LARGE BEDFORMS ON THE SHOREFACE AND UPPER SHELF, NOORDWIJK, THE NETHERLANDS

M.G. Kleinhans
(Utrecht University)

ABSTRACT

Large bedforms were studied along a 20 km transect from upper shoreface (12 m depth) to upper shelf (20 m depth), using current and wave climate, bed samples with various grain size analysis methods, lacquer profiles, multibeam and sonar. Three bedform classes were identified with wave lengths of the order of 1, 10 and 100 m, respectively. The smallest bedforms (dunes) are generated by tidal currents, while the larger bedforms (hummocks) are generated in sheet flow conditions in storms.

1. INTRODUCTION

Many sandy shorefaces and shelves are covered by hummocks, which is a three-dimensional bedform type with wavelengths larger than orbital ripples. Ancient deposits of shorefaces and shelves consist mostly of hummocky cross-stratification rather than orbital ripple stratification, indicating their common occurrence and preservation potential in the geological record. Hummocks are three-dimensional bedforms with lengths of the order of meters. They are associated with the high-energy sheet flow conditions and occur generally in coastal and shelf seas. This has consequences for the prediction of suspended sediment transport, because the effect of hummocks on concentration is very different from the effect of wave ripples (Green and Black 1999). Although sediment suspension over hummocks by wave stirring is similar to that over upper stage plane bed (sheet flow), the current roughness is probably affected by the hummocks which affects the net transport. Hummock occurrence is general (Duck, Nova Scotia, Australia, North Sea) but their genesis is enigmatic (Swift et al., 1983, Van de Meene et al., 1996, Amos et al., 1996, Li and Amos, 1999, Kleinhans et al., 2004, Passchier and Kleinhans, accepted) and more data is needed.

Passchier and Kleinhans (accepted) studied various superimposed bedforms on the Dutch shoreface and shelf and found four types of bedforms described as megaripples (Table 1) on top of two types of sandwaves. The discriminating properties were height, length, straight-crested (2D) or unconnected crests (3D) and crest line orientation. The megaripple lengths are of the order of 10 m and the sandwave lengths of the order of 100-1000 m. There are indications that the 2D megaripple crestline orientation is coupled to the sandwave crestline orientation. Interestingly, the orientation of one of the megaripple type has crests perpendicular to the coast and another roughly parallel. A crestline orientation perpendicular to the shoreline indicates bedforms migrating parallel to the coast, and the inferred genesis was current-formed dunes. The 3D megaripples were measured just after storms with significant orbital velocities of about 0.47 m/s over sands of 0.27-0.34 mm median size. Given the vicinity of their study area it is interesting to compare results.

The aim of this paper is to map bedform types (with emphasis on the hummocks) on the shoreface and shelf off Noordwijk, the Netherlands, and to assess under which conditions the observed bedforms occur. First, the large-scale morphology and sediment composition is determined along a cross-shore transect. Next, the (relic) bedforms found in multibeam and sonar surveys in calm weather are described and classified. Third, the stratification observed in boxcores is interpreted to aid genetic interpretation of the observed bedforms.

Table 1 *Megaripples found by Passchier and Kleinhans (accepted).*

Megaripple type	wavelength	height	crestline orientation	inferred mechanism
2D coast-parallel	1 – 40 m	O(0.01-0.1) m	91 – 132° North	current dunes
2D coast-perpendicular	5 – 15 m	O(0.1) m	10 – 81° North	calm weather, unclear
3D broken crestlines	5 – 15 m	O(0.1) m	–	storm waves
3D mound-like	20 – 40 m	O(0.1) m	–	storm waves

2 STUDY AREA

The study area is located off the Dutch coast near Noordwijk, The Netherlands (Figure 1). This area is on the southern limit of the shoreface-connected ridges. The study area is as far away as possible from the harbour jetties of IJmuiden and Rotterdam. The data collection of the SANDPIT project was focussed on a cross-shore transect located between 2 and 20 km offshore from the coastline. The current climate is mostly

determined by the semi-diurnal tides with a net northward current. The currents are of the order of 0.8 m/s in spring tide and 0.6 m/s in neap tide. The largest waves come from the north-west and the south-west.
The large-scale morphology of the Dutch shelf and coast is described in Van Alphen and Damoiseaux (1989). The shelf is covered in sandwaves from 20 km and further offshore. In most places the sandwaves are covered by smaller bedforms. These bedforms have a mixed genesis; current-related stratification was found after prolonged periods with small waves whereas wave-related stratification was found after stormy periods, most of which is hummocky cross-stratification from hummocks (Van de Meene et al., 1996).

3 MATERIALS AND METHODS

3.1 Bedform mapping

Sonar images were collected along the cross-shore transect on October 31, 2002, and February 18 and 26, 2003. The first was three days after the largest storm of the past ten years in this area with Hm0<6 m. The second two were after a relatively quiet period of three months with Hm0<2 m. The two February mappings were compared to test repeatability of sonar imaging and interpretation. All transects were mapped twice in opposite directions with one channel overlap in order to have two ensonification angles at most sites and four at the crossings of the transects. The total mapped area is 150 m wide. The sonar instrument was a Dowty operating at 325 kHz and a slant range of 100 m on both channels and was towed at a speed of 2.5 m/s. The depth of the sonar ideally was one tenth of the range, but on the shallow shoreface was of the order of 6 m. All coordinates given in this paper were determined by the ship-based differential global positioning system. The interpretation was done visually following Fish and Carr (1990) and Van Lancker (pers. comm.) after a contrast stretch (simple image enhancement) of the images.

