

# **The origin of megaripples, long wave ripples and Hummocky Cross-Stratification in the North Sea in mixed flows**

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## **Abstract**

Various types of megaripples on the North Sea shoreface and inner shelf were mapped with sonar and multibeam imaging (data reported herein and in Passchier & Kleinhans, this volume). The term megaripples refers to wave- and current-driven bedforms, but their dynamic origin in mixed environments is commonly unclear. Here, the origin of various types of megaripples is investigated using field measurements of current and wave conditions, sedimentological structures recorded in boxcores and a bedform stability diagram.

## **1. Introduction**

### **1.1 Scope and objective**

Numerous empirical classifications have been developed for bedforms generated in unidirectional flow, oscillatory flow and combined flow environments (e.g. Ashley et al. 1990). This indicates that the formation mechanisms of all the observed bedform types are far from understood. A common classification for bedforms in unidirectional currents in order of increasing bed shear stress is lower plane bed, current ripples, dunes, and upper plane bed. The exact limits in terms of shear stress depend slightly on grain size. So-called bedform stability diagrams (e.g. Southard and Boguchwal 1990) are therefore commonly given as diagrams with a flow parameter and a grain-size parameter. In oscillatory flow, the lowest energy condition is lower plane bed and the highest upper plane bed, commonly with sheet-flow. Just as current ripples and megaripples or dunes develop in unidirectional currents, wave ripples and (lunate) megaripples develop in wave-dominated environments. There are strong indications that megaripples are not just large wave or current ripples but are a genuine, separate class of bedforms (Ashley et al. 1990) with a different formation mechanism.

The formation mechanisms of bedforms formed in combined flow are not yet understood. Estuarine conditions received most attention (e.g. Dalrymple et al. 1978), but recently some datasets on megaripples (Vincent et al. 1998, Li and Amos 1999, Van Lancker et al. 2000, Gallagher 2003), hummocks (Amos et al. 1996, Green and Black 1999) and long wave ripples (Boyd et al. 1988, Hanes et al. 2001, Grasmeijer 2002) were collected in surfzones and shelf environments. Two bedform types, the long wave ripples (Hanes et al. 2001) and the hummocks (Amos et al. 1996), have defied classification in terms of bedform dimensions and flow conditions, and their genesis remains enigmatic.

The aim of this paper is to study the origin of megaripple-type features observed on the Dutch North Sea shoreface and inner shelf by comparing two contrasting conditions: immediately after a storm and after a quiet period with tidal current dominance. First a review is given on the origin of hummocks and long wave ripples. Then the field sites are described and the methodology is outlined. The tentative results are given. Finally the new data as well as some previously published data are compared in a bedform stability diagram and various hypotheses of bedform genesis are evaluated.

### **1.2 Origin of hummocks and long wave ripples**

Hummocks are three-dimensional low-angle features of several meters long and a few decimeters high, whereas megaripples have higher angles. Hummocks are preserved in deposits with hummocky cross-

stratification (HCS) as low-angle planar bedding, commonly in bundles reflecting the length and migration of the hummocks. Hummocks and HCS do not occur exclusively in shelf conditions (e.g. Swift et al. 1983, Van de Meene et al. 1996) but also on the shoreface (Green and Black 1999) and in the surfzone (Greenwood and Sherman 1986). (Except Southard et al. 1990 all references are to field studies.) The question is whether hummocks and wave and current megaripples are one and the same class of bedforms with the same or a similar formation mechanism (Swift et al. 1983). In dominant wave conditions with a small superimposed current, hummocks are formed on the shoreface and inner shelf of the (Dutch) North Sea (Swift et al. 1983, Van de Meene et al. 1996). With increasing current strength the hummocks become increasingly more asymmetrical and steep like megaripples.

Both the high-angle megaripples and low-angle hummocks are formed under high energy conditions and occur only above a flow threshold at which ripples are already present. Hummocks are usually associated with upper plane bed and sheet-flow conditions under waves. Sheet-flow in currents is rare and commonly associated with supercritical flow, in which other types of bedforms emerge (antidunes). In megaripples a steep slipface is present on one or two sides depending on flow asymmetry, where sediment intermittently avalanches at the angle of repose, yielding large-scale cross-stratification. Hummocks on the other hand have much lower angles, yielding low-angle planar bedding, commonly as intersecting bundles. This is not unexpected because of the high suspension rates and bed fluidisation associated with sheet-flow. It can therefore be argued that hummocks are flattened-out forms of wave-induced or combined flow megaripples.

