Sedimentology of a large field of lunate shaped bedforms in the Fehmarn Belt, Baltic Sea

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ABSTRACT: We discuss formation mechanisms of bedforms in the Fehmarn Belt, Western Baltic Sea based on their morphology and sedimentology. Characterised by the isolated occurrence and their lunate or crescentic shape at some instances the morphology resembles barchanoid dunes. The central part is of height O(1m) and often two tails of lengths in O (100 m) predominantly open towards the South-East, suggesting an active migration towards this direction. New data from a multibeam echo sounder survey, sediment cores and subbottom profiles reveal morphodynamics, sedimentology, and the internal bedding and challenge previous assumptions on the formation and dynamics of the bedforms.

1 INTRODUCTION

In the microtidal Western Baltic Sea, the occurrence of different bedform fields has been observed in earlier studies. Besides a prominent compound bedform field in medium to coarse sands (Feldens et al. 2014, Krämer et al., this volume), other assemblages of large, flow transverse bedforms occur in water depths exceeding 20 m (Fig. 1).

Figure 1. Location of the investigation area in the Western Baltic Sea. The white line surrounds the lunate bedform field. Indicated in red are the positions of short sediment cores. The scale bar is 30 km.

These low-relief bedforms have been reported in a region of about 217 km² in the central Fehmarn Belt. Their height is 0.5–1.0 m and about 50 m wide. The distance between the individual features is in the order of a few hundred meters. The crescentic planform geometry resembles barchanoid dunes, often with two tails of lengths in O(100 m) opening towards the E or SE.

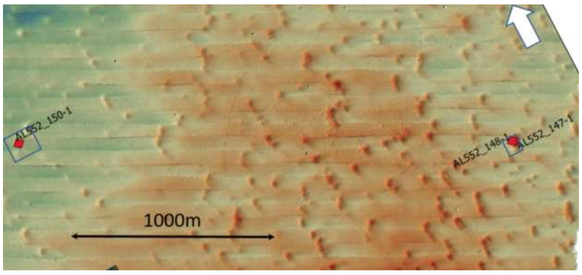

Figure 2. MBES bathymetry subset of the lunate bedform field in between different core locations NE of Fehmarn island (ref Fig. 1)

Jensen et al. (2003) termed these features *isolated sand-silt waves* because of their solitary occurrence in muddy to fine sediments. Based on a limited set of observations, they were first described as “NE-SW striking ridges of considerable length” without a clear asymmetry or preferred orientation. The authors noted that the features occur on various substrates ranging from late glacial clay in the western part of the Fehmarn Belt to Holocene marine mud in the eastern part of the strait.

The whole extension of the so called *lunate bedform field* was revealed by a large scale multibeam echo sounder (MBES) mapping in the framework of the environmental impact assessment for the large Fehmarn Belt tunnel construction (FEHY, 2013). In water depths of about 25 m, many similar bedforms of characteristic shape were identified as regularly spaced with distances between individual features of a few hundred meters, on an area of 217 km² (Fig. 1). The report assesses the bed roughness and speculates on a high activity of the bedforms i.e., migrations in the order of several meters per annum towards the NE or SW, however, based on a rather crude assessment of local sediment transport potential.

The lunate bedforms are also briefly mentioned in a habitat mapping report by Schwarzer & Unverricht (2020). They observed 350 of these features by side-scan-sonar mappings and subbottom profiling, described their heights of about one meter, a width of 50 m and a mean distance of 145 m between individual forms. The authors also mention internal cross-beddings that suggest a migration towards the NW during their formation. Underwater videos showed a high abundance of shells and living bivalves on the bedforms – in their study, interpreted as an indicator of recent low dynamics.

Although the existence, distribution, and role as roughness elements on the local hydrodynamics has been described before, the discussion on the genesis, morphology, and dynamics of these bedforms are still not conclusive.

The morphology and sedimentology of these bedforms is interesting, as they resemble a unique and characteristic morphological feature of the geodiversity of the Fehmarn Belt: Amongst active bedform fields (Krämer et al., this volume), adjacent remnants of paleo fluvial systems (Feldens & Schwarzer, 2012), and in a region of complex habitats and extensive human impact.