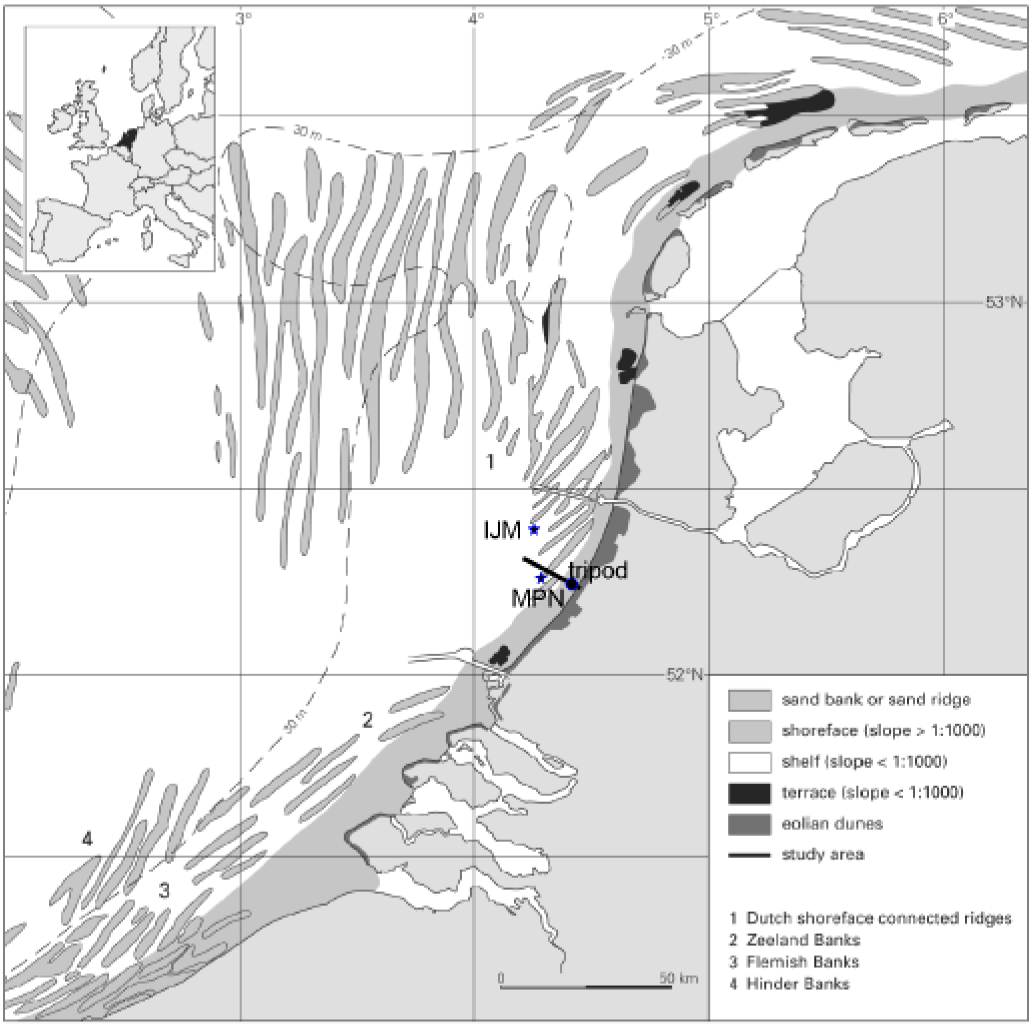

Figure 1 *Map of the study area (after Van de Meene et al. (1996). Inset map shows the position of the Netherlands in Europe. The wave stations MPN and IJM and the tripod at 2~km offshore are shown near the studied cross-shore transect. (Courtesy Margot Stoete, Kartlab, Utrecht University.)*

Multibeam echo-sounding data was collected along the transects of 200 m wide. Because of the limited path width of the multibeam, 8 to 15 paths were necessary to map the whole area. This took three days. The multibeam operated at 300 kHz at 5 m below the water surface. Sound velocity probes measuring temperature and salinity were used to correct the sound velocity. The ping rate was 10-15 Hz and the cruise speed was as low as 2 m/s in order to obtain the highest possible resolution. The data were corrected online for pitch, roll and heave of the vessel. The weather was very good and the heave was at most 0.05 m. The data were corrected afterwards for tidal water level fluctuations, measured at two stations on the cross-shore transect. Absence of striping in the image indicates that the corrections were done well. The estimated error (95%) of horizontal positioning is 0.05 m and of vertical bed level 0.02 m. Multibeam profiles were extracted from the data in a strip of 1 m wide at the north border, the centerline and the south border of the mapped area for further analysis.

3.2 Sediment sampling

Sediment characteristics of the bed were collected from Reineck boxcores by conducting grain size analysis and describing sedimentary structures at every 500 m between 1 and 21 km offshore. Boxcores were collected mostly on November 4, 2002 and March 4 and 17, 2003. Additional boxcores at 2, 5, 8.5 and 10 km offshore were collected in September-November 2003 for grain size analysis and lacquer profiles. The bed sediment was collected in layers of 0-2 cm (‘top’), 2-7 (‘bottom’) and 7-14 cm (‘substrate’) below the bed surface. The rationale was that the 2 cm of this top layer are already mobilised in current ripples and very small orbital ripples, contrary to the deeper layers, and on the shoreface the substrate layer consisted of basal shell lags, peat, clay and other sediments clearly different from the overlying active sediment.

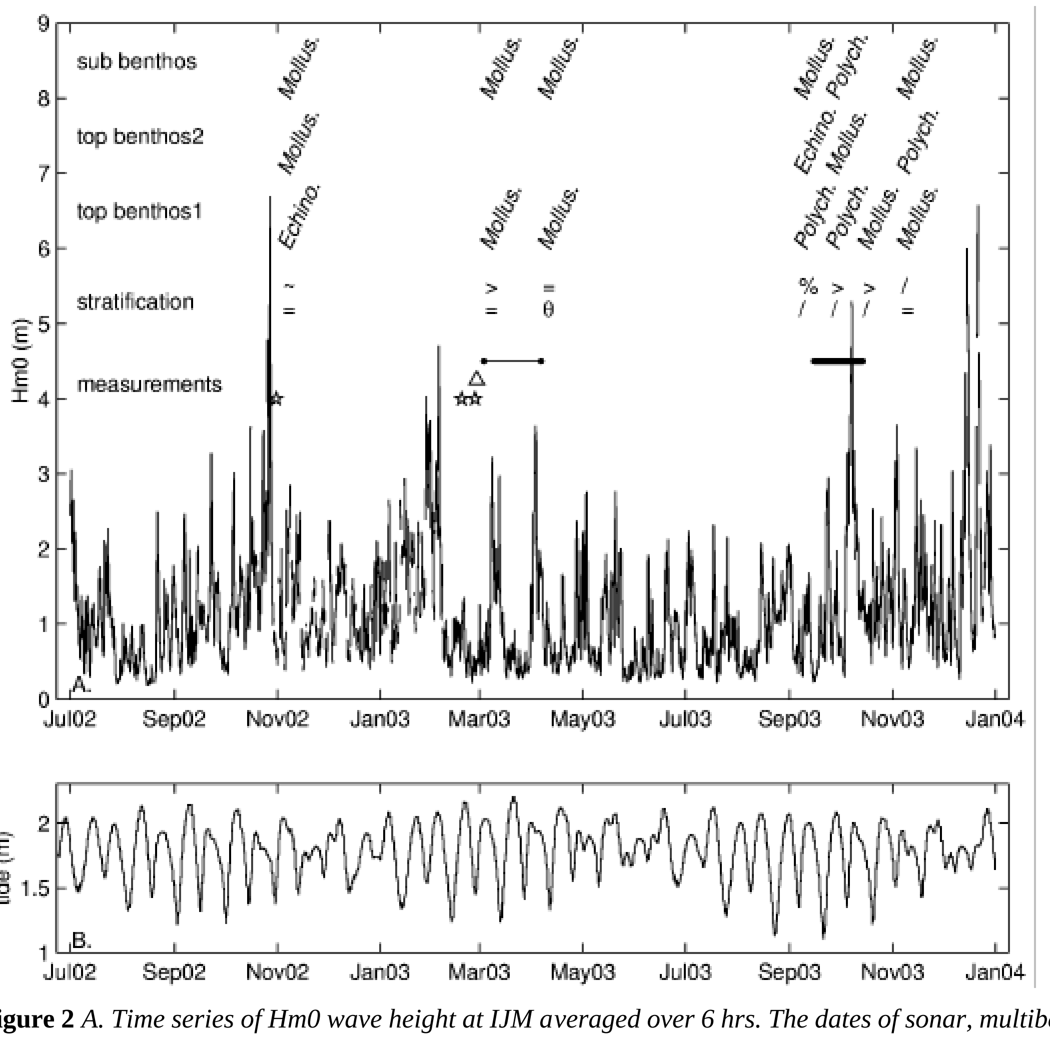

Figure 2 *A. Time series of Hm0 wave height at IJM averaged over 6 hrs. The dates of sonar, multibeam and tripod data collection are given as symbols. Stratification (discussed later) is given for the top, and macrobenthos taxa are given for top and sub-layers at 2 km offshore. ~: wave ripples, =: HCS, >: current ripples, /: current dunes, theta: shell lag, %: burrows. B. Time series of tidal water surface amplitude at MPN, indicating short-period spring-neap tidal fluctuations and the annual fluctuation.*

