Postglacial sedimentary regime around northern Sylt, South-eastern North Sea, based on shallow seismic profiles

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During the past 5 years the coastal zone offshore the northern part of the island of Sylt, has been investigated by sparker seismics and high-resolution subbottom profiling. The North Sea sector of the area is characterized by northward-directed sediment bypass as a result of strong long-shore (tidal) currents heading towards the Lister Tief. The southern part of Lister Tief is characterized by the presence of a major dune field with up to 8 m high compound dunes with wavelengths up to 350 m indicative of easterly-directed sediment transport (flood dominated). Further to the northwest, in the outer delta, a dune field suggesting westerly-directed sediment transport is identified. The two dune fields appear to be separated by minor indefinite bed forms. The northern part of the Lister Tief is characterised by the presence of a channel with a depth of 20-30 mbsf (meter below sea level) (30-40 msec TWT (Two Way Traveltime)) and displaying erosion towards the north. At the western termination of the channel the sediment transport pathway appears to be divided into two directions; one towards the outer delta, and one towards the sediment depocenter SW of Rømø. The Lister Ley is characterized by the presence of minor dunes, indicative of flood-current control, apart from a central zone where ebb-tide is responsible for northward-directed sediment transport. Sparker seismic and Chirp III data are consistent with processes having been persistent throughout the Holocene. Based on the study a model for the current direction and sedimentation regime is suggested.

Keywords: Wadden Sea, postglacial sedimentary regime, Tidal area of Sylt and Rømø, sparker seismic, Chirp III sub-bottom profiling.

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Introduction

Sylt, the northernmost of the Frisian Islands in the German part of the Wadden Sea, is separated from the Danish island Rømø (Fig. 1) by the tidal inlet Lister Tief. The inlet has a diurnal mean tidal range of 1.86 m and a tidal prism of 627 106 m^3 (Kystinspektoratet, 1999). Water depths (Fig. 1) in the area are known from bathymetric maps and, in addition, in the Lister Tief sea floor topography is known from radar imaging (Hennings & Herbers 2006). The types of bed forms and their locations have predominantly been inves-

tigated by means of side scan, echo sounding and radar imaging (Ulrich & Pasenau 1973; Hennings et al. 2004; Hennings & Herbers 2006). These data sets were obtained during individual investigations but were not repeated annually. The orientation of the bed forms and large-scale sediment transport patterns have thus been based on limited side-scan sonar data and sea-clutter images (Hennings et al. 2004) although isolated parts of the Lister Tief have been imaged at greater detail (Ulrich & Pasenau 1973, Hennings & Herbes 2006). A systematic investigation of horizontal and vertical extent of bed forms, erosional features
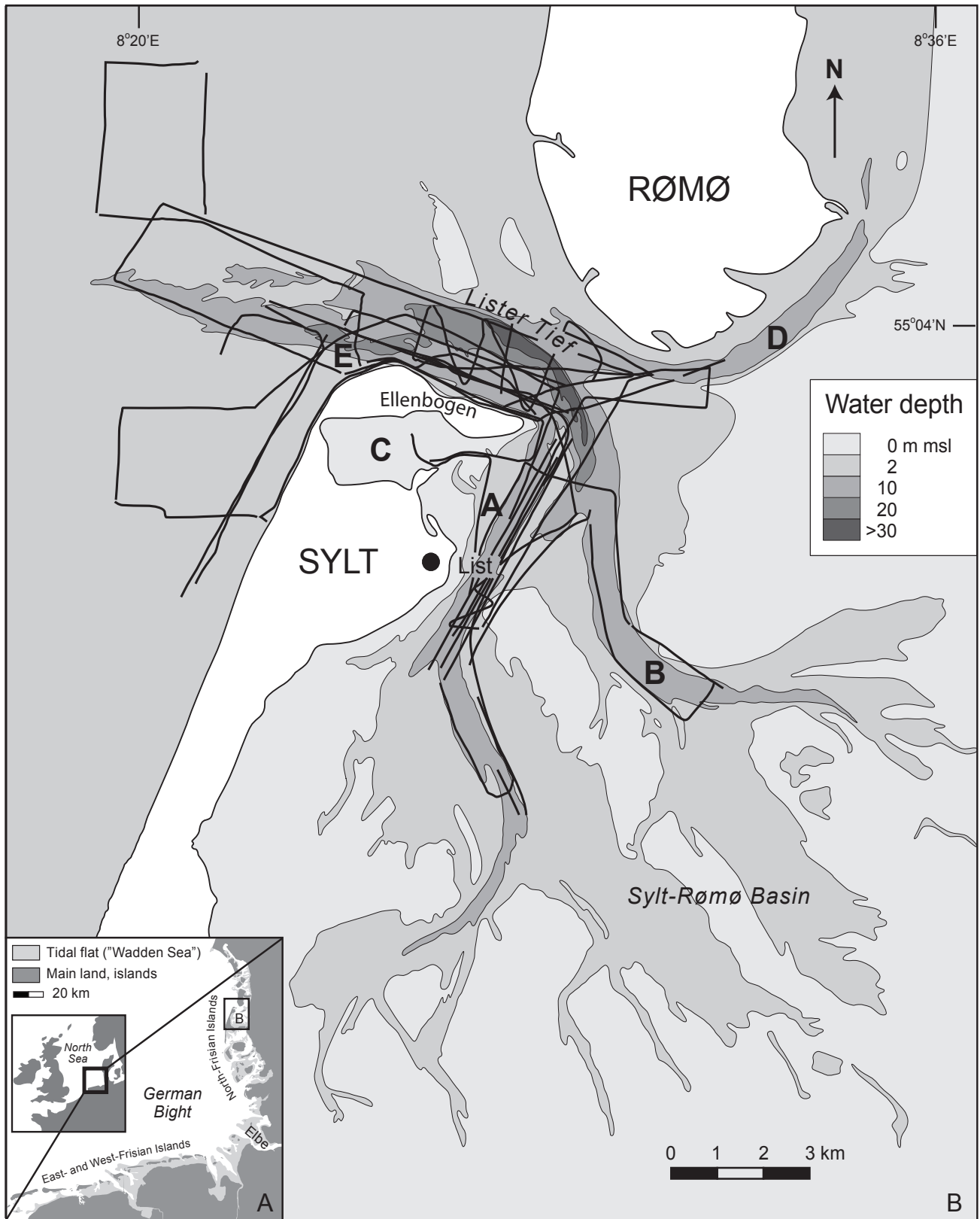
Fig 1: Overview map of the investigated area and bathymetry of the investigated area along with location of the sparker seismic profiles. The Chirp III data are located in the same area as the sparker data except for the area west of Sylt and the western most part of the Lister Tief. Bathymetry adapted from Lindhorst et al. 2008. The letters A, B, C and D designate Lister Ley, Højer Dyb, Könighafen and Rømø Dyb respectively. The letter E is referred to in the text.

and sediment by-pass, and their distribution, based on shallow seismic profiles has not previously been undertaken. To address this a large number of high resolution sparker-seismic profiles have been acquired offshore of the northern part of Sylt. These profiles cover the North Sea coastal zone and the adjacent Wadden Sea including the Lister Tief, Lister Ley, and Højer Dyb in the period 2004-2008 (Fig. 1). In order to improve resolution additional subbottom profiler data (Chirp III) were acquired in the Lister Tief and Lister Ley in 2009. From interpretation of the sparker and chirp III data, bed forms and areas of sediment by pass and erosion have been identified and mapped in this study. Based on the distribution of bed forms, erosional features and sediment by-pass signatures the overall transportation pattern around northern Sylt is interpreted and an overall model for the Holocene sediment transport regime is proposed.

