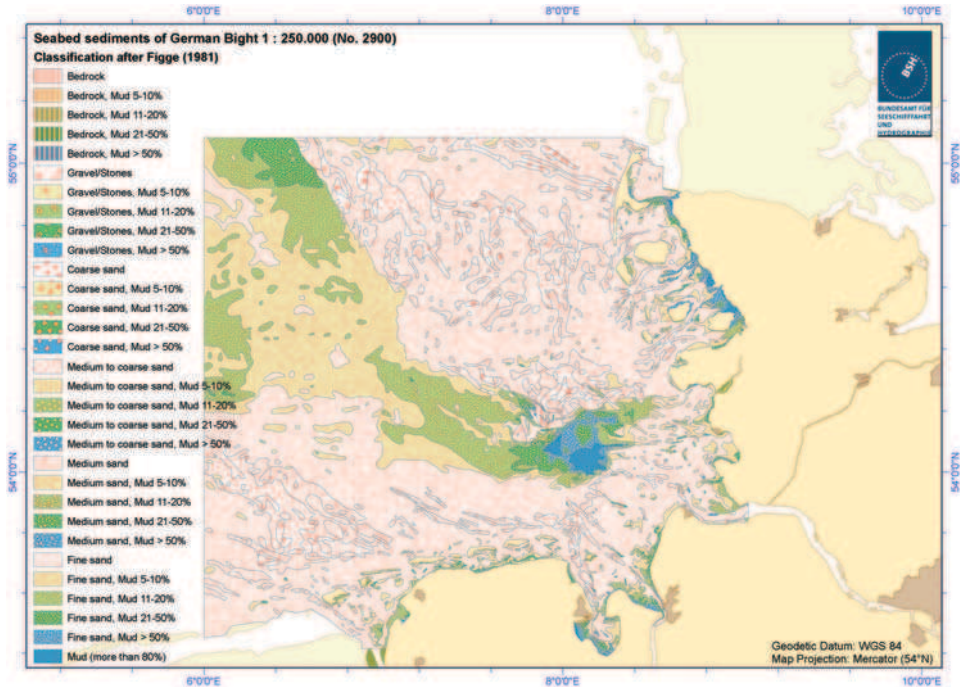
Fig. 3: Distribution of the surficial sediments (0–20 cm) of the German Bight (FIGGE, 1981).
(Source: Shelf Geology Explorer, BSH)

0–10 m, the thickness of the mobile sediment cover is up to 10 m; a relatively thin layer of mobile sandy material is located between 10–15 m of water depth, and a slight increase in thickness of 2–3 m with local maxima of about 5–6 m can be observed in water depths between 15–20 m. A conceptual model of the net sediment transport regime is inferred from this pattern. It comprises a relatively narrow zone of sediment in the littoral drift, resulting in a substantial sediment supply in the innermost German Bight and a shore-normal bed-load transport shifting sand to and fro in the coastal profile, with a net offshore component (ZEILER et al., 2000).

During storm surges, sediment from tidal flats and sand bars can be transported offshore for more than 50 km down to water depths of 40 m below MSL. The average volume of sediment transported by a single storm has been estimated to be about $4.2 \times 10^6 \, \text{m}^3$ (GADOW and REINECK, 1969). WUNDERLICH (1983) demonstrated that large-scale sedimentary structures are shifted during storm wave action and remain stable during calm weather periods. They undergo only slight reworking processes.