Sand is defined as $0.065<D<2$ mm, mud is defined as $D<0.065$ mm, with silt $0.002<D<0.065$ and clay $D<0.002$ mm. Grain size analysis was done in three ways. First, a few selected samples were sieved with 22 sieves between 0.053-2 mm as a quality control on the following, faster methods. Second, all samples were analysed in the Utrecht settling tube, and settling velocities converted to grain size. To determine the mud content, all samples were analysed with a laser particle sizer after treatment to de-coagulate clay flocculates and remove organic material such as shell hash and faecal pellets. The grain size distribution of the sand determined by the laser particle sizer did not represent the dirstribution by the settling tube well and is therefore not used.
Lacquer profiles of the (vertical) stratification of the top 0.2 m of the bed were made from 27 boxcores, mostly at 2 km offshore but also at 5 and 10 km for the period of November 2002 to November 2003. The profiles were made from two perpendicular, near-vertical sections (scraped clean) of undisturbed boxcore sediment by pouring lacquer over the section, air-drying, carefully painting cheese cloth on the lacquer, air-dry again and then gently pulling off the lacquered section. The lacquer penetrates deeper into sediment with higher porosity so sedimentary structures from wave ripples, hummocks, current ripples, sheet-flow, bioturbation and macrobenthos stand out clearly after careful brushing, while the colour indicates oxidised or reduced conditions and the presence of mud.

3.3 Auxiliarly data

Wave data between January 1, 1970 and December 31, 2003 (Rijkswaterstaat, pers. comm.) have been collected at the platform Meetpost Noordwijk (MPN) and the IJmuiden Munitiestort (IJM) (Figure 1). The water level data was used, and Hm0= significant wave height (m), Tm02= significant wave period (s) and Th0= wave direction (°) from the directional wave spectrum for 30-500 mHz (Figure 2). Sediment mobility parameters for waves, currents and for wave-current interaction are computed as in Kleinhans (2005, paper P, this volume. The results for water depths, currents, waves, and grain sizes representative for the shoreface and shelf areas are given in Table 2. A critical Shields parameter for the beginning of generalised grain motion of about θ_{cr}=0.03-0.06 may be assumed for both waves and currents. This value increases slightly with mud content and benthic consolidation. A common Shields criterion for the transition to sheet flow is $\theta_{sf}=0.172\ D^{-0.376}$ (Li et al., 1999), where D=grain size in cm. This gives θ_{sf}=0.69 for 0.25 mm sand and 0.64 for 0.3 mm sand.
Two existing datasets from literature were used. The first is the Noordwijk shoreface profiles of the JARKUS dataset, which is used here for illustrative purposes only to indicate the position of the study area relative to the nearshore zone. The second is median grain size data collected in the past decades along the Noordwijk cross-shore transect (TNO-NITG, pers. comm.) for comparison.

Table 2. *Estimated Shields parameters for currents and waves (separately) in representative conditions. The q_{cw} is the modified parameter for wave-current interaction, and q_{Max} is the (total) combined flow parameter. Bold Shields numbers exceed the criterion for sheet flow.*

depth	D_{50}	u_c	θ_c	Hm0	Tm02	u_o	θ_w	θ_{Max}	θ_{cw} Soulsby	θ_{cwMax} Soulsby
m	μm	m/s	-	m	s	m/s	-	-	-	-
13	220	0.4	0.05	2	6	0.42	0.28	0.28	0.08	0.29
13	220	0.8	0.19	4	8	1.15	**1.52**	**1.54**	0.35	**1.56**
18	250	0.4	0.04	2	6	0.26	0.11	0.12	0.06	0.12
18	250	0.8	0.16	4	8	0.84	**0.78**	**0.80**	0.27	**0.83**
18	300	0.8	0.14	4	8	0.84	**0.68**	**0.70**	0.23	**0.72**
22	300	0.8	0.14	4	8	0.67	0.46	0.48	0.21	0.50

4 RESULTS

4.1 Morphology, sediments and dynamics along the cross-shore profile

The cross-shore profile extracted from the multibeam data and JARKUS data clearly shows distinct morphological units (Figure 3). Starting at the coast, the coastal dunes rise 18 m above the mean sealevel (Dutch Ordnance Datum NAP). The beach and upper shoreface are characterised by an active sediment thickness of 1-3 m, which decreases to below the common echosounding accuracy of 0.1 m at 0.8 km

offshore. The middle and lower shoreface extend to 4.5 km offshore at a water depth of 17 m with a sudden break at the upper shelf. The shelf itself has an overall seaward slope of 0.0002.
While the shoreface is nearly planar, the shelf shows sandwaves with an alongshore wavelength of about 500 m and a height of 1 m at 10 km offshore and 2.5 m at 16.4 km offshore. They are clearly asymmetric with the steep slope facing north, and show up on the cross-shore profile as symmetric humps. There are strong and irregular distortions in the seabed from dredging activities at 13.5 and 16-17.5 km offshore.
On the shoreface and upper shelf, consolidated mud and peat layers are found at or just below the surface (Figure 3). On the high areas of the upper shelf (5 and 7-10 km), shell hash is found at the base of oxidized sands (0.15-0.2 m deep), in which many shells were deposited with the convex sides up. Further offshore anoxic, gray sand is found in the substrate. The penetration depth of the box cores is much less on the shoreface than further offshore. On the shoreface the box coring often had to be repeated because the core bounced of the bed due to consolidated mud, peat and shell hash.
The median grain size increases seawards from the seaward side of the surfzone (Figure 4) at 0.18 mm to 0.35 mm at the seaward end of the profile, with a rapid rise at 17 km offshore. In the onshore direction, it sharply increases in the surfzone and beach and then decreases sharply in the coastal dunes. At the base of the shoreface (3 km offshore), the top sand is much finer and muddier than the bottom sand. At 13 km offshore the D_{10} of the top is much smaller than of the bottom sediment and the sediment sorting expressed as D_{90}/D_{10} is larger. On average, the mud consists of 60% silt and 40% clay. The top layer has high peaks up to 40% of mud at 3, 5 and 10.5 km that are larger than in the bottom layer. The off-scale peaks of the sorting from the laser method are caused by the presence of large amounts of mud. The grain size probability distributions (Figure 5) indicate the variability within a method due to duplicate sampling within one boxcore and from various boxcores, which is estimated in general at about 5%.