Geological, physiographical and hydrographical setting

The present morphology of Sylt and adjacent areas are based on Mio-Pliocene sediments. These were deposited firstly under subtropical still-water conditions, in the form of silty clays, in a shallow sea near the coast. In the following period of lowering sea level, a sandy beach facies started to expand following the retreating sea. A riverine sandy facies followed and expanded in the Quaternary covering most of the Pliocene coastal sediments (Schwarzer, 1984). Glacial advances during the Pleistocene ice ages followed, however little is known of the extent that these affected the working area. Glaciers moved into the area for the last time during Saalian and dramatically changed its surface geomorphology. The facies units mentioned above were faulted, broke into pieces and were overthrusted (Schwarzer, 1984). They outcrop on the western and eastern sides of the central island. The western side became heavily eroded when the sea returned after the Weichselian sea-level low stand. Marine erosion started to affect the area from approx. 7 kaBP. Moraine deposits soon formed steep cliffs that retreated with the approaching North Sea and eroded materials started to form barrier spits to both the north and south. The northern recurved spit system grew predominantly due to swash bar accretion (Lindhorst et al., 2008), whereas the hooked-spit system that forms the northernmost part of Sylt, termed Ellenbogen, (Fig. 1) built up mainly as the result of longshore sediment transport ('beach drift') and accretion. The age of Ellenbogen is approximately 1300 years (Lindhorst et al., in press).

Coastal protection measures appear to have strongly influenced sedimentation along northern Sylt's coast line. Installation of groins in 1936 has most likely fixed the western coastline of Ellenbogen that was prone to strong erosion, and seaward progradation restarted. Paving of part of the beach in 1938 for bank protection purposes in NW Ellenbogen largely stopped erosion in this area but led to sediment bypass processes that also caused decreasing northward progradation of the system. Finally, beach nourishments to compensate for erosional loss were started in 1971 all along the west coast of Sylt. This caused growth rates in northern Ellenbogen to increase significantly due to enhanced sediment supply (Fürstenau, 2007; Lindhorst et al., in press).

While Sylt is subject to strong erosion along its western coast, Rømø is permanently gaining material – partly in the form of swash-bar accretion - and thus shows seaward progradation.

Today, the Sylt/Rømø tidal basin spans about 400 km². of which 67% is subtidal (10% above, 57% below −5 m in the channels) and 33% is intertidal (Lane et al., 2000). Tidal water exchange runs exclusively through the narrow Lister Tief tidal inlet. The inlet is the entrance to an artificial bight area as the free water flow is limited to the North as well as to the South by artificial dams connecting the islands of Sylt and Rømø to the mainland. The Lister Tief is the deepest (c. 40 m of water depth) of a set of three tidal channels (Rømø Dyb, Højer Dyb, Lister Ley, Fig. 1)) that merge from east into the List Tief. A volume of about 1100 m³ of water passes the List Tief at maximum current speed of 1.3 ms⁻¹ during one tidal cycle (Backhaus et al, 1998).

Due to the high-energy environment, medium and coarse sands (in places also including gravel and small boulders) dominate the channels, becoming gradually finer with decreasing water depth.

One of the most pronounced and prominent marine sand fields in the German coastal waters is found in the Lister Tief (Hennings & Herbers 2006). The area has been investigated over the years by various types of survey techniques. Ulrich & Pasenau (1973) carried out seven sounding profiles in a test area of the inlet and found that in the northern part most of the bed forms are ascribed to ebb-tide processs whereas in the southern part they are ascribed to flood-tide. They showed that sand dunes with a mean height of 3 m migrated approximately 60 m pr. year. Along the western coast of northern Sylt Ulrich & Pasenau indicate that sand drift is active. Bayer & Higelke (1994) presented an overview of Königshafen, a small sheltered bay on northern Sylt formed during the latest Holocene and suggested that input from dune sand from westerly directions and the formation of a sand spit system have caused substantial morphological changes up to

the present time. Before the formation of Ellenbogen 2250 to 1300 years ago, Königshafen was sheltered by a large sandy spit that developed between 5000 and 6000 years BP (Lindhorst et al., 2008). Ahrendt & Pesch (2001) applied GIS to illustrate the spatial distribution of sediment layers and suggested that offshore northern Sylt the base of the Holocene is situated at a depth of 20-30 mbsf. The sea bed morphology and the Lister Tief tidal channel show a complex configuration of different bed forms with moving sand waves. A sand-wave migration rate of 80 m pr. year has been measured (Hennings & Herbers 2006). Small-scale ripples and dunes are superimposed on large dunes up to 11 m high and often with a crest to crest distance that exceeds 300 m (Hennings & Herbers 2006). Hennings & Herbers also reported ebb dominated dunes to the north and flood dominated dunes to the south. Thus parts of Lister Deep have previously been in-

vestigated in some detail whereas the remaining area offshore northern Sylt has not been imaged in detail. This is in contrast to the rather detailed studies carried out onshore Sylt (Lindhorst et al., 2008; Lindhorst et al., in press.).