Similar processes are postulated by DIESING et al. (2006) for so-called "sorted bedforms" in offshore waters of the eastern part of the German Bight. They assume that extreme storm events play a major role in the generation of these structures, whereas average tidal currents form and maintain their final shape. It is noteworthy that the widespread sorted bedforms have shown stable patterns over a period of more than 26 years.
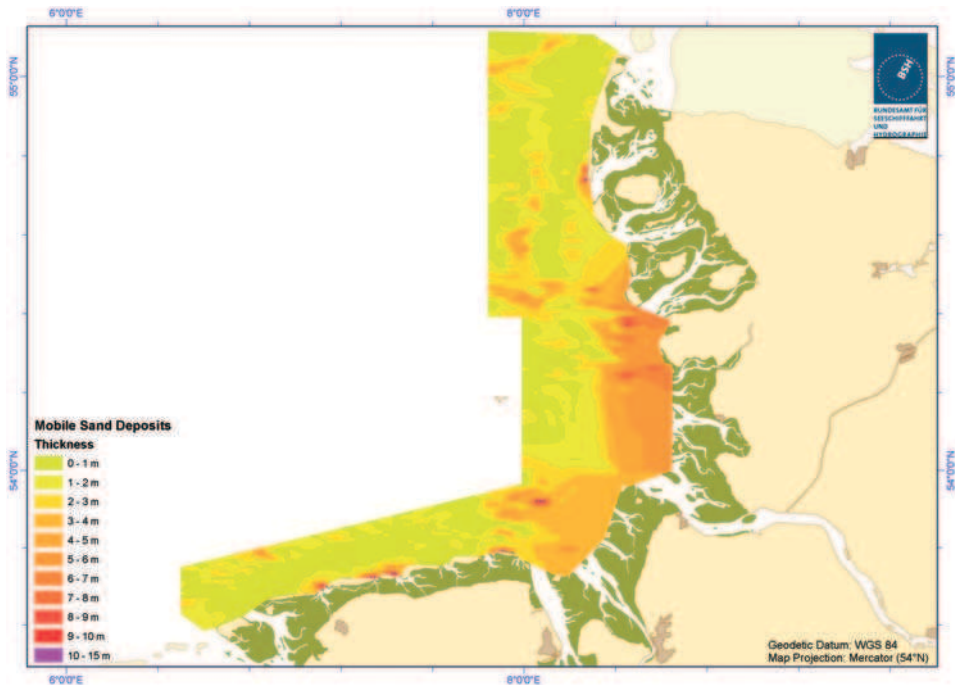
Fig. 4: Thickness of the mobile sand cover along the German North Sea coast (ZEILER et al., 2000).
Source: Shelf Geology Explorer (BSH)

2.2 Tidal Flats

The tidal flats of the Wadden Sea form the interface between the open North Sea and the mainland. They extend from Denmark to the Netherlands over a distance of about 450 km and can reach a width of up to 25 km along the German coast. This marginal belt between the barrier islands, whose genesis differs from the North to the South (KOHLUS, 1998), and the mainland is comprised of salt marshes, extensive intertidal flats, numerous tidal gullies and streams. The sediments mainly consist of fine sand with various proportions of slightly coarser material or mud (silt and clay) (AHRENDT, 2006). Depending on the geological development, locally peat or clay-rich layers can be found in the subsurface (STREIF, 1990).

The overall thickness of the sediment body can reach nearly 40 m (AHRENDT, 2006). The surficial sediments show a typical zoning from predominantly sandy sediments in more exposed areas to muddy deposits in sheltered or more elevated parts. Overall, a dominance of sandy flats with a mud content of less than 10 % is observed (BERNER et al., 1986; BAYERL et al., 1998; KÖSTER, 1998; RICKLEFS and ASP NETO, 2005). The present distribution of muddy intertidal sediments (more than 50 % silt and clay), however, is mainly limited to small areas. This is due to a lack of adequate depositional environments mainly as a consequence of intensive land reclamation activities along the marshland coasts since the early Middle Age (FLEMMING and ZIEGLER, 1995; BROCKAMP and ZUTHER, 2000). Land reclamation and the substantial reduction of catchment areas resulted in an enlargement of the East Frisian barrier islands and a decrease of mudflats and salt-marsh areas as well. Along with a rising MSL and the increase in

wave energy, fine-grained particles have been eliminated from the sheltered backbarrier areas behind the islands (e.g. VAN STRAATEN and KUENEN, 1957; FLEMMING and BARTHOLOMÄ, 1997).

The deposits in the channels cover a wide range of different sediment types. It can reach from very coarse lag sediments of Pleistocene till (AHRENDT, 1992) over strongly cohesive Holocene layers (BERNER et al., 1986; RICKLEFS and ASP, 2006) to outcrops of peat. Most common, however, are recent sandy to partly muddy deposits (e. g. POERBANDONO and MAYERLE, 2005). On pure sandy channel beds, mega-ripples and submarine dunes are very common (ULRICH, 1979; MAYERLE et al., 2005). Especially in the main tidal channels of North Frisia, where coarser sandy sediments prevail, the seabed is partly characterized by sand waves of up to several meters height (ULRICH and PASENAU, 1973; HENNINGS et al., 2004).