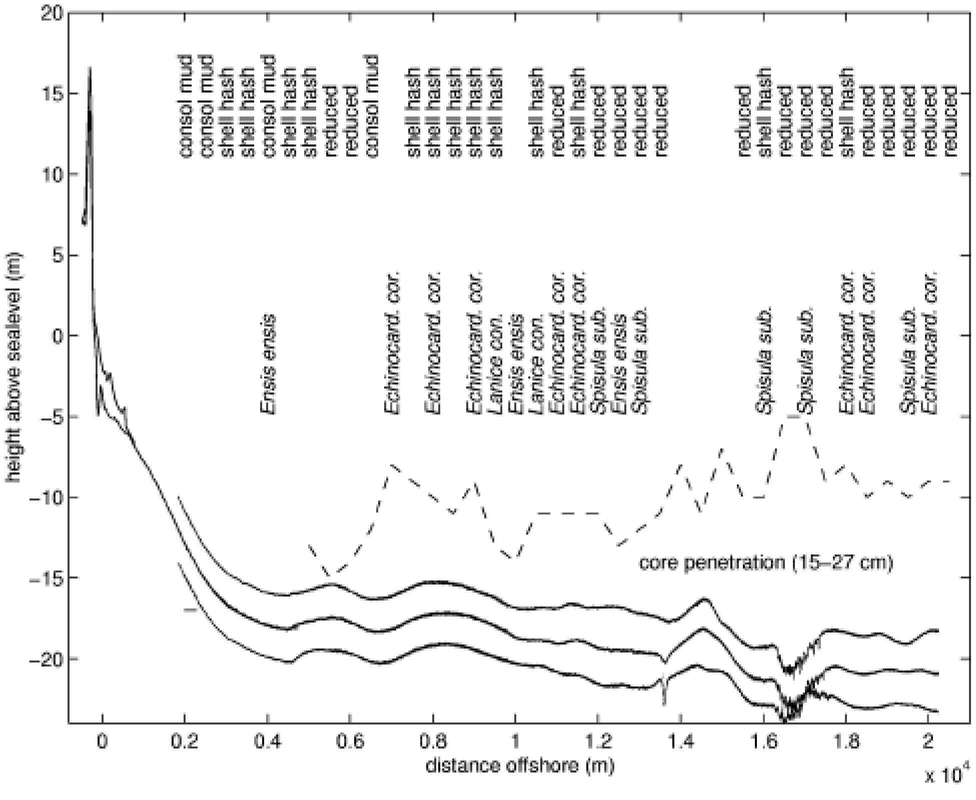

Figure 3 *Cross-shore bathymetry from the multibeam and JARKUS data, including benthos information and boxcore penetration depth (indicative scale). The multibeam profiles were extracted from the data in a strip of 1 m wide at the north side (+2 m offset in graph), the middle and the south (-2 m offset). The JARKUS data is represented as envelopes for the full dataset, indicating the thickness of activity of the bars in the surfzone.*

4.2 Bedforms

The multibeam images (Figure 6) show bedforms at many locations. Small straight-crested but highly irregular two-dimensional (‘2D’), and isotropic three-dimensional (‘3D’) bedforms of 10-20 m long were dominant on the slopes and tops of the sandwaves. In the troughs, large bedforms, or depressions, of 100-200 m long were dominant with increasing superposition of smaller megaripples from sandwave trough to top. On the shoreface, a few isolated depressions were found with elongated forms in cross-shore direction and depths of up to 1 m. The largest form (extreme right in Figure 6F) had 2D ripples within the depression with shore-parallel crests. Moving window fft-spectral analysis confirmed the visually determined bedform dimensions.

The sonar images (Figure 7) revealed a much more detailed picture of the bedforms. There are two persistent classes of bedforms: I, small straight-crested 2D bedforms of about 1-2 m length and II, larger forms of both 2D and 3D morphology of about 5-20 m long. Note that the larger forms are the same as the small forms on the multibeam images, whereas the smallest forms on the sonar are invisible on the multibeam. The smallest bedforms (I) on the sonar are all oriented perpendicular to a NNW direction (crestline orientation ENE), which is deviating from the shoreline direction (NEN). These bedforms occur on the whole shoreface and, in February 2003, at 10-11 and 14 km offshore. The larger forms (class II) have two orientations which are neither perpendicular nor parallel to the shoreline but in N (or S) and E (or W) direction. In October 2002, just after the largest storm of the past decade, class II bedforms occur only at 5.5, 10-12 and 18 km offshore. In February 2003, after a quiet period, they are prominently present along most of the Noordwijk transect.

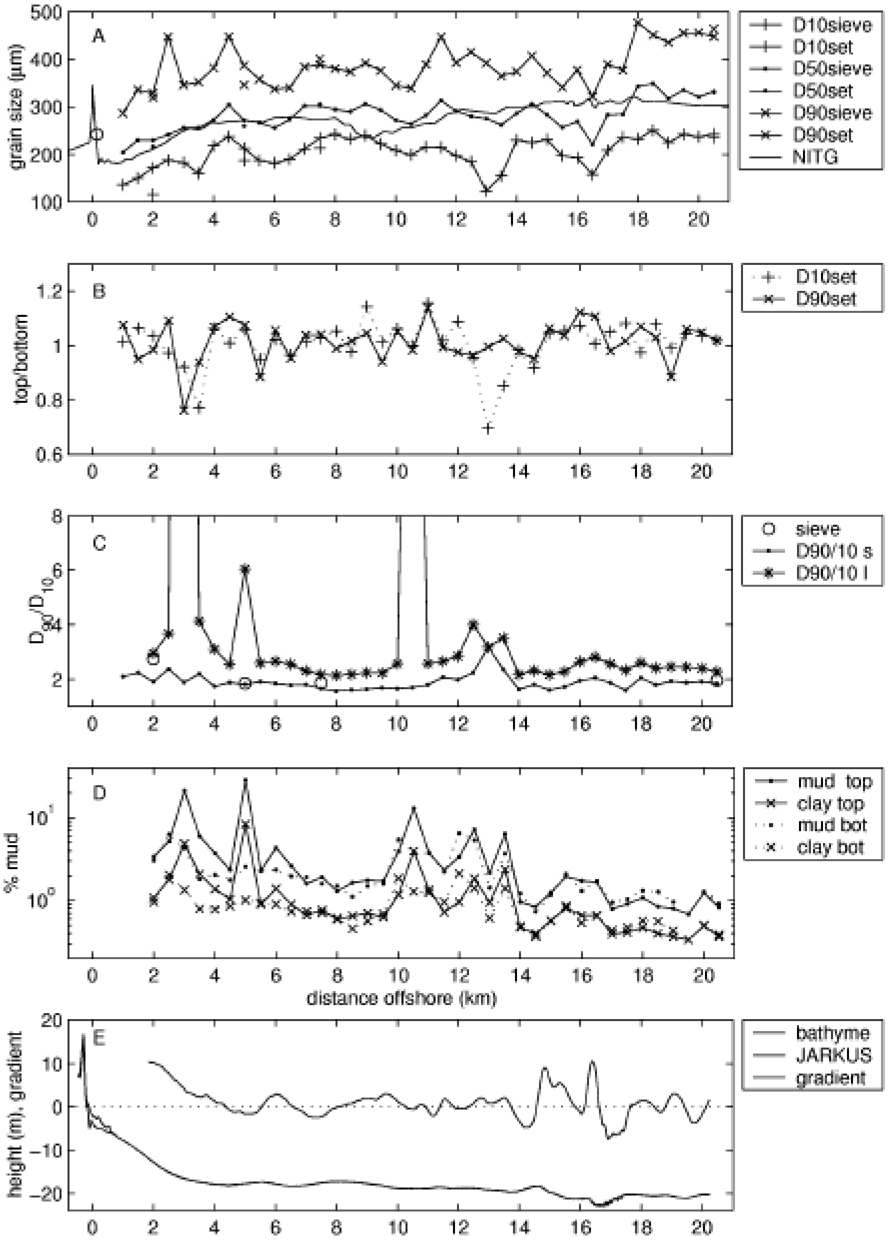

Figure 4 *Sediment characteristics along the cross-shore transect, averaged per 500~m location. A. D_{10}, D_{50} and D_{90} of the top layer from the settling tube (connected by lines) and sieving (isolated symbols) methods, and D_{50} from the NITG data. B. Ratio of top/bottom layer for D_{10} and D_{90} C. Sediment sorting expressed as D_{90}/D_{10} from all three methods. D. Mud and clay content of the top and bottom layer of the bed. E. Bathymetry from multibeam and JARKUS, and the gradient (multiplied with 2000).*

