Development of subaqueous barchan dunes due to lateral grain size variability

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Abstract
Bathymetry has been measured in the northernmost tidal inlet of the Wadden Sea using a multibeam echo sounder (MBES) system coupled with long-range kinematic (LRK)-positioning. Dune celerities increase from the centre line of the channel towards the sides as dune heights decrease. This has resulted in straight crested dunes developing into barchan dunes. Flow depth and flow velocity, recorded using an acoustic Doppler current profiler (ADCP), are practically constant across the channel. Bed sampling in the inlet channel has revealed a significant positive correlation between mean grain size and dune height. This suggests that barchan dunes develop due to a decrease in grain size away from the channel centre line. Furthermore, the barchan dunes are in a process of splitting up into smaller dunes adjusting to the decrease in grain size.

Introduction
Studies on subaqueous dunes and dune movement in the field have primarily been based on single longitudinal bed profiles in rivers and tidal channels (e.g. Van den Berg, 1987). Less is known about the lateral shape of dunes. In the Fraser River, Canada, Kostaschuk & Villard (1996) reported dunes with a curved, concave-downstream planform with crests that are continuous for 300 m across the channel. Carling et al. (2000) observed barchan dunes in the River Rhine, Germany, extending c. 120 m across the channel. Recently Dinehart (2002) described dunes in the San Joaquin River, USA, with crests oriented c. 45° from the banks. Barchan dunes can also be identified on the bathymetric data presented by Abraham & Pratt (2002) from the Upper Mississippi River, USA.
The aim of this study is to investigate the effect of lateral mean grain size variability on the development of subaqueous barchan dunes in a 3000 x 650 m section of the Grådyb tidal inlet channel in the Danish Wadden Sea (Fig. 1).

Study area
The Grådyb tidal inlet is located on the Danish west coast between the barrier spit Skallingen to the NW and the barrier island Fanø to the SE and connects the northernmost tidal basin of the Wadden Sea with the adjacent North Sea (Fig. 1).
The tides are semi-diurnal with a mean tidal range of about 1.5 m and a tidal prism in the order of 150×10^6 m^3. The width of the channel is c. 1 km and the mean depth is 10-13 m. The channel is ebb-dominated with maximum ebb and flood current velocities of c. 1.50 and 1.25 ms^{-1}, respectively (Bartholdy & Anthony, 1998). The bed of the channel is composed of sandy material.

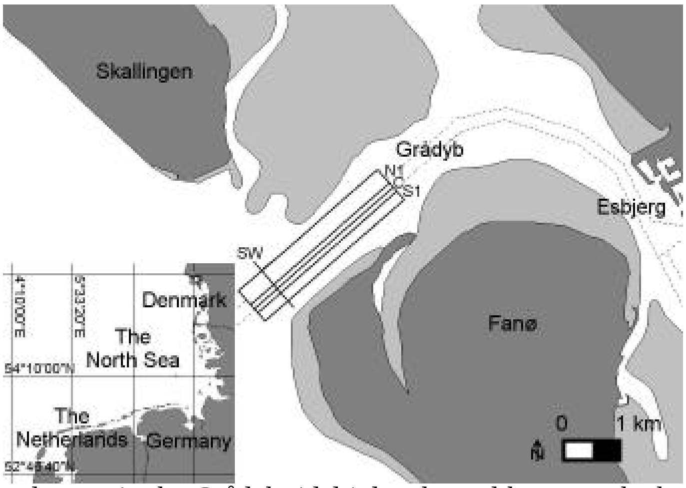

Fig. 1. Location of the study area in the Grådyb tidal inlet channel between the barrier spit Skallingen and the barrier island Fanø in Denmark. MBES surveys in 2002 (see Fig. 2) and 2003 have been conducted in the enclosed area (3000 x 650 m). ADCP measurements in 2003 have been conducted along the lines N1, C, S1, and SW.