The hummock length scales to some extent with orbital diameter (Southard et al. 1990), but the thickness of the laminae in HCS is, like the depth of the sheet-flow layer, determined by grain size. It is interesting to note that also suborbital and anorbital ripples scale with grain size rather than orbital diameter (orbital wave ripples scale with the orbital diameter), as do megaripples in combined flow environments (Doucette 2000, Van Lancker et al. 2000).

Related to this are recent observations that wave ripples may occur simultaneously in two lengths. E.g., Hanes et al. (2001) found a clear bimodal distribution of long ripples with length < 0.35 m (SWR) and short ripples with length > 0.5 m (LWR). The bimodality suggests that SWR and LWR have different formation mechanisms (Boyd et al. 1988, Hanes et al. 2001, Grasmeyer 2002). One could argue that the long ripples are relics of higher energy wave conditions, because these bedforms are all rather large so reworking and removal takes time. However, this cannot explain bimodal distributions of bedform lengths. Li and Amos (1998) found LWR immediately after a storm peak with sheet-flow conditions. Li and Amos (1999) concluded that these post-storm bedforms associated with sheet-flow are actually hummocks and have HCS. Since the lengths and environments of LWR in general are comparable to those of wave megaripples and hummocks, it is hypothesised that they are the same type of bedforms.

The above is summarised in the following hypotheses: Hummocks, long wave ripples and megaripples are genetically related and express a continuum of bedform morphology in various combinations of flows. Wave megaripples and LWR are purely wave-generated, dunes or current megaripples are purely current-driven and hummocks are a mixed class. All these bedform types occur (with overlap) in energy conditions intermediate between those of SWR and sheet-flow and commonly form in the aftermath of storms. The dimensions are mostly determined by the grain size, and only to limited extent by orbital diameters, flow velocities and water depth. The low-relief form and near-sheet-flow conditions cause the formation of HCS in wave-induced megaripples, hummocks and long wave ripples.

## 2. Study areas and methods

Three areas were studied off the Dutch coast: the first (NW2) and second (NW8.5) on the inner shoreface and inner shelf (2 and 8.5 km offshore, water depths 12 and 18 m, respectively) at Noordwijk (EU-SANDPIT data). The third area (NITG1) is on the lower shoreface further to the north (water depth 16 m), was mapped partly before and partly after a gale ( $H_{sig} < 3$  m), and is described in Passchier & Kleinans (this volume). The first two areas were mapped with multibeam and sonar-imaging techniques in October 2002 (sonar only) after a large storm ( $H_{sig} < 6$  m) and in Februari 2003 (sonar and multibeam) after a quiet period. The NW2 and NW8.5 areas were part of a cross-shore transect extending between 2 and 20 km off