Bathymetry

Bathymetric and sparker seismic track data (Lindhorst et al. 2008, Fig. 1) and another recently published sea floor topographic map (Hennings & Herbers 2006) are in overall agreement with the depth-to-seabed map based on the acquired seismic profiles (Fig. 2). However, depth variations are shown in more detail in the bathymetric data (Fig. 2). West of Sylt the approximately uniform increase in depth to the west is
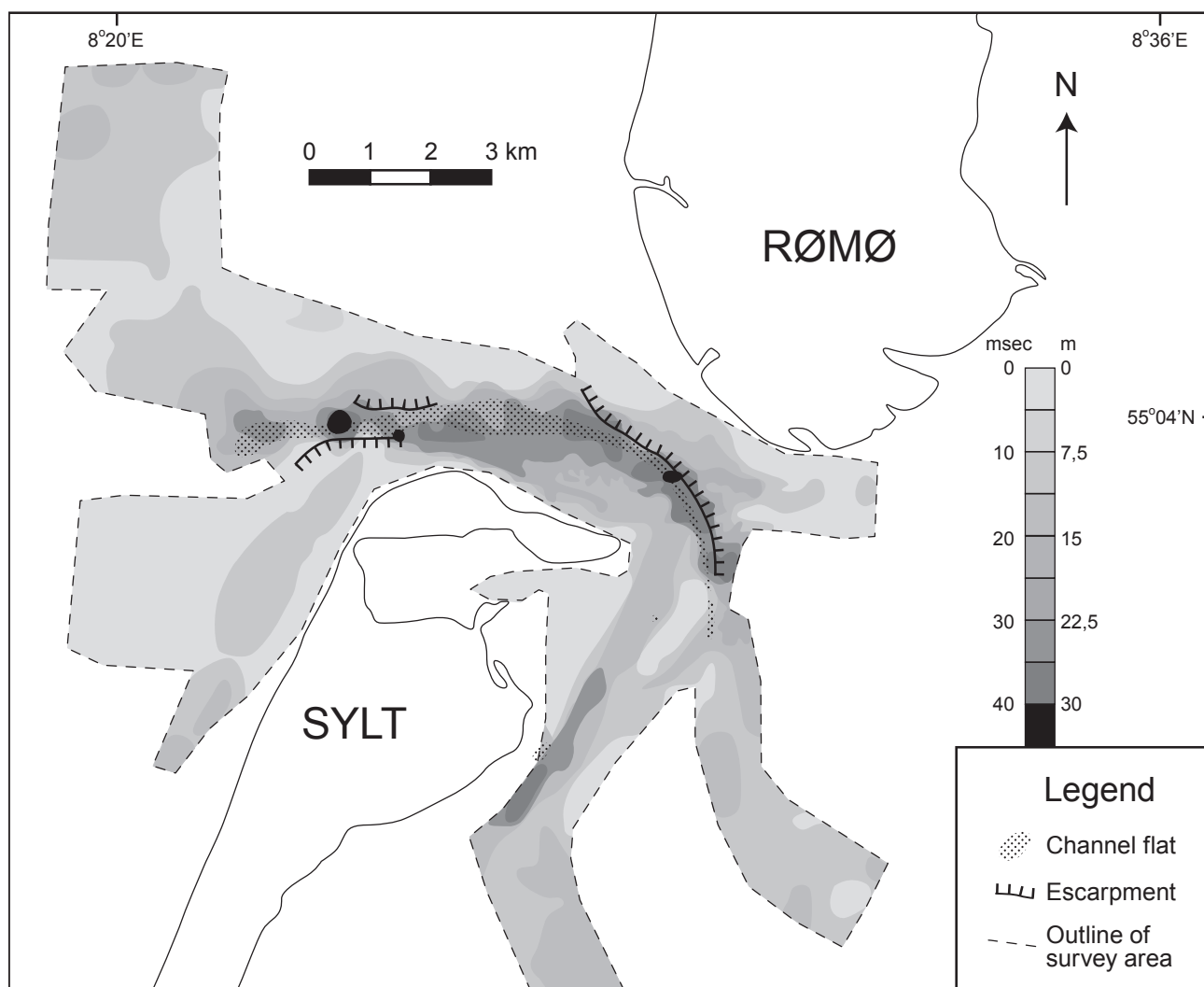

Fig. 2: Bathymetric map based on the sparker-seismic profiles acquired in this study along with locations of erosional escarpments and flatbased channel as interpreted on the sparker and Chirp III data. Depth in TWT sec. Depthlegend in TWT sec and m.

disrupted by a shallow channel striking approximately NNE-SSW (Fig. 2). The channel meets a NW trending topographic high (marked as E on Fig. 1), not connected to the island, located some 750 m from the coast NW of Sylt. Further seaward in a north-western direction, ca. 2.5 km off the coast, the seabed deepens to around 18 m and an ENE trending depression leads towards the main inlet of the Lister Tief. This channel area continues further to the NNE and becomes the Lister Tief. Bathymetric maps (Figs. 1 & 2) display that the sea-floor topography show a curved channel (marked as channel flat in Fig. 2) running in a SE-NW direction as also seen by Hennings & Herbers (2006). Channel depth locally reaches 35 m. On the eastern side of Sylt two additional channels are found: One parallel to the SSW-NNE strike direction of the island – the Lister Ley (marked as A on Fig. 1) - which is deepest (ca. 25 m) in its western part, the other – the Højer Dyb (marked as B on Fig. 1) - is found further to the East with a maximum depth of 14 m. The Königshafen tidal area at the northern part of Sylt (marked with a C on Fig. 1) consists of tidal flats separated by a meandering main channel. East of Lister Tief a narrow NE-SW trending channel – the Rømø Dyb (marked as D on Fig. 1) - is leading up along the SE coast of the Danish island of Rømø.

Data and Methods

High-resolution seismic data were acquired in 2006-2009 by the use of AWI (Alfred-Wegener Institute for Polar- and Marine Research, Wattenmeerstation Sylt, Germany) research vessel Mya, a small catamaran vessel with draught of 0.65 m. The data acquisition was part of a collaboration project between AWI, IGG (Department of Geography and Geology, Copenhagen University, Denmark), and GEUS (Geological Survey of Denmark and Greenland), with participation in 2005 by University of Kiel (RV 'Littorina') and in 2007 and 2009 by University of Hamburg. The weather conditions were excellent to very good for four of the five cruises whereas the 2007 data were acquired under more unfavourable sea state conditions.

The sparker data were acquired in 2005-2008 as single channel data. The ship speed was held at 5 Kts and the distance in time between consecutive shots was set to 0.5 sec. The vertical resolution of the data is approximately 0.5 m. The quality of the raw sparker data was improved by processing using the software ProMax. For the data acquired during the surveys carried out in 2005, 2006 and 2008 the processing included: Gain correction and Band Pass Filtering. In addition to these two processes the data acquired in

2007 were subject to F-X decon and dipscan in order to reduce noise. The data reveal a sub bottom depth penetration of 0.1 s TWT (Two Way Travel time) corresponding to 80 m applying a velocity of 1600 m/s for sediments. Sea floor multiples are present on all data and the data are single fold. The sparker-seismic data are measured in TWT s. Where depth in meters is mentioned, a velocity of 1470 m/s has been used for sea water.

For detailed investigations of the upper ca. 20 m of the sub-sea floor a high-resolution Chirp III sub-bottom profiler system was used in 2009 towed at a ship speed of 5 Kts. The Chirp III is able to operate in two frequency bands; 2-7 kHz and 10-20 kHz. The data were acquired with the low frequency band that provides a good compromise between sea-floor penetration and resolution of 15 cm. The Chirp III data are of good quality in spite of multiples and, in some cases, interference of the out and in going signal.