Methods

Bathymetric surveys were conducted aboard the RV Senckenberg on the 10^{th} of September 2002 and the 11^{th} of July 2003. The bathymetric data were recorded using a Seabat 8125™ (RESON) multibeam echo sounder (MBES) system operating at 455 kHz and the 6042 v. 7™ (RESON/QPS) data collecting and processing software package. The number of beams is 240 with an along- and across-track beam width of 1° and 0.5°, respectively, yielding a swath coverage of 120°. The ping rate is 40 Hz. The vertical resolution of the MBES system is in a sub-centimetre scale (www.reson.com). The lateral resolution is a function of flow depth and vessel speed. For instance, a flow depth of 15 m results in an across-track resolution of 0.13-0.52 m due to the across-track beam width of 0.5°. A vessel speed of 2.5 ms^{-1} (5 kn) results in an along-track resolution of 0.06 m. Therefore a cell size of 0.5 m was chosen when gridding the bathymetric data. The MBES system was coupled with the AQUARIUS 5002™ (THALES/DSNP) dual frequency (L1/L2) Long Range Kinematic (LRK) Global Positioning System (GPS). The vertical and lateral accuracy of the positioning system was better than 0.05 m and 0.03 m, respectively (Lutz & Gounon, 2001).

The flow velocity data were collected aboard the RV Senckenberg on the 15^{th} of July 2003 using a BB1200™ (RDI) acoustic Doppler current profiler (ADCP) operating at 1200 kHz and the WinRiver™ (RDI) data acquire and playback software package. The vertical resolution of the ADCP is 0.25 m and the lateral resolution, at a vessel speed of 2.5 ms^{-1} (5 kn), is 5-10 m. The resolution of the flow velocity is 1 mms^{-1} and the accuracy is ±0.25% of the flow velocity relative to the ADCP velocity ±2.5 mms^{-1} (www.rdinstruments.com).

Bedform dimensions and celerities were determined from the bed topography in 2002 and 2003 along lines N2, N1, C, S2, S1 extracted from the bathymetric grid (Fig. 2 or 4). Bedform length (L) is defined as the trough-to-trough distance, and bedform height (H) as the distance from the crest to the line defining the bedform length. Bedform celerity is determined as the average movement of the troughs and the crest over time. The bedforms are described according to the classification recommended in Ashley (1990), which distinguishes, according to bedform length, between ripples (<0.6 m) and dunes (>0.6 m), the dunes being further divided into small (0.6-5 m), medium (5-10 m), large (10-100 m), and very large (>100 m).

Mean flow velocities are determined at bedform crests in lines N1, C, S1, and SW (Fig. 1 and 2) by insertion of the dimensionless depth $e^{-1} = 0.368$ of the logarithmic velocity profile (e.g. Yalin, 1977, 1992) into a determined crest-specific logarithmic regression line. This crest-specific logarithmic regression line is found from the three ensembles of the ADCP flow velocity measurements positioned closest to the considered crest. Logarithmic correlations are considered insignificant if the significance level (p) is higher than 0.0005, and are accordingly rejected. Plotting the accepted crest mean flow velocities against simple crest ensemble average flow velocities yields the regression line $V = 0.98u_{average}$ ($r = 0.967$, $n = 20$, $p<0.0005$). Subsequently ensemble average flow velocities are used and referred to as mean flow velocities, since $V \approx u_{average}$.

Results

The bed of the channel is covered with large to very large compound dunes (Fig. 2). The deep part in the NE corner of the study area consists of a hard ground primarily comprising firmly packed shell material draped by a thin layer of sand (Bartholdy et al., 2002). Bedform heights of maximum 0.5 m indicate the thickness of this sand layer.

Dune crests extending across the tidal inlet channel in both 2002 and 2003 are located in the relatively straight part of the channel in the SW part of the study area (Fig. 2). Hereafter, the focus will be on this area. In total, 11-12 dunes were identified along lines N2, N1, C, S1, and S2 (Fig. 2 and 3).