The system of the tidal flats has always undergone an intensive internal rearrangement of deposited sediments. According to ZEILER et al. (2004), bed-load transport rates of 400 m³ m⁻¹ a⁻¹ in the North Frisian Wadden Sea are around five times higher than in the adjacent open water zone of the German Bight. Especially under the influence of an increasing sea level and/or an augmented mean tidal range, a deepening of inlets and tidal channels is expected (HOFSTEDE, 2002) and can be partly observed (e.g. HIGELKE, 1998). Another evidence of the adaptation of the depositional environment to a changing hydrodynamic forcing is the landward migration of characteristic morphological elements. This holds for the sandy barriers with a migration rate between 15 and 27 m a⁻¹ (HOFSTEDE, 1997) along the meso-tidal coasts of East and North Frisia as well as for the small supra-tidal sands (EHLERS, 1988; RUNTE, 1994) and exposed sand banks of the open tidal flats in the low macro-tidal innermost German Bight (RICKLEFS et al., 2005).

Input from the English Channel, erosion of the East Anglian coast as well as discharge from the rivers can be considered as the main sources of fine-grained material (silt and clay) in the North Sea. Based on clay mineral analyses, PACHE et al. (2008) could demonstrate that the Helgoland mud area is a main deposition centre for suspended particulate matter discharged by the River Elbe. The distribution of fine-grained material (especially clay) is coupled to hydrodynamic transport patterns in the German Bight. According to EISMA and IRION (1988) most of the fine-grained sediment deposition takes place in the tidal flats (Wadden Sea). While 3–7 × 10⁶ tons of suspended particulate matter (SPM) is accumulated in the German Bight, 12–19 × 10⁶ tons per year are transported into the Norwegian Channel (DYER and MOFFAT, 1998).

2.3 E s t u a r i e s

In the Elbe and Weser Estuary, the seabed is dominated by distinct morphological features such as channels and sand spits, sand waves in channels or longitudinal sand bars (REINECK and SINGH, 1973) dependent on the strong tidal influence, grain size distribution and sediment availability.

Pronounced migrating bed-forms occur on the sandy river bed of the Elbe and Weser estuary. WEVER and STENDAL (2000) measured a migration speed of a minimum of 45 cm d⁻¹ in the Elbe River. For the Weser/Jade estuary, minimum migration speed is higher by a factor of 2 (SCHROTTKE et al., 2006). The migration of these bed-forms shows a cyclic pattern which correlates with the tidal cycle.

3. Baltic Sea

The Baltic Sea is the second largest brackish water body in the world. For its ecosystem, the Drodgen Sill in the Øresund and the Darss Sill between Gedser Rev and Fischland-Darss, with depth of only 7 m and 18 m, respectively, below Mean Water Level (MWL) are the most important features (Fig. 5). These sills control the water exchange with the North Sea, which is not continuous, but depends strongly upon westerly storms. This results in oxygen-rich North Sea water inflow into the Baltic Sea basin, 73 % of which pass via the Darss Sill (JACOBSEN, 1980), whilst the remainder goes over the Drodgen Sill.