Both data sets were interpreted on a workstation using GeoGraphix software. The seismic profiles were interpreted applying the principles of seismic stratigraphy where boundaries of seismic units are mapped by the use of reflector terminations. The internal reflection pattern interpreted, along with the outer shape of the seismic units, enabled identification of individual geological structures e.g. bed forms and erosion scars. The large number of 2D profiles enables us to get a 2.5D image of local structures. In cases where dunes were crossed at right angles by the seismic profiles, the direction of the dune migration was interpreted as either flood or ebb oriented. However a number of poorly defined, often nearly symmetrical, dune structures are located outside the major dune fields and in these cases the dunes have been termed "indefinite". When present in areas clearly dominated by either flood or ebb transport, the sediment transport direction of these dunes has been concluded accordingly. Generally, our data confirm the bed form configuration observed in the Lister Tief by Ulrich & Pasenau (1973); Hennings et al. 2004 and Hennings & Herbers (2006).

The data, which were acquired during the 5 years field observations, show consistency in the location of the mapped larger structures, but the individual dunes can not be correlated on intersecting profiles of the various surveys. This is explained by the fact that the larger dunes move considerable distances per year (80 m/year Hennings & Herbers 2006 and 60 m/year Ulrich & Pasenau 1973).

Interpretation

From the interpretation of the seismic profiles we identify the following groups of structures: dunes of various sizes, escarpments and other erosional features, flat-channel-floor environments, large-scale foresets, and in addition, areas characterised by non-deposition interpreted as sediment by-pass corridors (Fig. 3).

1. Transverse dunes

A large number of dunes of various heights and lengths have been identified on the sparker and Chirp III profiles. Most of the dunes appear as individual structures on the sparker profiles but complex dunes where two or more individual structures merge are also present (Figs. 4-9). Smaller structures not resolved
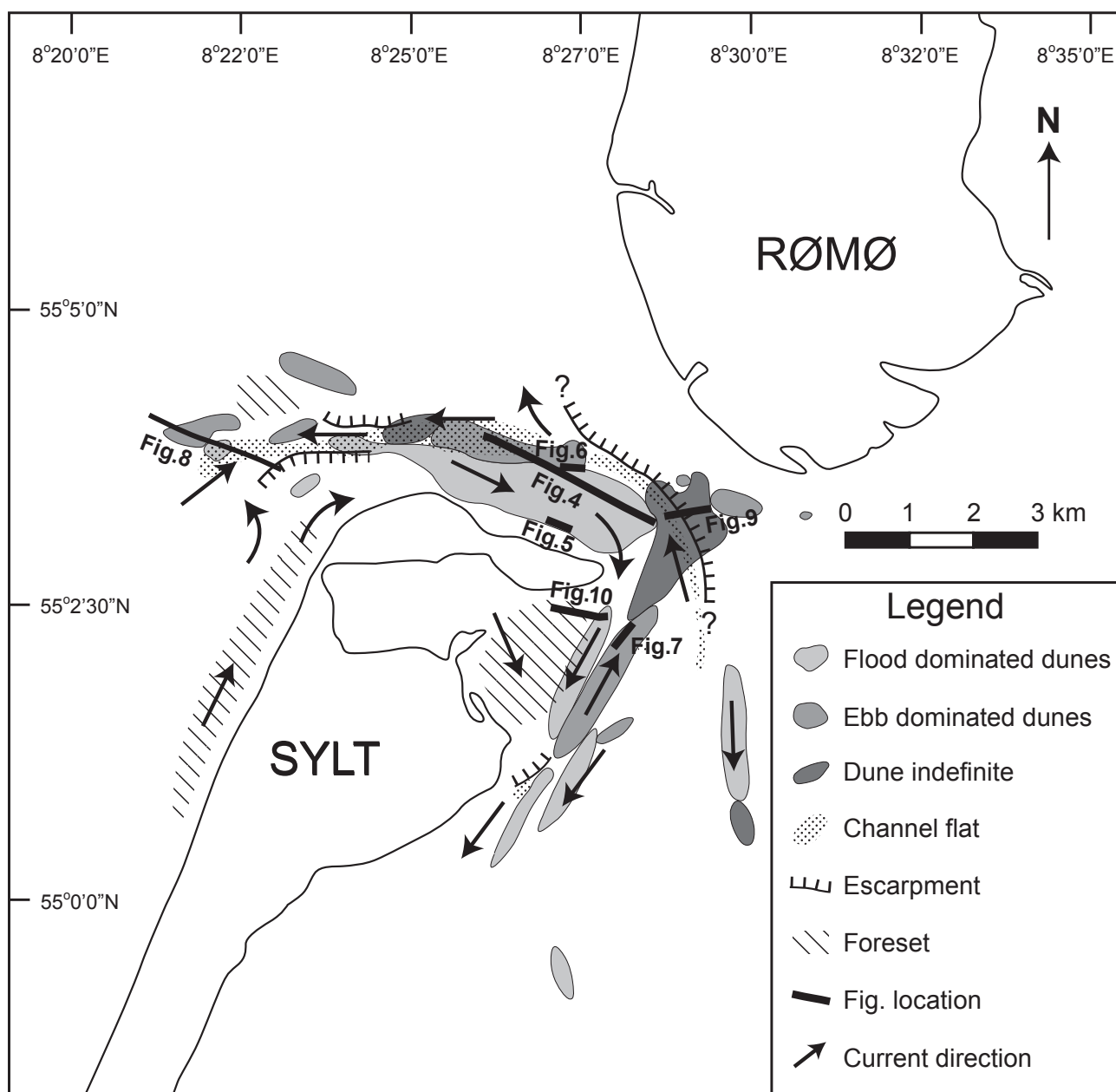

Fig 3: Facies map showing the distribution of observed bed forms, interpreted current directions and figure location.

at the seabed displayed in the sparker records can be documented by the Chirp III acoustic images (Figs. 5 & 7). Internal structure of the dunes and the underlying units can be studied in detail as available of the scale of seismic resolution (0.5 m for sparker profiles and 15 cm for Chirp III data). The Chirp III data, in particular, show remarkable details in the internal construction of dunes (Figs. 5, 6 & 7). The dunes have a slightly inclined stoss side and a rather steep lee side and display internal progradation (Figs. 4-8). In most cases the dunes overly older dune structures or were deposited on flat surfaces (Figs. 5-7) sometimes bounding well-defined foresets below (Fig. 8). They can also be found in the channel floor areas (Figs. 8-9). Dune structures showing similar orientations can be followed on parallel seismic profiles. This gives the overall orientation of the dunes as being transversal and oriented almost perpendicular to the coast, as can also be seen on sidescan data from Lister Tief and on acoustic soundings data (Hennings et al. 2004; Ulrich & Pasenau 1973). Along some of the seismic profiles parallel to the strike of Lister Tief and the Lister Ley the asymmetry of the dunes is in the opposite direction, indicating two apparent directions of sediment movement (Figs. 4 & 8). The geographical distribution of the dunes shows that the dunes are located in individual areas according to their orientation (Fig. 3). The dunes in the Lister Tief and Lister Ley seem to be oriented according to the direction of the flood and ebb dominated tides. Flood dominated structures are found in four individual areas: at the entrance to the Lister Tief and within the Lister Tief near the coast of Sylt in a large area up to approx. 4 km long and approx. 1 km wide, along the channel flanks in the central part of the Lister Ley, and in the Højer Dyb (Fig. 3). The length and height of the structures vary in such a way, that the smaller types are found in the sector of the dune field facing the incoming tide with a gradual increase in dune size in the inflow direction. The largest forms are found in the NE part of the dune field in the Lister Tief where the dunes wavelengths are up to 350 m (extension at the sea floor) and 8 m high (Fig. 4). Based on the results of Bartholdy et al. (2002, 2005) from a similar environment in an inlet north of the study area (Grådyb) this most likely signals a grain-size difference, where the largest compound dunes are formed in medium to coarse grained material.