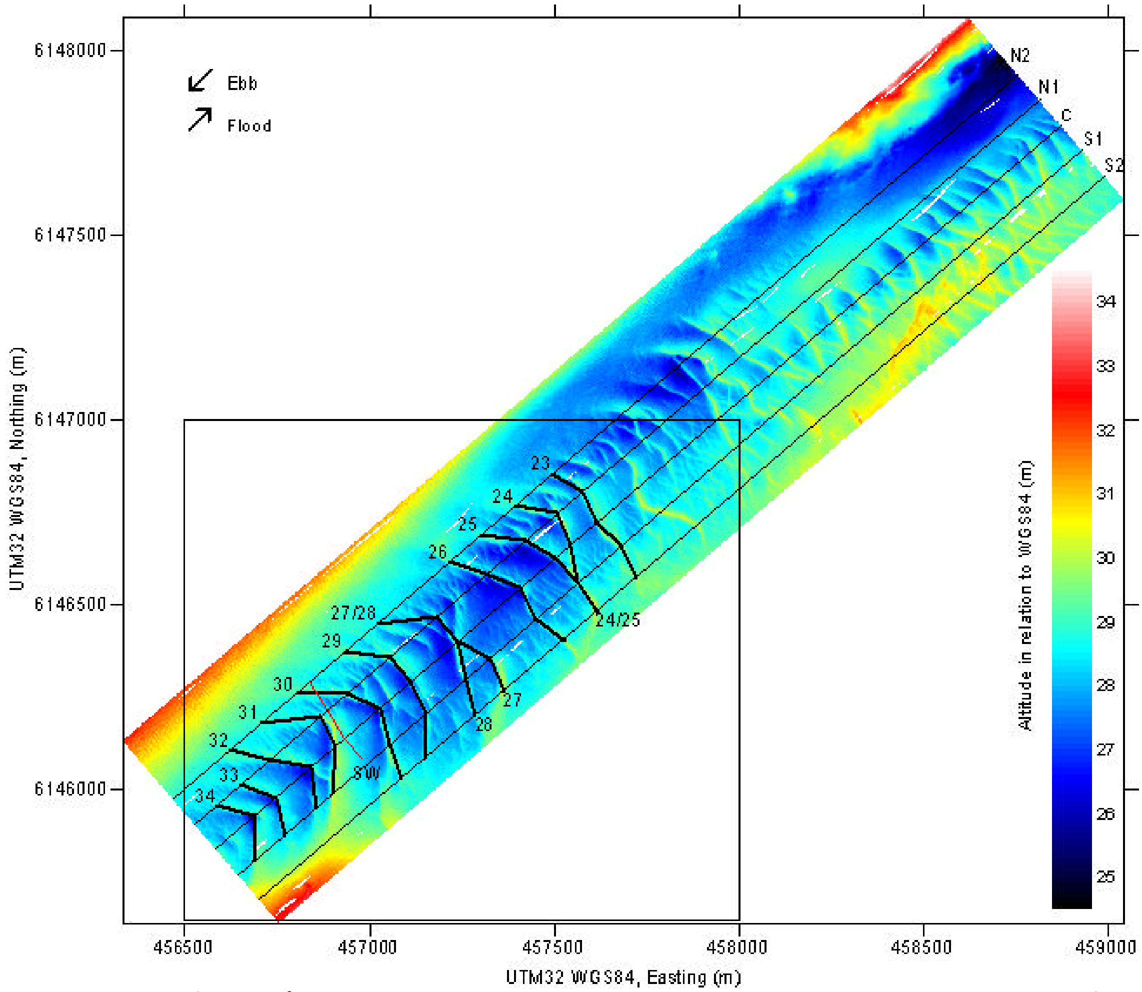

Fig. 2. Bathymetry of the Grådyb tidal inlet channel. The grid is 3000 x 650 m with a cell size of 2 x 2 m. Dune crests extending across the channel in both 2002 and 2003 are marked with poly-lines numbered from 23 to 34. Lines N2, N1, C, S1, and S2 mark the locations of the bed profiles in Fig. 3. ADCP measurements are conducted in cross section SW (red) and along lines N1, C, and S1. Water depth according to mean low water spring (MLWS) in relation to altitude according to WGS84 is given by: MLWS = WGS-39.624 m.