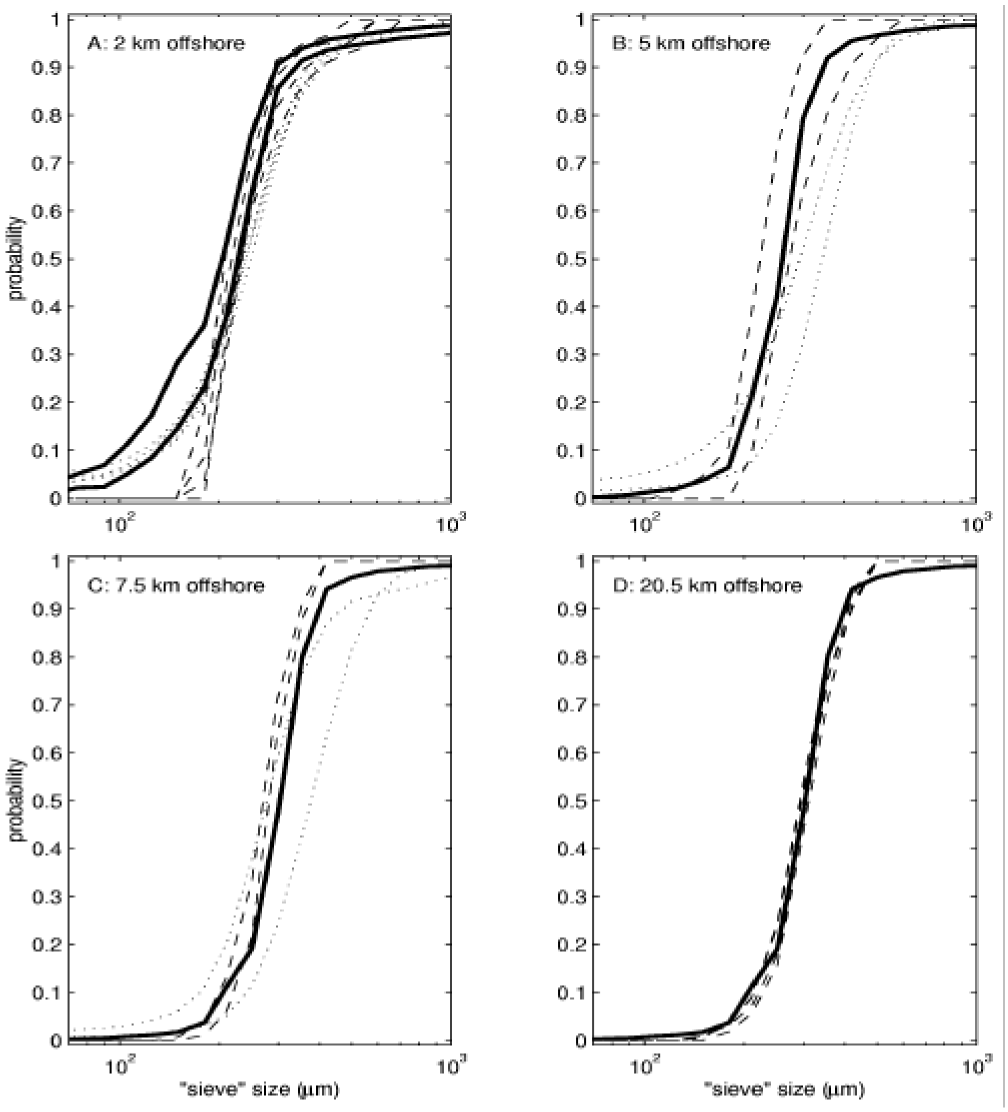

Figure 5 *Cumulative grain size distributions from dry sieving, settling tube and laser methods for four locations along the transect.*

4.3 Sediment stratification

Van de Meene et al. (1996) is followed for terminology to describe and interpret stratification. Examples of the lacquer profiles are given in Figure 8 and the results are summarised in Figure 2. The lacquer profiles at 2 and 5 km offshore of November 2002 are dominated by 10-15 cm thick bundles of low-angle and horizontal lamination, which is interpreted as hummocky cross-stratification (HCS) (Figure 8A). The hummocks were formed in the fall of the heavy storm of October 2002. On top is a 2 cm thick set of cross-lamination with chevron upbuilding, which is interpreted as (small) wave ripples (Figure 8B). During the storm it was neap tide so current velocities were small. Below the HCS, a layer of shell hash with some horizontal lamination is found at 2 km offshore only (more HCS at 5 km), with the shells commonly convex-upwards, indicating deposition in waves rather than *in situ* death. The sand in the shell layer is anoxic, whereas the overlying sand is oxidised. This is interpreted as a shell lag worked down to the base of the active HCS layer.
The March, April and November 2003 lacquer profiles at 2 and 10 km offshore are also dominated by HCS. Contrary to the November 2002 profiles, the top 3 cm at 2 km was steep-angle cross-stratified with angles to two opposite directions, sometimes with thin clay or silt drapes between a change of direction (Figure 8C, Figure 8F). This is interpreted as current ripples or dunes of the reversing tidal current.
The profiles of the two September and the October dates are dominated by steep-angle cross-lamination or stratification with bioturbation (Figure 8D,E). The tidal range in this period is large. The 3 cm top layer of small-scale cross-lamination is interpreted as current ripples, whereas the large-scale cross-stratification with sets of 5-15 cm thick and sometimes thin draped bundles of mud are interpreted as current dunes.