Ebb dominated dunes are found in five areas; to the west and north of the inlet to the Lister Tief, in the western part of Lister Tief to the north of the flood dominated dune field, at the north-eastern part of Lister Tief, and in the middle and eastern side of the northern part of the Lister Ley (Fig. 3). The length and height of the structures vary but the dimensions of the ebb dominated dunes seem to be smaller than those of the flood dominated bed forms (Fig. 4).

From the 2D seismic sparker profiles a number of other dune structures are apparently lacking the characteristic shape that indicates direction of sediment transport movement (Figs. 4 & 9). Theses structures are found in four places: at the western part of the Lister Tief, in the eastern part of Lister Tief where it meets the Lister Ley, in the central part of the Lister Ley, and in the Højer Dyb (Fig. 3). At all these locations the structures are located in an area in between the flood and ebb dominated dune fields. The only exception is the Højer Dyb where the structures are located immediately to the south of the flood dominated dunes. This strongly suggests that either the structures have been crossed at too small an angle (unlikely), or that the structures are exposed to a varying current regime which shapes the structures such that they do not belong to either flood or ebb dominated environment. These structures are located in an area exposed to the interference of changing current systems.

2. Erosional features

The seismic stratigraphic interpretation shows that pronounced erosion of former deposits occurs as erosional truncation is observed at the sea floor at four locations. Two of these locations are found at the inlet of the Lister Tief, the third along the north-eastern part of Lister Tief, and the fourth in the Lister Ley close to List (Figs. 2, 3, 8 & 9). The erosional scar at the inlet of the Lister Tief, at the landward side of the flood dominated dunes of the inlet, cuts into the north-eastern part of the NW-trending high extending from Sylt. The scar zone is 600 m wide and is at about 20 m depth (Fig. 8). At the seaward side of the Lister Tief inlet, a scar is located west of the flood dominated dunes with evidence of erosional activity towards NE. The scar here is 150 m wide and 10 m high. Along the northern flank of the Lister Tief a pronounced erosional scar zone is observed to the north of the flood dominated and the "indefinite" dune area (Fig. 9). The zone is up to 26 m wide and up to 10 m high (Fig. 9). The northern and southern extension of the escarpment is outside the data coverage. At the eastern coast of Sylt, towards the north, an abrupt apparent erosional scar is found which is app. 120 m wide and up to 9 m high (Fig. 3). It can, however, not be excluded that this feature is part of a progradation system from a different direction.

3. Flat channel floor

On parts of the seismic profiles the sea floor is remarkably flat in two areas. Combining observations from all the seismic profiles it is found that a large continuous area with a flat channel floor is found from the inlet of the Lister Tief, along the northern flank of the Lister Tief and following the Lister Tief around the northeastern extremity of Sylt into the Højer Dyb (Figs. 2, 3 & 9). On the flat channel floor some dune structures are found (Fig. 9). The flat channel floor forms the deepest part of the surveyed area and is found immediately south of the continuous erosion scar observed in the Lister Tief (Fig. 3). At the seaward entrance to the Lister Tief the flat channel floor occurs west of the scar but landwards of the flood dominated dune field (Figs. 3 & 8). The width of the flat channel floor area is largest at the western inlet of the Lister Tief where it reaches approx. 270 m and narrows in an eastern direction being only 25 m at the entrance into the Højer Dyb. The other area of a seemingly flat channel floor is located in the western part of the Lister Ley close to List (Fig. 3).

At the entrance to the Lister Tief, ca. 300 m north of the main channel, the western part of an abandoned channel at least 300 m wide is located by one sparker profile. The channel extends to the north of the sparker profile. On the crossing profile, pronounced infill is seen in the channel. The inclination of the southern flank and the depth to the base of the abandoned channel resembles the present day channel south of here. The width of the two channels is also in the same range.

4. Large-scale Foresets

Large-scale foresets or clinoforms are observed in three areas (Fig. 3). The largest foreset system is found at the seaward side of the flat channel floor area at the North Sea inlet to the Lister Tief (Figs. 3 & 8). The direction of sediment movement is towards the East. Another group of foresets is found along the western coast of Sylt in the small NNE trending channel (Fig. 3). Here the foresets show that the direction of movement is to the NNE. The third location is in the Königshafen area (Figs. 3 & 10). Here the precise direction of foresets can not be estimated; however they seem to reflect sediment movement from the coast of Sylt into the Lister Ley.

5. Areas of non-deposition

In two areas no depositional features are present at the sea floor. One, in the westernmost part of the study area and the other, in the flat-channel-floor area, associated with the Lister Tief.

Discussion

Sparker data image the bedform configuration at the sea floor and display subsurface penetration to approx. 0.1 s TWT (ca. 75-100 mbsf (meters below sea floor)). These data are supplemented by Chirp III data that show details down to ca. 15-20 mbsf with a vertical resolution of approx. 3.5 times greater than that of the sparker data. From the interpretation of the seismic and subbottom profiler records a number of different geological structures can be identified. Among the observed bed forms, the dunes show sediment transport direction and prevailing sedimentation regime in the study area. The interpretation of the seismic profiles also reveals other large-scale, current-induced sedimentary systems enabling the compilation of a map illustrating an overall model for long-term sediment distribution and inferred bottom current regime responsible for sediment transport in the area (Fig. 3).