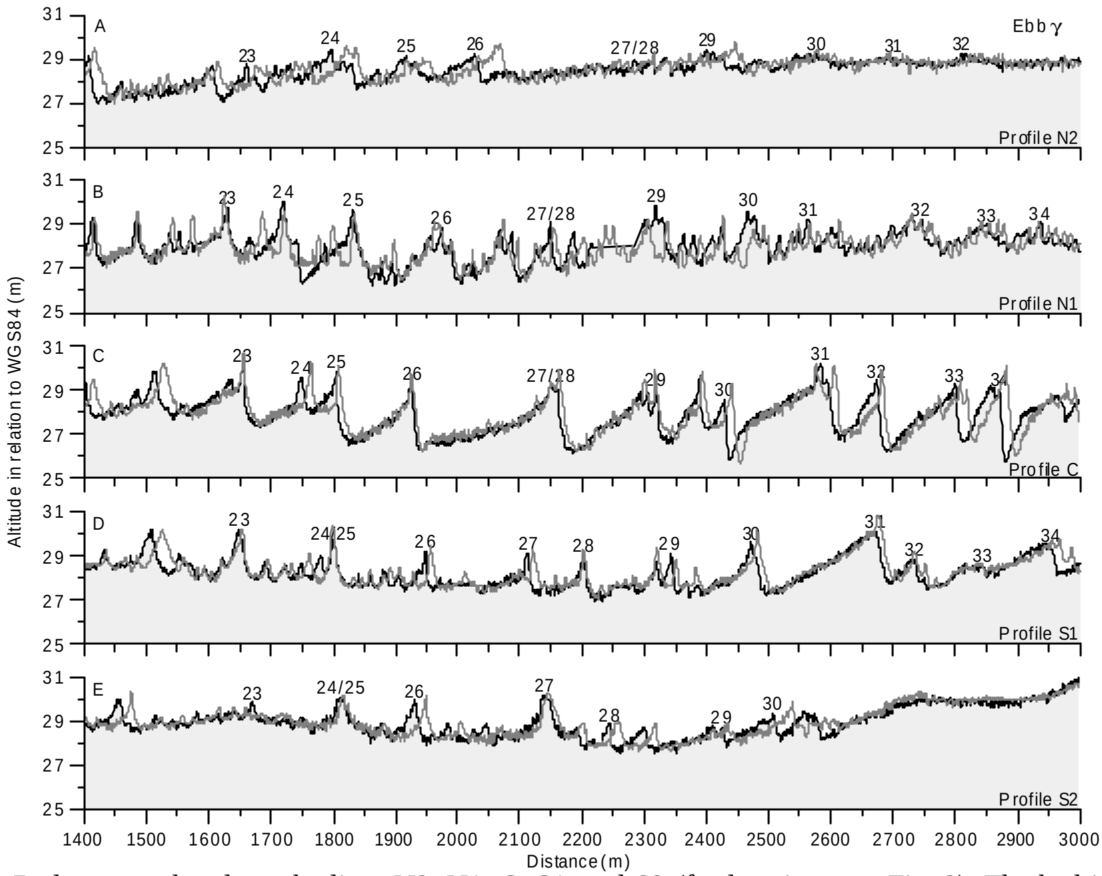

Fig. 3. Bed topography along the lines N2, N1, C, S1, and S2 (for locations see Fig. 2). The bed in 2002 and 2003 is marked with black and grey lines, respectively. The bed profiles are extracted from 3000 x 10 m bathymetry grids with cell sizes of 0.5 x 0.5 m. The calculated dimensions and celerities are determined from the identified (numbered) dunes.

The locations of the identified dune crests show a net ebb directed dune migration (Fig. 4). Furthermore, the dune crest migration increases from the centre line of the channel (line C) towards the sides (line N2 and S2) (Fig. 4, 5C, and 5D).

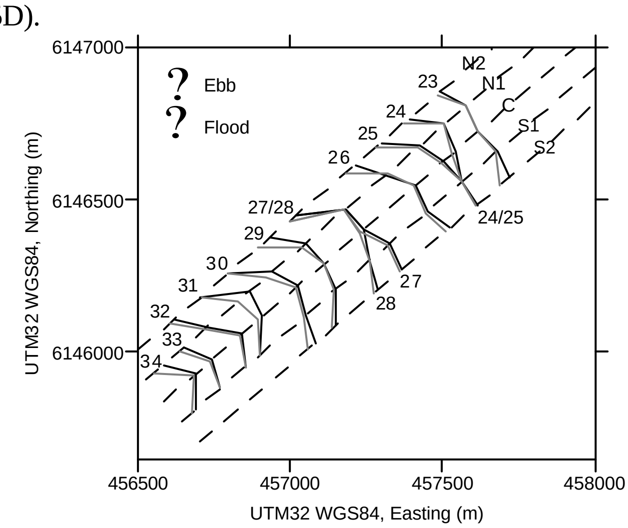

Fig. 4. Detailed map of the identified dune crests in 2002 (black) and 2003 (grey). Lines N2, N1, C, S1, and S2 are marked with dashed lines.