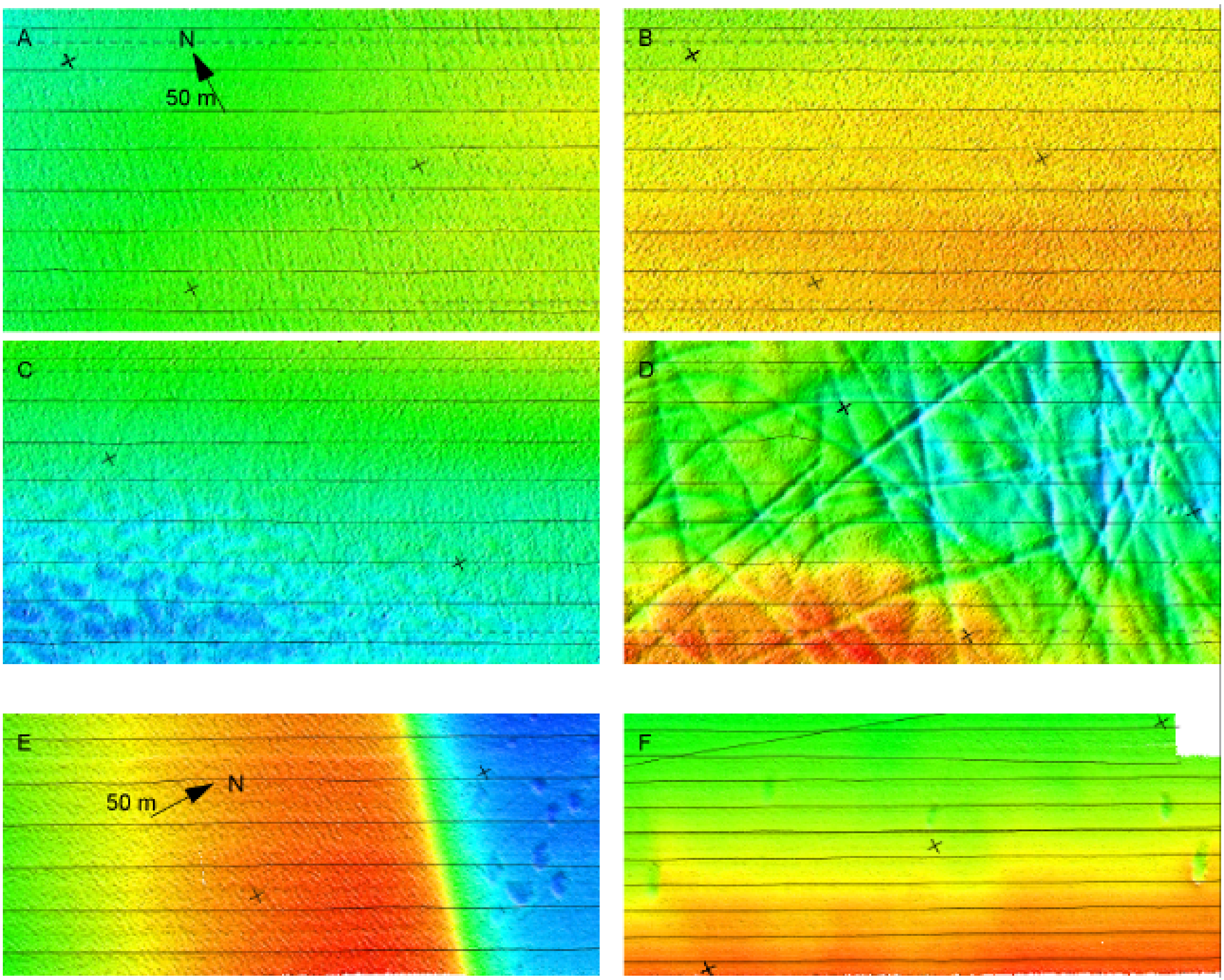

Figure 6 *Examples of shaded bathymetry from the gridded multibeam data. Distance between + is 200 m (length of arrow is 50 m), all images on the same scale. Red is relatively high, blue low. Figs. A-D from the cross-shore profile, with north arrow of Fig. A; E and F from the alongshore profiles, with north arrow of Fig. E. A. 2D bedforms of class II, seaward side of first sandwave, 5.5 km offshore. B. 3D bedforms of class II, top of second sandwave, 8.5 km offshore. C. Depressions (class III) in trough, 13 km. D. Dredging marks (point suction), 16.5 km offshore. E. Crest, top, lee-side and trough of highest sandwave, 16.4 km with 3D bedforms of class II superimposed (left and middle) and depressions (class III). F. Isolated depressions on the shoreface, 2 km.*

5 DISCUSSION: GENESIS OF BEDFORMS

The critical Shields parameter is only barely exceeded by tidal currents over fine sediment, except in the most extreme current velocities occurring on the flood peak of spring tides in spring and autumn (Table 2). The critical Shields parameter is always exceeded by 2 m waves. The sheet flow criterion is easily exceeded for 4 m waves in the finer sand in 18 m water depth, and sheet flow stratification is indeed common on the study site. The water depth has no effect on the Shields parameter of the current. For waves, however, the water depth variation on the shelf has a larger effect than the grain size variation: the θ_w at 22 m water depth (in the troughs) is much smaller than that at 18 m water depth (on the sandwave tops), while the 0.25 mm sand is only slightly more mobile than the 0.30 mm sand. Wave-current interaction enhances the current Shields numbers only slightly despite the large waves and can be neglected.
From the Shields numbers and Figure 7 in Kleinhans (paper Q, this volume) it is obvious that the wave-dominating conditions lead to the expectation of wave-generated but current modified bedforms such as wave ripples of various shapes, possibly with current ripples superimposed, oriented hummocks and sheet flow. Given the relic nature of the large bedforms found in the multibeam and sonar imaging, the bedforms are probably preserved from waning storm, whereas the smallest bedforms could be formed after a prolonged quiet period by the currents, probably aided by small waves to mobilise and enhance sediment transport by the currents (Passchier and Kleinhans, accepted, Van Dijk and Kleinhans, accepted).