From the seismic data, the characteristic lee and stoss-side configuration of the dunes are identified and this is supported by information from sounding profiles and side scan sonar data (Ulrich & Pasenau, 1973; Hennings et al. 2004). Along some seismic profiles dunes indicating opposite current directions are found (Fig. 4). The spatial distribution of the transverse dunes shows two groups based on direction of sediment transport, which are ascribed to flood and ebb dominated tidal regimes as also suggested by Ulrich & Pasenau (1973), Hennings et al. (2004), and Hennings & Herbers (2006) (Fig. 3). Apart from these flood and ebb dominated dunes a third group of bed forms at the sea floor is identified. These are presumably also dunes, but were either crossed at oblique angles by the seismic profile or found in an environment strongly affected by both flood and ebb current activity and are therefore, called here "indefinite" dunes (Figs. 3, 4 & 9). Moreover, on some sparker profiles it is observed that some dunes are complex and appear to consist of a superimposed dune system, in contrast to most of the other dunes that seem to be singular, structures. Due to the higher resolution of the Chirp III data, these individual structures are identified as being made up of a number of smaller structures e.g. ripples or small scale dunes (Figs. 5 & 7) that all migrate in the same direction as the overall pronounced single standing dunes. Sometimes a merg-

ing of the small scale structures is observed. Similar findings based on sidescan data from the Lister Tief are also reported (Hennings & Herbers 2006).

As referred to before, in the Lister Tief the ebb dominated dunes are found located to the north of the flood dominated dunes and south of the flat channel floor area. This is expected as the flood oriented dunes most likely formed due to the Coriolis force acting on the flood current. In the northern part of the Lister Tief the ebb dominated dunes are found in the central part of the channel. In the Rømø Dyb the ebb dominated dunes are found in a shallow area NE of the large erosional scar.

Pronounced erosiononal scars are found at the sea floor where erosional processes cut into older deposits (Figs. 3, 8 & 9). From the entrance to the Lister Tief and along its northern boundary towards the entrance to the Højer Dyb a pronounced flat channel floor area, locally with some isolated dune structures, is found immediately south of the erosional scar. This area is located north of the flood-dominated dune fields (Fig. 3). The width of the channel varies and is largest in the western part of the Lister Tief, while narrowing markedly towards the NE.

Foresets are observed extending along the western coast of Sylt towards the entrance of the Lister Tief. They are also found at the seaward entrance of the Tief and in the Königshafen area (Figs. 3, 8 & 10).

In the seaward area our data indicates mainly non-deposition, i.e. sediment bypassing prevails in these areas.

Along the west coast of Sylt the presence of the elongate channel striking NE-SW indicates significant current action concentrated here. Accordingly, foresets observed here show a NE sediment transport direction all the way up to the northern end of Sylt where an elevated area acts as a barrier forcing the current transport path to bend seaward and/or to pass between this high and the coast of Sylt (Fig. 3).This reflects a northward sediment transport system along the coast of Sylt towards the Lister Tief. The flood-dominated dune field north of Sylt is seen in its overall form to be rather stable although individual structures do move. From side scan sonar (Hennings et al. 2004) data we see that the dunes are transverse and migrating, which concurs with our observations. The location of the dune field implies that a major deposition area is found in the Lister Tief immediately north of Sylt which is also reflected by the coastline configuration (Fig. 3).

North of this flood dominated dune field an ebb dominated dune field is located. The spatial extent of this dune field is smaller than found for the flood dominated dune field, whereas the individual dune structures are also smaller. Along the northern side of the ebb dominated dune field a flat channel floor area is found in the deepest part of the Lister Tief. As de-scribed before, the width of the flat channel floor area varies. This suggests that current speed is strongest in the areas where the channel is most narrow. From the observation of the distribution of the flood and ebb dominated dune fields in relation to the nature of the flat channel floor area and adjacent erosional scar, it is suggested that bottom current action here is dominated by the ebb tide, which due to Coriolis force, causes the strongest erosion at the northern slope of the Lister Tief (Fig. 3). More to the west, where the flat channel floor area and the erosional scar diverge, i.e. roughly midway in the Lister Tief, bifurcation of the sediment transport current is suggested. One branch continues westward through the Lister Tief where sediment are deposited as an ebb dominated dune field, whereas the other branch of the current continues in a northern direction along Rømø and loses speed here, leading to sediment deposition SW of Rømø.

Where the Lister Tief and Lister Ley meet at the NE extremity of Sylt, a large number of indefinite dune structures not attributable to either flood or ebb dominated processes are observed. These are located in an area where strong flood and ebb currents meet and this likely causes highly turbulent and complex hydrodynamic condition, with strong gyre formation, affecting the dune configuration in this area. Also, further south in the Lister Ley, indefinite dunes are observed that may reflect interaction between currents from the Lister Tief, Lister Ley and Højer Dyb combined with current processes originating from Königshafen Bay.

In the Königshafen area the water depth is very shallow and foresets point to a transportation direction from west to east in the platform areas, but as the area is virtually dry during ebb tides it is suggested that the foresets are not related to the present current regime but may be the result of older sedimentation processes (e.g. overwash, aeolian transport) originating from the west and directed towards the east, as suggested by Bayer & Higelke (1994). At the eastern termination of the foresets, flood dominated dunes are found in the Lister Ley and the dunes continue in a southward direction. An apparent erosional scar is located at the south western termination of the foreset area and the erosional scar and flood dominated dune structures concur with Corioli forcing of the incoming flood current controlling sediment transport here. In the central part of the Lister Ley a larger ebb dominated dune field is located showing that here northward directed currents are responsible for sediment movement. In the northern part of Højer Dyb flood currents controlling sediment movement appear to dominate again (Fig. 3)

The mapped bed form and channel configuration with the proposed sediment transport model for the Sylt Rømø area strongly resembles the overall model of an ebb tidal delta suggested by Hayes (1980). It was

suggested that well developed ebb tidal deltas occur in areas of large tides and smaller wave heights, which seems to apply to the Lister Tief area.

Furthermore, the results of the presented work show similarities to the work from ebb-tidal delta of Texel Inlet further south in the Wadden Sea (Sha 1990). The Marsdiep separates the barrier island Texel from the mainland at Den Helder. Using the results of the analysis of a large number of box and gravity cores, it was found that flood dominated bed forms are located along the coast of the mainland south of the inlet, and in the southern part of the Marsdiepnear Den Helder. In the northern part of Marsdiep ebb-dominated bed forms with a height of up to 3 m were found. It was shown that the flood dominated bed forms in the tidal inlet are up to 8 m high and thus considerably larger than the ebb dominated bed forms. Comparing the results of Sha (1990) and the present work shows, that Marsdiep and Lister Tief are comparable, both acting as ebb channels. The bed form distribution shows that flood dominated bed forms are located in the southern part of the inlet and that ebb dominated bed forms prevail in the north. In both areas the flood dominated bed forms are larger than the ebb dominated ones. A schematic diagram showing the morphology of ebb-tidal deltas based on examples from inlets of West Frisian Islands is shown by Sha (1990). Applying this diagram to the present study, reveals similarities suggesting that the Lister Tief is the main ebb channel. In the Sylt area, the flood channel is probably represented by the shallow channel and zone of non-deposition located along the west coast of Sylt. Landwards of the Lister Tief the flood and ebb current act on a smaller scale in the Lister Ley and the Højer Dyb, and still show flood, ebb and indefinite bed forms indicating the transitional zone between these two sediment transport current regimes. From the dataset it thus seems likely that the northern part of Sylt is building further to the north and Rømø is being enlarged to the southwest which may be associated with continued erosion at the escarpments and a further deepening of the Lister Tief.