In the centre of the channel, the average dune height is 3.06 m whereas at the N and S side of the channel it is 1.16 m and 1.57 m, respectively (Fig. 5A and Table 1). This shows a decrease in dune heights from the centre line to the sides of the channel. The lateral distribution of dune heights with the line of maximum dune heights in the centre of the channel is slightly shifted to the N in the most north-westerly part of the area (Fig. 5B).
The average dune length and height along the most south-westerly 100 m section of line N2, i.e. 2900 m to 3000 m in Fig. 3A, is 7.88 m and 0.41 m, respectively. Along the corresponding section of line S2 the average dune length and height is 5.16 m and 0.22 m, respectively (Fig. 3E).
In the centre of the channel the average dune celerity is $10 my^{-1}$, whereas at the N and S side of the channel it is 26 my^{-1} and 23 my^{-1}, respectively (Fig. 5C and Table 1). There is hence an increase in dune celerities away from the centre line of the channel. The lateral distribution of dune celerities shows minimum dune celerities in the centre of the channel with a slight shift to the S in the SW part of the area and to the N in the NW part of the area (Fig. 5D).

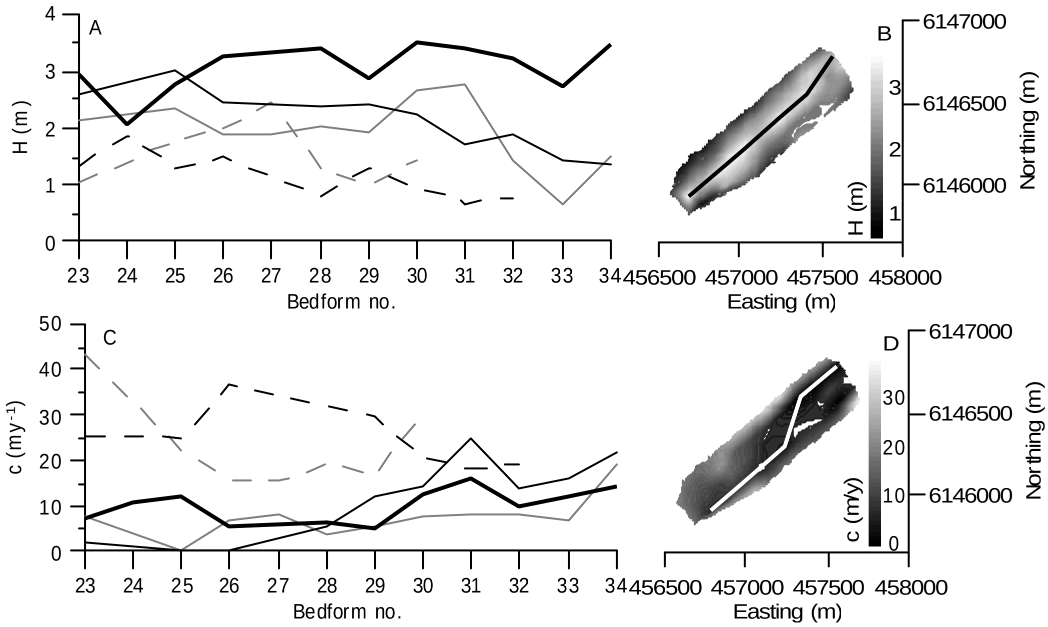

Fig. 5. A) Dune heights (H) along the lines N2 (black-dashed), N1 (black), C (black-bold), S1 (grey), and S2 (grey-dashed) and B) their spatial distribution. For the locations of the lines see Fig. 2 and 3. C) Dune celerities (c) along the same lines and D) spatial variability of the dune celerities.