The Baltic Sea is a very 'young' brackish water environment, which is extremely diverse compared to other seas regarding geological prerequisites, physical forcing of sediment mobility and environmental conditions. Due to its young geological history and the on-going uplift and subsidence processes (SCHWARZER et al., 2008, this volume), the surface sediment distribution and the upper part of the subsurface are very patchy; they are mainly of Quaternary origin. Particularly, compared to the tide-dominated North Sea, the surficial sediment distribution in the non-tidal Baltic Sea is much more heterogeneous; it is patchy on both, small and large spatial scales. This observation is confirmed by different maps (Fig. 6 and 7), for example TAUBER and LEMKE (1995), TAUBER et al. (1999), HERMANSEN and JENSEN (2000). The deep basins function as sinks for fine-grained sediments (silt and clay), whilst sandy material is deposited in the more shallow areas. Relict sediment remains, where till or other glacial deposits pinch out at the seafloor and are directly affected by waves.
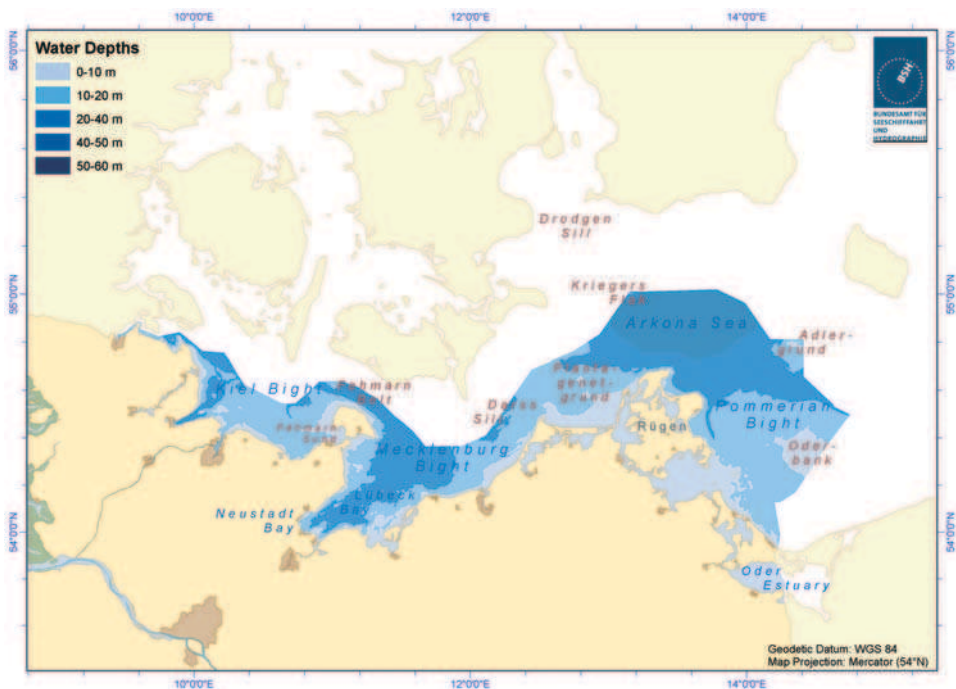

Fig. 5: Seabed Morphology of the South-western Baltic Sea including localities mentioned in the text.
(Source: CONTIS [BSH])

Legend

Mud

Sandy mud - muddy sand
(~ 20 - 80% sand)

Sand, partly gravel/stony

Fine sand

Medium sand

Coarse sand

Gravel, stones, residual deposits
and/or crysralline bedrock

Residual deposits on till

Residual deposits on Quatanary clay/peat

Residual deposits on Pre-Quatanary sediments
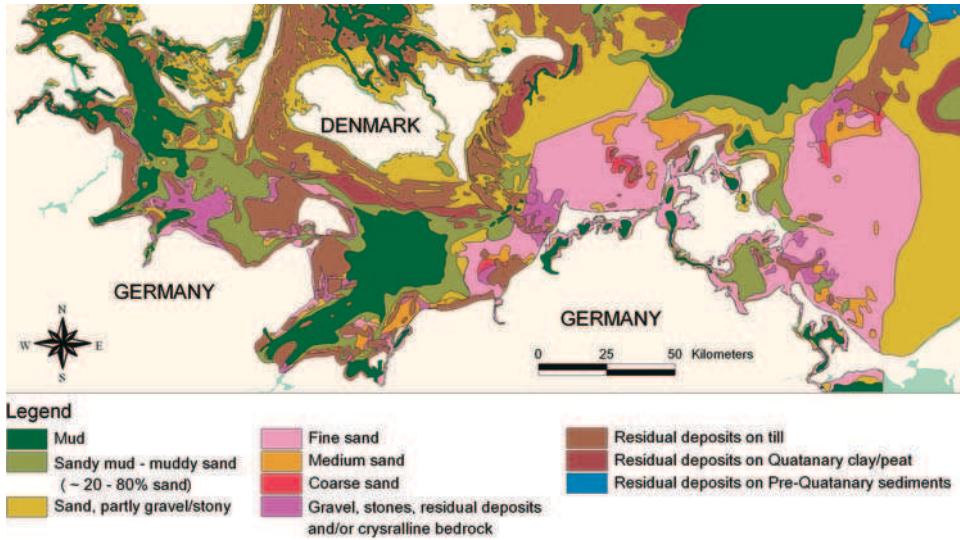
Fig. 6: Distribution of the surficial sediments of the South-western Baltic Sea. Source: REIMERS, H.-CH. (2008): Sea Bottom Sediment Map of the Westen Baltic, State Agency for Nature and Environment Schleswig-Holstein; based on HERMANSEN and JENSEN (2000): Digital Sea Bottom Sediment Map around Denmark and data of the Federal Maritime and Hydrographic Agency, Germany (BSH) and the Christian-Albrechts-University of Kiel; compiled by A. SEKINKER (2002)