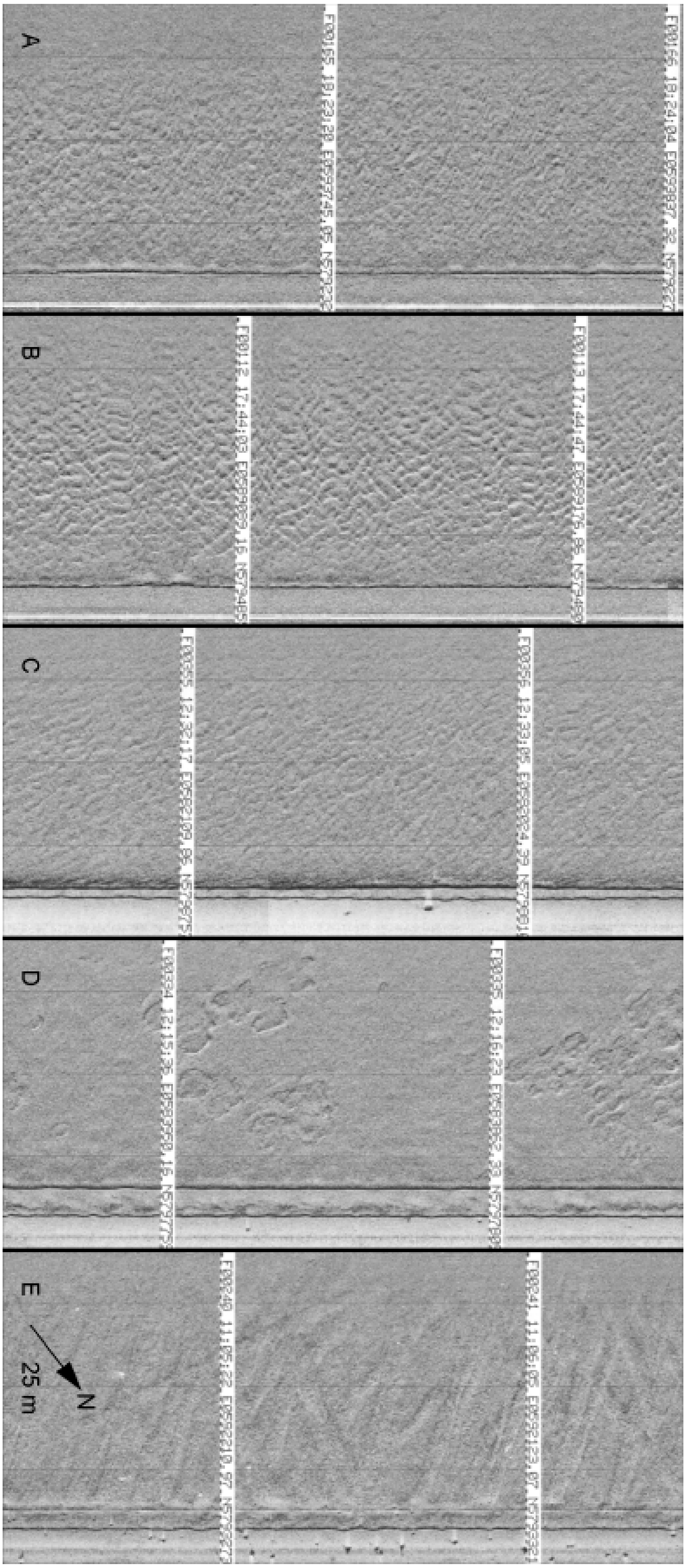

Figure 7 *Examples of sonar images. The arrow points to the north and has a length of 25 m. Horizontal and vertical scales are equal. A. Superimposed 2D class I and 3D class II bedforms, 3.6 km offshore, February 18. B. Superimposed 3D class II bedforms, 10 km, February 18. C. Irregular 3D large bedforms class II, 18 km, October 31. D. Depressions (class III), 16 km, October 31. E. Beam trawl fishing tracks, 6.5 km, October 31.*

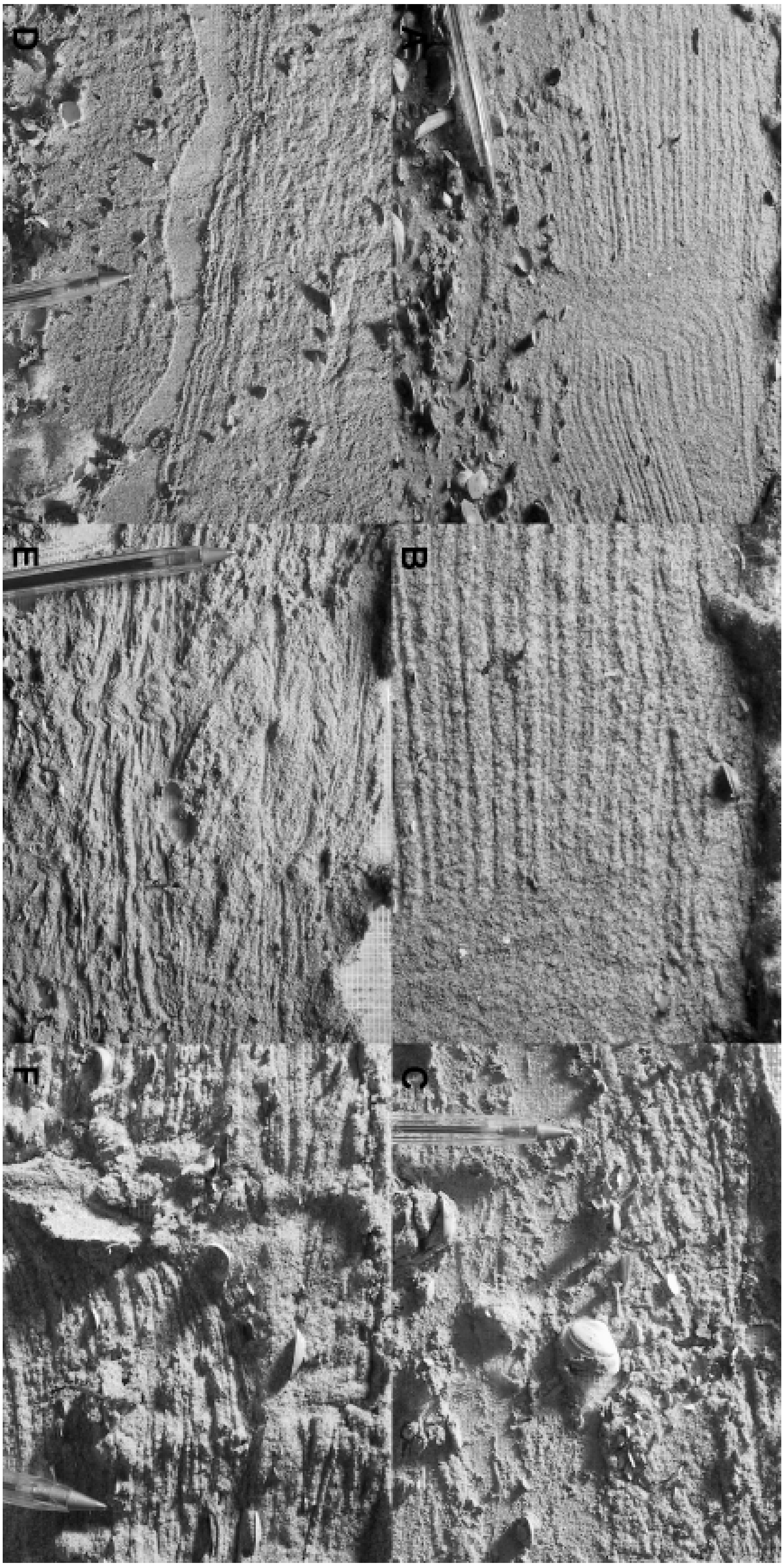

Figure 8 *Examples of lacquer profiles (rotated 90° clockwise). Pen (8 mm thick) for scale. A. Wave ripples (top), HCS with a burrow (middle) and shell lag (bottom), November 7, 2002. B. Detail of A. C. Current ripples (top) and dunes (middle) on a bioturbated layer (bottom), March 4, 2003. D. Current ripples and bioturbation (top) and preserved current ripples under clay drape (middle), September 16, 2003. E. Current ripples (top), current dunes (middle) and bioturbated HCS (lower half), October 14, 2003. F. Current dunes (top) and bioturbated HCS, November 7, 2003.*

Class I bedforms are current dunes. The dunes do not occur on positions with the largest grain sizes, so they are preferably formed in finer sediment which is more mobile in current-only conditions. The dunes are smaller than 5 cm because they only show up on sonar, and this small size could be created by currents in a short time. The crest-normal direction is almost parallel to the current direction. The only known wave-generated 2D bedforms are straight-crested orbital flow ripples with wave lengths in the order of the orbital diameter (<2 m during storms), and which occur only in coarse sand when the wave direction is unchanged for a longer period of time. Although their orientation is not exactly parallel to the coast, their straight crests and orientation do not agree with a wave origin. Moreover, the lacquer profiles after summer clearly show current-related stratification. These bedforms are similar to the smaller bedforms in the 2D coast-parallel megaripples class of Passchier and Kleinhans (accepted).