Maximum mean ebb flow velocities have been determined at the crests of dunes 23 to 34. Along line C, the average mean flow velocity is 1.02 ms^{-1}, whereas along lines N and S it is 0.93 ms^{-1} and 0.95 ms^{-1}, respectively (Table 1). Furthermore, maximum mean ebb flow velocities at the intersections of cross-section SW with lines N2, N1, C, and S1 over the back of dune 31 (Fig. 1 or 2) indicate the same trend with a small decrease in mean flow velocity away from the centre line of the channel (Table 1). The average maximum mean ebb flow velocity in cross-section SW is 0.88 ms^{-1} with a standard deviation of 0.08 ms^{-1} ($n = 275$), which gives a coefficient of variation of 10%. Thus there is a small decrease in mean flow velocity from the centre to the sides of the channel, but the relative change is considerably smaller than the changes in dune dimensions and celerities (Table 1), i.e. the mean flow velocity across the channel is practically constant in the considered area.
The average bed levels along the lines N2, N1, C, S1, S2 have been determined as the average altitudes at mean dune height. Along the centre line of the channel the average bed level is 28.25m whereas at the N and S side of the channel it is 28.62 m and 28.89 m, respectively (Table 1). Hence there is a small increase

in the average bed level, i.e. decrease in flow depth, from the centre line to the sides of the channel. However, the relative change is very small (Table 1).

Table 1. Average dune lengths (L), heights (H), celerities (c), and mean flow velocities (V) at the dune crests along lines N2, N1, C, S1, and S2, and over a dune back along the intersections of cross section SW with lines N2, N1, C, and S1 (for locations see Fig. 1 and 2). Average bed level (h) in relation to WGS84. Mean grain size (d_{50}) is determined after Bartholdy et al. (2002) (see text). Channel centre to channel side deviation is determined according to (C-0.5(N2+S2))/C and presented in percent.

Profile	N2	N1	C	S1	S2	Deviation (%)
L (m)	149	137	122	131	152	23
H (m)	1.16	2.21	3.06	1.93	1.57	55
c (my^{-1})	26	10	10	8	23	145
V (ms^{-1}) dune crests	-	0.93	1.02	0.95	-	8
V (ms^{-1}) dune backs	0.84	0.76	0.88	0.81		6
h (m WGS84)	28.62	28.27	28.25	28.56	28.89	2
d_{50} (mm)	0.369	0.442	0.478	0.427	0.404	19

Discussion

The Grådyb tidal inlet channel is characterised by a decrease in dune height from the centre line to the sides of the channel (Fig. 5A, 5B and Table 1). Bokuniewicz et al. (1977) reported a similar pattern in Long Island Sound, USA.

What is the controlling factor of the decrease in dune height away from the centre of the channel?

Soulsby (1997) states that the most reliable formulas for determination of dune height are those proposed by Yalin (1977) and Van Rijn (1984) where dune height scales with flow depth. In the Grådyb tidal inlet channel this is not the case since the flow depth is practically constant across the channel (Table 1).

Flemming (2000b) argues that different dune size hierarchies may exist side by side in situations where the flow is characterized by lateral, i.e. cross-flow velocity gradients. In rivers it is commonly known that mean flow velocity decreases from the centre towards the banks due to the frictional effect, but the effect becoming insignificant in channels with width/depth ratios in excess of c. 15 (e.g. Knighton, 1998). The Grådyb tidal inlet channel, having a width of 360 m even from line N2 to S2 and a mean depth of 10-13 m, has a width/depth ratio of c. 30. Hence changes in mean flow velocity due to channel side friction can be neglected. This is also supported by the measurements, which show a practically constant mean flow velocity in the considered channel reach (Table 1). An alternative factor controlling the dune dimensions has therefore to be considered.