Analyses of new high resolution bathymetric observations, shallow sub-bottom profiling, and sediment analyses of individual bedforms contribute to the discussion on the formation and transport mechanisms. Data from sediment cores and subbottom profilers reveal the sedimentology, internal bedding, and cross-stratification of the central bedforms.

2 METHODS

Research cruises with the German research vessel ALKOR to the Fehmarn Belt were conducted in 2020, 2021 and 2022. During the expeditions, the bedform field was investigated by multibeam echo sounder mapping, parametric echo sounder profiles, gravity coring and bed surface sediment grab sampling. Grain size distributions were measured in the CAU Kiel, sedimentology laboratory.

We used a NORBIT - iWBMS STX with RTK positioning to measure high-resolution bathymetry of a part of the bedform field. The sound velocity profile was corrected by regular updates based on CTD casts.

Subbottom profiles were measured with a hull-mounted Innomar SES parametric echo sounder. Settings were optimised for high-resolution data of the first few meters below the seafloor.

Short sediment cores were taken with a gravity corer. Additionally, bed surface samples were taken by Van Veen grab sampling. RTK GNSS positioning and very good navigation by the captain and helmsman allowed the precise sampling of the bedform at defined positions.

Sediment grain size distributions of surface and core samples were measured with a Beckman Coulter LS 13320 Laser Diffraction Particle Size Analyzer in the range of 0,017 µm to 2000 µm.

3 RESULTS

During a series of expeditions, an area of about 6 km² was (re-)mapped with multibeam and parametric echo sounders. The processed high-resolution bathymetry confirms the existence of individual bedforms in heights in the order of one meter, which often feature a crescentic shape with a density of about 50 bedforms/km². Where present, the extremities ("*horns*") resemble the shape of barchanoid dunes, opened towards the SE. Successive surveys indicate little or no mobility of the bedforms.

In the high-resolution MBES data, sharp, angular features, predominately on the Western side of the bedforms, are present. Based on earlier and recent underwater camera observations, these are interpreted as accumulations of mussels and shell fragments, which were also observed on top of the bedforms.

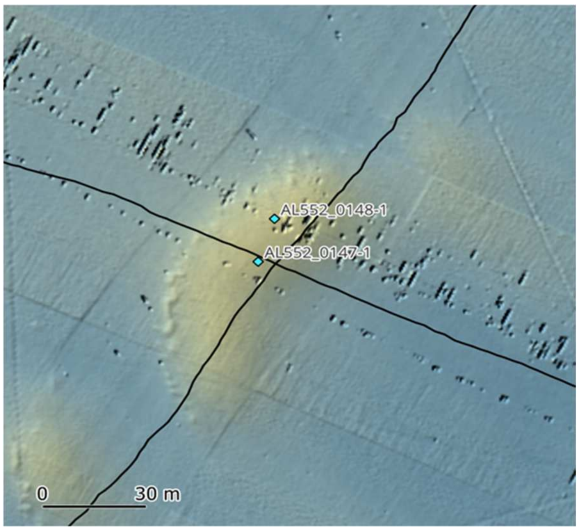

Figure 3. MBES bathymetry of one lunate bedform and position of cores 147-1 and 148-1 near the crest of a lunate bedform. Straight lines N-S and WSW-ENE are trawling marks. Wiggles and gaps at the overlap of NW-SE bathymetric profiles are hydroacoustic artefacts.

The parametric echo sounder reveals subbottom horizontal bedding without characteristic anomalies like acoustic blanking, faults, or others below and between the bedforms (Fig. 4). The internal structure of the bedforms above a continuous horizontal reflector is characterised by internal cross-bedding in multiple sets. The predominant internal bedding is dipping towards the NW, while some sets are also in the opposite direction. These subbottom features are similar at all investigated bedforms.

Several surface samples in between and across the lunate bedforms classified the upper centimeters as silty sand, with varying fractions of 65 to 85% sand, 12 to 30% silt, and less than 7 % clay. Crest samples had up to 10% higher sand content than the surrounding areas (Steinert, 2020).