Class II bedforms are (oriented) hummocks. Given their orientation a completely current origin is very unlikely. Rather, their orientations agree with the directions of the largest storm waves from the southwest and northwest. The hummocks occur either subimposed under the small current dunes or in two directions simultaneously. Passchier and Kleinhans (accepted) showed one multibeam dataset of the shoreface area which was partly collected just before and partly just after a gale. Before the gale, the area was covered by trawl beam tracks and relic bedforms, while just after the gale, two classes of bedforms had reformed: 5-10 m 3D hummocks on top of 20-30 m 3D hummocks, demonstrating that these bedforms are wave-generated. Moreover, the lacquer profiles clearly show HCS after the October 2002 and February 2003 storms with Hm0>4.5 m, which clearly resembles that produced in laboratory conditions (Arnott and Southard, 1990, Southard et al., 1990) and in the field (Swift et al., 1983, Greenwood and Sherman, 1986). The sheet flow condition at the field site is exceeded during storms in agreement with references cited above (Table 2). They occur most clearly on the slopes and tops of the sandwaves at 5 and 8 km offshore, where the grain size is the largest, but, similar to class I, also near 13 km offshore on a low area with smaller D_{10}. The bedform height decreases rapidly up the shoreface where the sediment is also rapidly fining, but the length remains constant. They are both the largest and shortest (steepest) on the top of the second sandwave at 8 km offshore. In some cases the class II bedforms are clearly anisotropic, that is, oriented. This indicates that the tidal current modified the hummocks during and/or after formation (both occur, given the pure HCS and large-scale cross-stratification in the lacquer profiles), which otherwise would have been isotropic. These observations point to a mixed flow genesis of the class II bedforms. Compared to Passchier and Kleinhans (accepted) their descriptive megaripple classes (except the smaller megaripples in the first class) have been combined into one genetic bedform class. These results are comparable to those of Van de Meene et al. (1996), Amos et al. (1996) and Li and Amos (1999) on the Nova Scotia shelf.

Class III are enigmatic features. These occur dominantly on the landward sides and in the troughs of the sandwaves. On the sonar they appear as depressions with rippled or planar beds ('inverted plateaus') rather than positive relief bedforms. On the multibeam class II bedforms are increasingly superimposed on the class III features. On the shoreface, comparable but more isolated depressions were found with elongated forms in cross-shore direction and depths of up to 1 m. The latter are almost certainly erosional features rather than 'depositional' bedforms.

6 CONCLUSIONS

Three bedform classes were identified with different length scales, morphologies and genesis (sandwaves excluded). Class I bedforms are small current dunes, which emerge on finer sands in quiet periods. Class II was identified as hummocks associated with the near-sheet flow hummocky cross-stratification (HCS) with mixed wave and current genesis. Class III bedforms are irregular depressions in the troughs of the sandwaves, of which the formation remains enigmatic.

In waning storm (Hm0>3-4 m) hummocks with horizontal, near planar stratification are formed. In neap-tidal currents, as in November 2002, small symmetric wave ripples are formed on top. In spring-tidal currents, as in October 2003, the HCS grades upwards into steep-angle cross-stratification from currents. In calm, current-dominated conditions (possibly with Hm0<2 m), current dunes and ripples with steep lee-sides are generated. In addition, relic hummocks of earlier storms are reworked into more current-formed bedforms. The current dunes occur mostly in the finest sands, while the hummocks occur in all sands which is related to the sediment mobility in their formative conditions.

7 REFERENCES

Amos, C.L., Li, M. Z. and Choung, K.-S., 1996. Storm-generated, hummocky cross-stratification on the outer-Scotian shelf. Geo-Marine Letters 16, 85-94.

Arnott, R. W. and Southard, J. B., 1990. Exploratory flow-duct experiments on combined-flow bed configurations, and some implications for interpreting storm-event stratification. Journal of Sedimentary Petrology 60, 211-219.

Fish, J.P. and Carr, H.A., 1990. Sound underwater images. A guide to the generation and interpretation of side scan sonar data. American Underwater Search and Survey, Ltd, Lower Cape Publishing, Orleans, MA, USA.

Green, M. O. and Black, K. P., 1999. Suspended-sediment reference concentration under waves: field observations and critical analysis of two predictive models, *Coastal Engineering* 38, 115-141,

Greenwood, B. and Sherman D.J., 1986. Hummocky cross-stratification in the surf zone: flow parameters and bedding genesis, Sedimentology 33, 33-45.

Kleinhans, M.G., Passchier, S. and Van Dijk, Th.A.G.P., 2004. The origin of megaripples, long wave ripples and Hummocky Cross-Stratification in the North Sea in mixed flows. In: Marine Sandwave and River Dune Dynamics II, International Workshop, April 1-2 2004, University of Twente, The Netherlands. Proceedings Hulscher, S., Garlan, T., Idier, D. Eds, 142-151.

Li, M. Z. and Amos, C. L., 1999. Sheet flow and large wave ripples under combined waves and currents: field observations, model predictions and effects on boundary layer dynamics. Continental Shelf Research 19, 637-663.

Passchier, S. and Kleinhans, M.G., accepted. Observations of megaripples and hummocky cross-stratification in the Dutch coastal area and their relation to currents and combined flow conditions. Journal of Geophysical Research – Earth Surface.

Southard, J. B., Lambié, J. M., Federico, D. C., Pile, H. T. and Weidman, C. R., 1990. Experiments on bed configurations in fine sands under bidirectional purely oscillatory flow, and the origin of hummocky cross-stratification. Journal of Sedimentary Petrology 60, 1-17.

Swift, D.J.P., Jr., A.G.F., Freeland, G.L. and Oertel, G.F., 1983. Hummocky cross-stratification and megaripples: a geological double standard. Journal of Sedimentary Petrology 53(4), 1295-1317.

Van de Meene, J. W. H., Boersma, J. R. and Terwindt, J. H. J., 1996. Sedimentary structures of combined flow deposits from the shoreface-connected ridges along the central Dutch coast. Marine Geology 131, 151-175.

Van Alphen, J. S. L. J. and Damoiseaux, M. A., 1989. A geomorphological map of the Dutch shoreface and adjacent part of the continental shelf. Geologie en Mijnbouw 68, 433-443.

Van Dijk, Th.A.G.P. and Kleinhans, M.G., accepted. Processes controlling the dynamics of compound sand waves in the North Sea, The Netherlands. Journal of Geophysical Research – Earth Surface.

8 ACKNOWLEDGEMENTS

The research was funded by EC MAST, MAS3-CT97-0086. I am indebted to The North Sea Directorate and the National Institute for Coastal and Marine Management, both of the Dutch Directorate-General for Public Works and Water Management, for constructive cooperation in the data collection and processing, in specific the crews of the research vessels Mitra, Zirfaea and Arca, to Ben de Jong for technical matters and numerous suggestions, to Rob Lambij, René van der Aar for help with multibeam and sonar data interpretation and to Marien Boers and Ben Dierikxs for loads of planning and management. The fruitful discussions with Sandra Passchier, Thaienne van Dijk and Sytze van Heteren of the Netherlands Institute of Applied Geosciences (TNO-NITG) are much appreciated, and Sytze is thanked for making median grain size data available. Vera van Lancker is thanked for helpful suggestions concerning sonar interpretation. Aart Kroon and Gerben Ruessink are thanked for making grain size data (surface samples) and bathymetry (JARKUS) of the surfzone off Noordwijk available.