Based on two separate bed sample sets, taken with a Van-Veen grab from the present study area in 1992 and 1999, Bartholdy et al. (2002) found a highly correlated (r = 0.97) relationship between dune height and mean grain size. The relationship is expressed by the power function $H = 3.73M_Z^{-3.22}$ with $M_Z = -\log_2 d_{50} = -\log d_{50}/\log 2$ where M_z is mean grain size in phi, and d_{50} is the corresponding mean grain size in mm. Insertion of the average dune heights in lines N2, N1, C, S1, and S2 (Table 1) yields a decrease in mean grain size of c. 0.1 mm from the centre line of the channel to the sides (Table 1). This decrease in grain size could be confirmed from bed samples taken by a Shipek grab in 2003 at the crests of 6 dunes, namely dune 25, 26, 31, 32, 33, and 34 (the grain size analyses are still in progress). The observation is in agreement with Flemming (2000a) who argues that the larger the grain size, the larger the maximum potential dune size.

In the Grådyb tidal inlet channel dune celerity increases away from the centre of the channel as dune height (or dune area) decreases (Fig. 5A, B, C, D and Table 1). Patterns of increasing bedform celerity with decreasing bedform dimensions due to the smaller volume of sediment that has to be moved is well documented (e.g. Dinehart, 2002). Consequently, barchan dunes would develop in the Grådyb tidal inlet channel due to the faster dune celerities along the sides of the channel.

This suggests that a laterally constant flow velocity and a decrease in grain size will produce a decrease in dune dimensions (e.g. Flemming, 2000a; Bartholdy et al., 2002) resulting in an increase in dune celerities (e.g. Dinehart, 2002). And since the mean flow velocity is practically constant across the channel, i.e. no reduction in dune celerity, barchan dunes are expected to develop. This has been demonstrated in this study.

The average dune dimensions in the centre of the channel follow the relationship suggested by Flemming (1988). However, this is not the case closer to the channel sides where the dunes get lower and longer (Table 1 and Fig. 6). This suggests that the large to very large dunes at the sides of the channel simply are perturbations adjusting to different conditions, in this case a different mean grain size. A similar adjustment is seen in the course of the flow reduction from spring to neap tide where larger dunes split up into smaller ones with the larger spring-tide dunes still being discernible at neap tide (Flemming & Davis, 1992). The dune dimensions along the most south-westerly 100m section along line N2 and S2, i.e. 2900 m to 3000 m in Fig. 3A and 3E, where the large to very large dunes could not be identified follow the relationship suggested by Flemming (1988) (Fig. 6). This indicates that these areas have adjusted to the decrease in mean grain size.

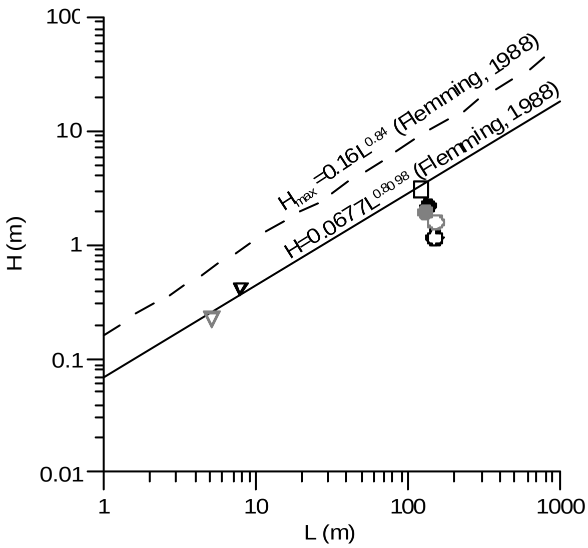

Fig. 6. Scatter diagram showing average bedform height (H) versus average bedform length (L) in lines N2 (black circle), N1 (black dot), C (square), S1 (grey dot), and S2 (grey circle). Black and grey triangle: line N2 and S2, respectively, from 2900 to 3000 m (for locations see Fig. 3). Line and dashed line: global and upper height limit relationship, respectively, according to Flemming (1988).

Conclusions

Based on the analysis of bathymetry, flow velocity, and grain size, the development of subaqueous barchan dunes in the Grådyb tidal inlet channel in the Danish Wadden Sea is suggested to be due to a decrease in mean grain size from the centre line of the channel towards the sides. Furthermore, the more rapidly migrating flanks of the barchan dunes in the Grådyb tidal inlet channel simply seem to be an adjustment in response to the decrease in mean grain size.

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