Conclusion

A large number of high resolution 2 D seismic (sparker and Chirp III) profiles have been acquired during the period 2005 to 2009. The data reveal bedform configuration and sub-bottom structures to a depth of 75-100 mbsf for the sparker data and ca. 20 mbsf for the Chirp III data and thus add valuable information to previously obtained sidescan seabed information. The data show several geological and dynamic bed form features, i.e. flood and ebb dominated dune fields, flat channel floor areas, a large continuous erosional scar as well as evidence of smaller scale erosion. The dunes are transverse type with varying dimensions and a maximum length of up to 350 m and height up to 8 m. The investigation carried out here indicates that sediments are transported along the western coast of Sylt towards the entrance of the Lister Tief. In the Lister Tief near Sylt a very large, flood-dominated dune field is found. More to the north in the Lister Tief a flat channel floor area with a large erosional scar cutting the northern slope of the Tief and ebb dominated dunes have been found. This shows that ebb dominated currents control sediment transport and erosion processes in the northern sector of the Lister Tief. In the western part of the Lister Ley channel foresets prograde from the Königshafen area into the channel where they terminate in an area characterized by flood dominated dunes. In the eastern part of Lister Ley flood dominated dunes are also present, while in-between outgoing, northerly ebb currents govern sediment transport. Evidence for erosion and northward sediment transport along the west coast of Sylt with deposition along the north coast of Sylt is also reflected by the beach development in this area. The seismic data indicate narrowing and deepening of the Lister Tief at the same time as significant sediment deposition occur SW of Rømø. In the main, the proposed sediment transport model for the Lister Tief tidal inlet areas is in overall agreement with models suggested by Hayes (1980) and Sha (1990). The present study applying different acoustic techniques thus adds important information to our understanding of sediment transport patterns in a Wadden Sea tidal inlet.
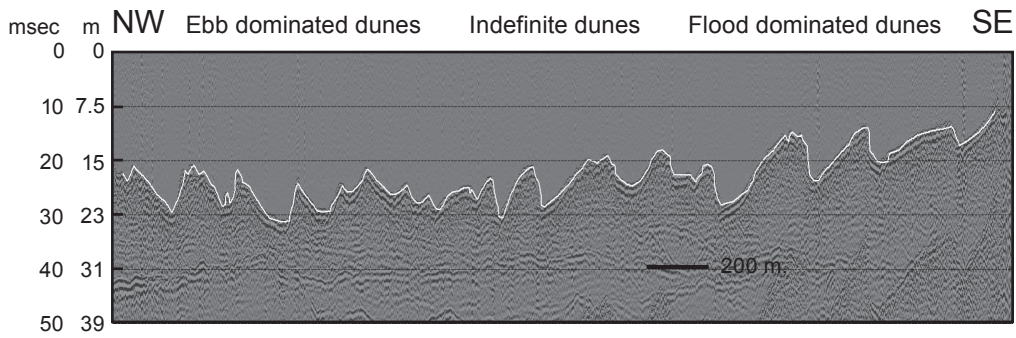
Fig. 4: Sparker profile from the central and western part of the Lister Tief showing flood and ebb dominated dunes. In between "indefinite" dune structures are located. Internal structures are seen in the upper part of the dunes. Vertical scale is in msec TWT and in m (velocity of soundwave in water 1500 m/s and 1600 m/s for sediments). For location of profile see Fig. 3.
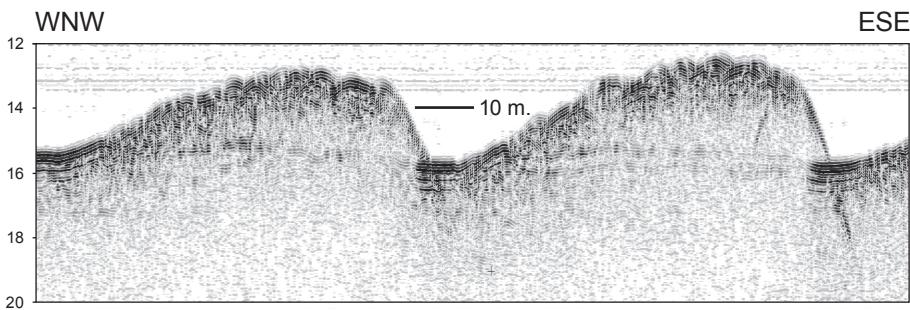

Fig. 5: Chirp III profile from the southern part of Lister Tief. This figure shows large, up to ca 3 m high dunes with an inferred sediment transportation to ESE indicative of flood dominated dune structure. The dune is located on top of a marked, horizontal reflector found at 15-16 m below present sea level. In several cases this reflector is seen to outcrop in the trough in between the dunes and presumably consists of a pavement of coarser sediment. Reflectors revealing internal structures are seen in the upper part of the dunes. The surface of the dunes is seen to be made up of smaller structures. Depth in m. For location of profile see Fig. 3.
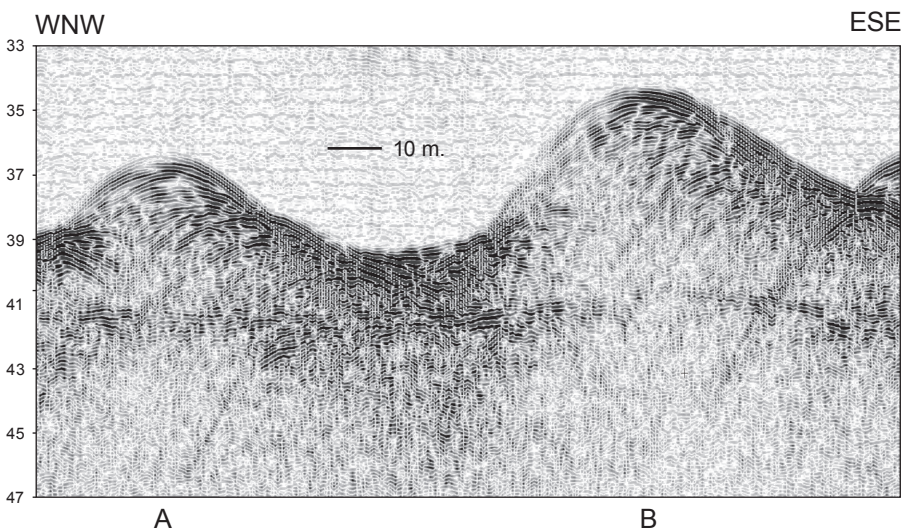
Fig. 6: Chirp III profile from the central part of the Lister Tief. The figure shows 4-5 m high dunes with a marked internal (foreset) reflection pattern typically indicating sediment transport conform to the topographic asymmetry of the dune which in this case is ebb dominated and thus towards the WNW. This is most clearly demonstrated in case of dune B at the ESE part of this profile. Note that in this case a mainly (sub) horizontal reflector is seen at a depth of 40-41 m, i.e. well below the depth of the horizontal reflector described in Fig. 5 and 7. In the case of dune A the reflector at a depth of 40-41 m is slightly upbending likely due to velocity pull up effect. Depth in m. For location of profile see Fig. 3.
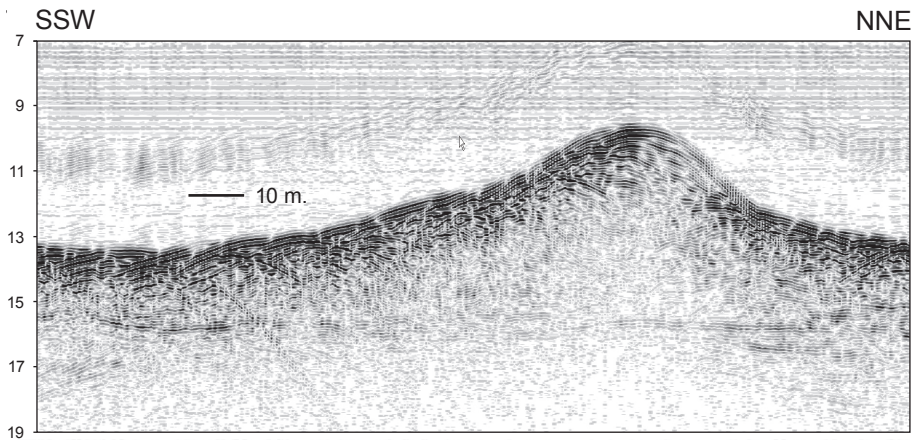
SSW   NNE