Fig. 7. Distribution of the surficial sediments of the German Baltic Sea (TAUBER and LEMKE, 1995; TAUBER et al., 1999; TAUBER, unpubl.). (Source: Shelf Geology Explorer, BSH)

3.1 Offshore Waters

The bathymetry of the Baltic Sea is controlled by the presence of sills and deep basins, which developed during the last glacial period. These basins increase in size and depth from west to east.

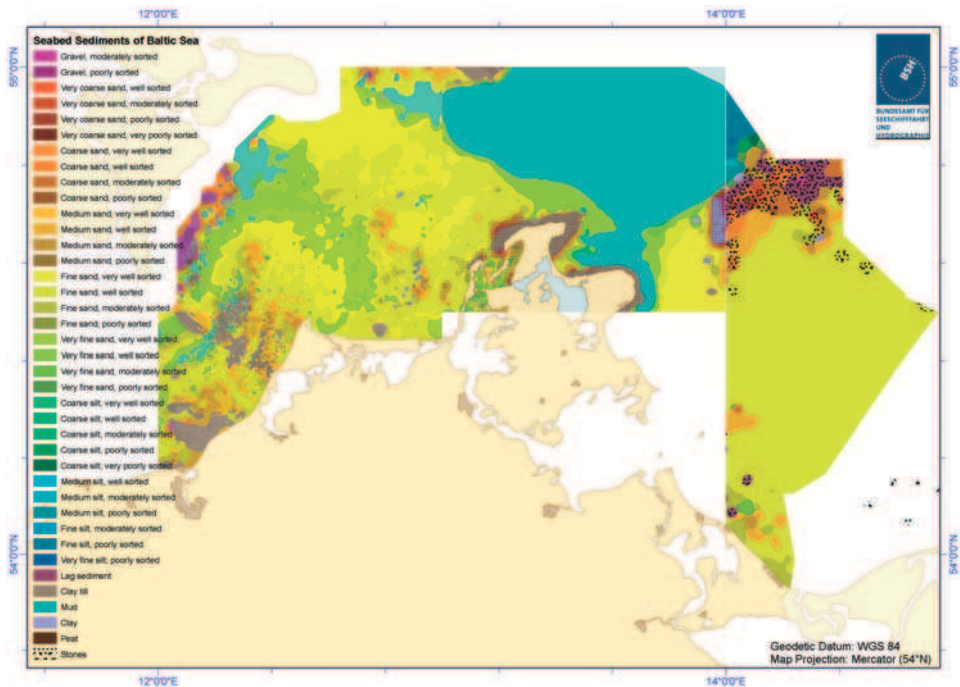The morphological structure of the south-western Baltic Sea is formed by Kiel Bight in the western part. It is mainly characterized by the presence of deep (c. 35 m) melt-water channels. Fehmarn Belt and Sund separate Kiel Bight from Mecklenburg Bight. This bight has a maximum water depth of 25 m and splits up into several smaller bays, namely Lübeck Bay and Neustadt Bay. In the eastern part of the German sector, Arkona Basin is the deepest basin of the south-western Baltic Sea with a maximum water depth of 45 m. It is flanked by the shoals of Kriegers Flak and Adlergrund at the eastern edge. Both shoals are of glacigenic origin. The Pommeranian Bight is situated between Adlergrund and the Oder estuary. It features a relatively shallow sandy bottom with the prominent shoal of Oder Bank.

In offshore waters, morphological features are mainly coupled to the strong-current-environments of the straits. In Fehmarn Belt (Fig. 8) and Darss Sill, the strong inflow of saline bottom waters from the North Sea form sand wave fields with crest heights of up to 5 m (WERNER and NEWTON, 1970; WERNER et al., 1974; LEMKE et al., 1994; SCHWARZER and DIESING, 2003; FELDENS, 2008). Mega-ripples were also observed on the shoals in shallow waters such as Plantagenetgrund (GROMOLL, 1992).