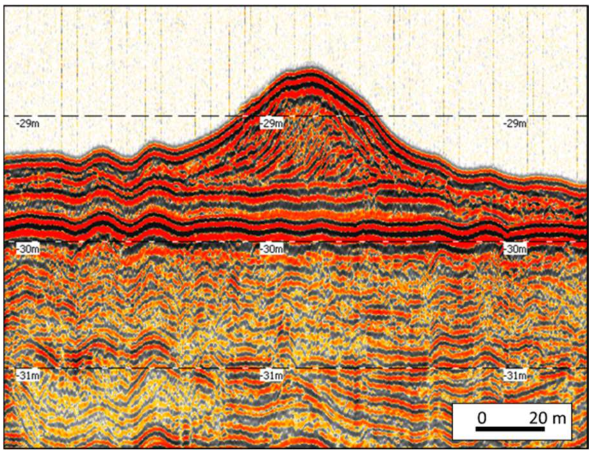

Figure 4. Subbottom profile across the centre of a lunate bedform driven from NW (left) to SE (right). Horizontal lines indicate meter distance in the vertical.

A gravity core taken near the crest of of one of the bedforms (Fig. 3) shows differences between sediments of the bedform, sediments at the base, and the layers below: The bedform itself is composed of bioturbated silty sand with layers of complete and fragmented bivalve and gastropod shells. Below is a layer of 0.2 m of grey muddy sediment, interpreted as a freshwater gyttja deposit. The layers below feature beddings of silty sands and sandy silts in variable thicknesses.

4 DISCUSSION

Previous studies have described the occurrence of a large number of *low-relief bedforms* in the central Fehmarn Belt in the Western Baltic Sea. Their origin, drivers, and development remain speculative so far. Although the lunate or crescentic shapes and isolated occurrence suggest formation in sediment-starved conditions (cf. *barchanoid dunes*) and mobility towards the SE, other characteristics and new field data question this approach.

In this area the (recent) environment is not sediment starved. Mobile fine sands and silts are abundant in variable thickness, also between the individual bedforms.

Furthermore, the interpretation of internal cross-beddings observed in subbottom profiler data does not support SE migration of the bedforms.

In fact, no (residual) mobility was observed throughout three years of observation, although the central Fehmarn Belt is prone to higher current velocities (and sediment transport rates), compared adjacent areas of Mecklenburg Bay and Kiel Bay .

If no connection to recent forcing can be drawn, the bedforms may be relict features. Their origin would then be connected to different stages of paleo-environmental conditions throughout the complex Baltic Sea history (Feldens & Schwarzer, 2012). Besides local emergence, the discussion of the origin and formation mechanisms of relict features must then consider other possibilities, including the breaching of formerly continuous 2D ridges, the various shapes of periglacial geomorphology, aeolian formation during sea level lowstands, and erosive rather than depositional formation. Dating of the sedimentary layers is required, to confirm or reject any of these possible scenarios of bedform formation.

Other ideas on bedform development have been discussed earlier. In FEHY (2013) also pockmarks were mentioned as possible generation mechanisms. In fact, Krämer et al. (2017) show shapes and distributions of pockmarks of somehow similar widespread and low relief character - however, in much different high energetic conditions, other sediments, and with clear subbottom indicators for fluid seepage. The latter are missing in the Fehmarn Belt observations. Also, the resemblance to crescentic comet marks was mentioned; however, no initiation mechanism is evident to support this theory.

Observations of the high abundance of complete and fragmented shells in and above bedforms need better interpretation. Dedicated studies are currently investigating the mutual interaction of seafloor fauna and bedform formation. Further work covers AMS ^{14}C dating of bivalve shell and plant remains for an age model of the sediment cores.

5 CONCLUSIONS

We discuss the origin and development of a large field of low-relief bedforms in the central Fehmarn Belt in the Western Baltic Sea. Despite high-resolution data on the morphology, sedimentology of the features, formation mechanisms and the mutual interactions with sea floor fauna remain inconclusive.

6 ACKNOWLEDGEMENTS

The authors thank captain and crew of R/V ALKOR for their excellent support. We thank the organisers of the MARID conferences for keeping up the spirit and providing a home for bedform enthusiasts.

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