Fig. 7: Chirp III profile from the northern part of the Lister Ley. This figure shows a large, up to ca 3 m high dune with an inferred sediment transportation to NNE indicative of ebb dominated dune structure. Internal reflector pattern is seen within the dune indicating that the dune is migrating towards the NNE. The dune is located on top of a marked, horizontal reflector found at 15-16 m below present sea level overlain within the trough by a few meters of (sandy) sediments. This reflector which continues below the sand waves thus appears to form the base of the (migrating) dunes. From our data set it can not be determined with confidence, whether the reflector represents an older, early Holocene transgression horizon, or has been formed in relation to later dune formation and migrational processes. Depth in m. For location of profile see Fig. 3.
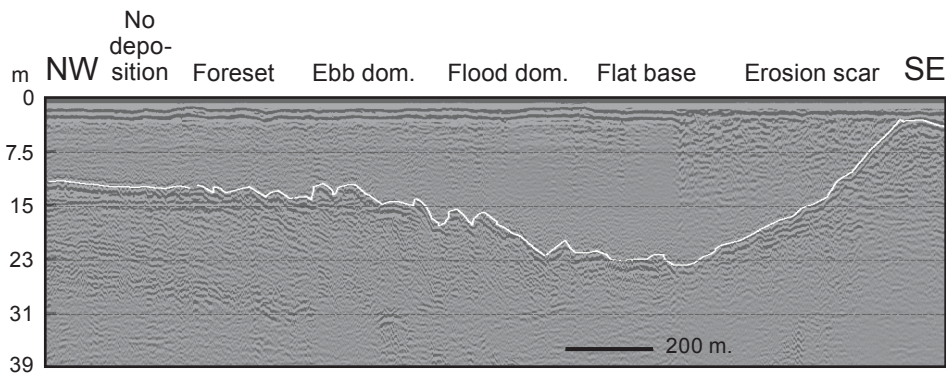
Fig 8: Sparker profile at the outer entrance to the Lister Tief showing erosion scar in relation to the topographic high NW of Sylt, a flat channel floor area, flood and ebb dominated dunes and area of no deposition. At the NW part foresets are seen in a depth interval of ca. 2-20 m below sea floor. Vertical scale is in msec TWT and in m (velocity of soundwave in water 1500 m/s and 1600 m/s for sediments). For location of profile see Fig. 3.
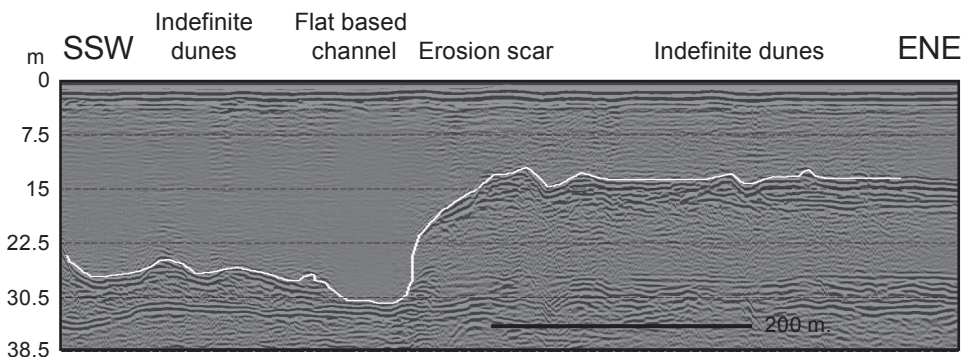

Fig 9: Sparker profile from the eastern most part of the Lister Tief showing a pronounced erosional scar, flat based channel, and "indefinite dunes" in the channel and at a higher level ENE of the erosional scar. Vertical scale is in msec TWT and in m (velocity of soundwave in water 1500 m/s and 1600 m/s for sediments). For location of profile see Fig. 3.
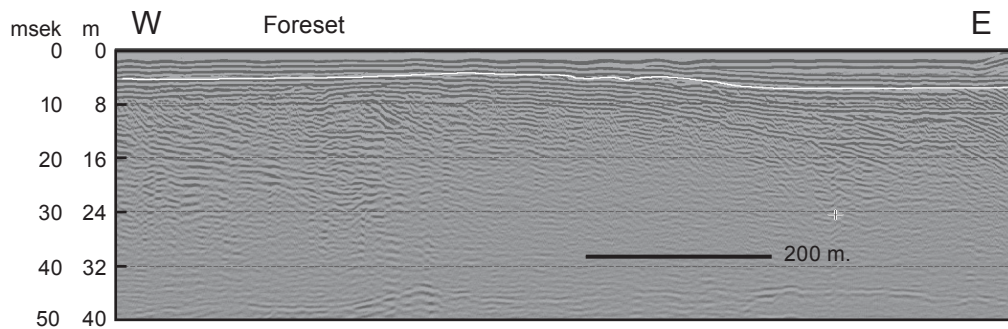
Fig 10: Sparker profile from the Königshafen area showing foreset indicating an eastern direction of sediment transport. Vertical scale is in ms TWT and in m (velocity of soundwave in water 1500 m/s and 1600 m/s for sediments). For location of profile see Fig. 3.

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