Although the sediment distribution is strongly affected by the subsurface geology, a depth-dependent overall zoning of surface deposits can be found (SEIBOLD et al., 1971). Along the coasts and on the submarine sills and shoals of the south-western Baltic Sea, coarse-grained lag deposits form a thin layer of a few decimetres on top of till deposits in water
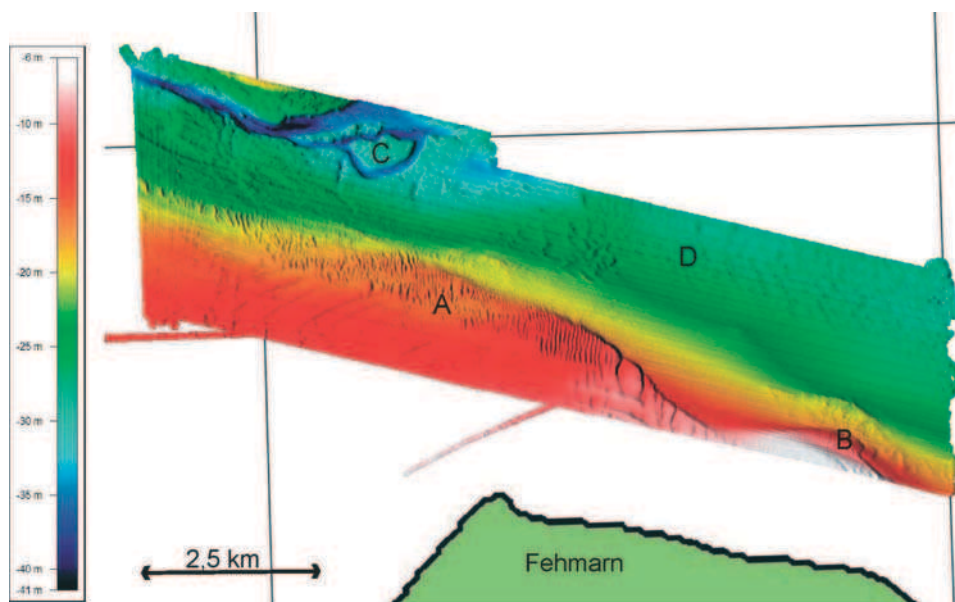

Fig. 8: Morphological features in the highly dynamic Fehmarn Belt (FELDENS, 2008).
(Source: Institute of Geosciences, University of Kiel)

depths of 5–15 m. These sediments result directly from the abrasion of the underlying till deposits. Material with grain sizes within the range of sand is removed by wave and current action, leaving the coarser components behind (SWIFT et al., 1971; TAUBER et al., 1999). Lag deposit areas are often found to be surrounded by well-sorted fine to medium sands. Except for areas in the immediate proximity of the coast and abrasion platforms, these sand layers are relatively thin, for example only 0.5 to 2 m in Kiel Bight (SEIBOLD et al., 1971) and the inner Mecklenburg Bight. Significant amounts of marine sediments are found in the deeper basins and channels of the Baltic Sea, where fine-grained, organic-rich sediments (mud) accumulate (WERNER et al., 1987; LEMKE, 1998; HARDERS et al., 2005). Depending on the water depth, the grain-size decreases from coarse to fine silt while the content of organic matter increases to 10–15 % (WINTERHALTER at al., 1981).

Comparison of two sonar images (mosaics) in the Pomeranian Bight confirm the relatively stable pattern of seabed sediments of several years on the lower shore-face (TAUBER and EMEIS, 2005). Even bottom currents with maximum velocities of 30 cm s^{-1} could not mobilize the sand. However, a significant portion of fine-grained material (mud, fluff) has evidently been advected in the bottom boundary layer under moderate hydrodynamic conditions.

ZIERVOGEL and BOHLING (2003) observed that the erosion behaviour of mud in the Mecklenburg Bight was dominated by the fluffy surface material, whereas the underlying silt fraction showed a higher erosion threshold due to its cohesive behaviour. Their comparison of near-bottom hydrodynamic forcing and experimentally derived critical shear velocities indicates a storm-controlled particle (mud and fine sand) transport in the bight. Based on statistical analysis of sedimentological parameters and hydrodynamic modelling, BOBERTZ and HARFF (2004) found evidence that the preferred transport pathways for clastic material in the south-western Baltic Sea are based on the direction of the average current vectors. An exception represents the Pomeranian Bight, where sediments have not been accumulated under present-day conditions. According to WEHNER (1990, in BOBERTZ and HARFF, 2004), they are of glacio-fluviatile genesis during the late Pleistocene.

3.2 Nearshore Zone

Typical features in shallow waters are nearshore bars which are highly dynamic morphological structures depending on wave climate and sediment availability (SHORT, 1999; SCHWARZER, 2003). They occur mainly in front of lowlands where several nearshore bars exist down to 6 m below sea level. Seawards of active cliffs these nearshore bars are often missing or exhibit only one long-shore bar. Their thickness seldom exceeds 2.5 m in the southwestern Baltic Sea. However, these morphological features have a significant influence on coastal stability as waves are breaking and energy is dissipated around these bars.

Wave conditions and sediment transport in shallow coastal waters depend upon exposure to the main wind and wave direction. Within this context, the coastline of the southern Baltic Sea is exposed to both north-easterly and westerly winds. For comparison, within the south-western Baltic Sea (Germany and Denmark) where fjords and bays are common, the most effective wind direction inducing coastal currents and sediment mobilisation varies considerably; it includes all directions, even south for some stretches of islands.

SCHWARZER et al. (2003) could demonstrate that waves are the main controlling factor of seasonal variations of the upper shore-face. Morphological changes induced by storm events remain on a decadal scale, whereas the lower shore-face shows a more stable sedimentological and morphological behaviour; changes are only measureable on centennial and millen-

nium scale, because long-term process such as sea-level fluctuations or neo-tectonics are the main driving forces there. SCHWARZER and DIESING (2001) investigated the sediment dynamics and geo-morphological changes on seasonal and annual scales in two different sandy nearshore areas of the south-western Baltic Sea. By using a new method called "tracer stick method", they found a geographical variation of seasonal maximum mobility which moves offshore during the stormy winter conditions. However, the intense sediment mobility did not invoke substantial morphological changes in every case, especially with respect to seasonality.

3.3 Coast

There are several types of coastlines along the south-western Baltic Sea. In general, Pleistocene cliffs are alternating with Holocene barrier systems, mainly consisting of spits and lagoons. Large sections of these coastlines are retreating at an average rate of 0.2–0.3 m per year and maximum rates of up to 1.5 m per year (SCHWARZER et al., 2003; ZIEGLER and HAYEN, 2005). East of Rügen Island, the coastline turns towards a formation which looks as if equilibrium conditions between erosion and accumulation predominate; however, even here the coast is eroding. Approximately 70 % of the coastline of the State of Mecklenburg-Vorpommern, extending from Mecklenburg Bight to Oder Estuary, is under permanent retreat (HARFF et al., 2004).

Natural sediment sources within the region are active cliffs and the seafloor, from which sediment is abraded (SCHROTTKE, 2001). The erosion of the active cliffs is controlled by storm events combined with high water levels. The rate of retreat of the active cliffs of Schleswig-Holstein is 24 cm a^{-1} on average (ZIEGLER and HAYEN, 2005) and up to 30 cm a^{-1} for the cliffs of Mecklenburg-Vorpommern. SCHWARZER (2003) emphasizes that the nearshore processes have to be taken into consideration for a comprehensive understanding of coastal dynamics. The rates do not increase linearly with depth, but are highly dependent of the type of substrate and wave dissipation. Material from cliff retreat and nearshore abrasion is transported by long-shore currents and is substantially involved in the formation of the Holocene barrier systems. SCHROTTKE (2001) measured seafloor-abrasion rates of 2–5 cm a^{-1} in water depths down to 6.5 m and at a distance from the shore of up to 300 m. In many cases, the amount of sediment supplied by seafloor abrasion is underestimated, sometimes completely neglected. Depending upon the composition of the Quaternary deposits and the exposure to the main wind and wave direction, such sediment supply can be of the same order of magnitude as the supply from the exposed parts of the retreating cliff (SCHROTTKE and SCHWARZER, 2006).

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