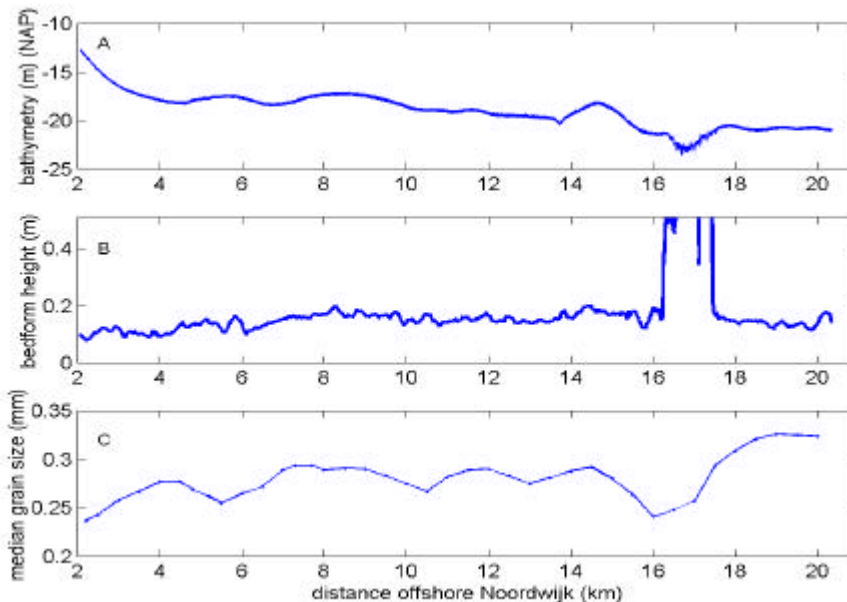
the coast. Cross-shore (18 km long) and long-shore (2 km long at 2, 10 and 16.4 km offshore) profiles were extracted from the unfiltered, tide-corrected SANDPIT multibeam data along which the bedform heights were estimated as follows. The 2.5 and 97.5 percentiles of bed-surface height were computed in a moving window of 200 m long in each of which the bed was detrended with a 2<sup>nd</sup> order polynome. The result is an estimate of the bedform height along the profiles. With the multibeam data the elevation of bedforms can be quantified, but the vertical noise level is 0.1 m which excludes the smallest bedforms regardless of their length. The sonar is sensitive to smaller bedforms depending on the illumination direction of the transducer, but required image interpretation.

Wave conditions (not given in detail here) were recorded at the Meetpost Noordwijk platform which is located 9.5 km off Noordwijk, and the near-bed orbital velocities were computed using linear wave theory. The current conditions were recorded with EMF sensors on a benthic tripod within 1m above the bed. At a later stage of the SANDPIT project more detailed data from the benthic tripod at NW2 will be available for study of the hydrodynamics in the bottom boundary layer.

The sediment characteristics were determined from boxcores by conducting laser grain size analysis and describing sedimentary structures. Lacquer profiles of the (vertical) stratification of the top 0.2 m of the bed were made from boxcores in area NW2. Lacquer profiles are made from a near-vertical section (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 and bioturbation stand out clearly.

### 3. Results

The cross-shore profile and the three long-shore profiles are given in Fig. 2. The estimated bedform heights are in the order of 0.2 m along the profiles, except on the inner shoreface between 2 and 4 km offshore where the bedform height decreases to the noise level, and between 16 and 18 km offshore where suction dredging took place. The median grain size of the bed is between 0.25 and 0.30 mm on most locations, and decreases on the inner shoreface between 2 and 4 km offshore.



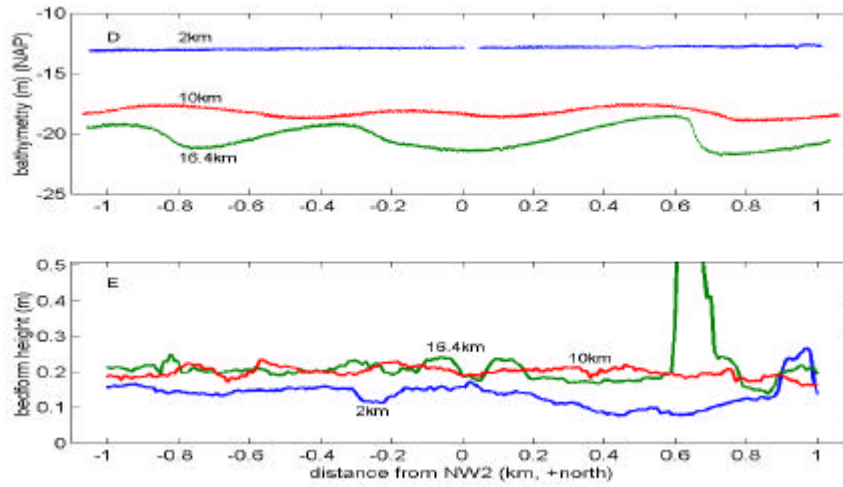


Fig. 2 – Cross-shore (a) and long-shore profiles (d) of the bed surface, estimated bedform height (b, e) and median grain size (c). The anomaly at 16-18 km offshore is due to suction dredging.

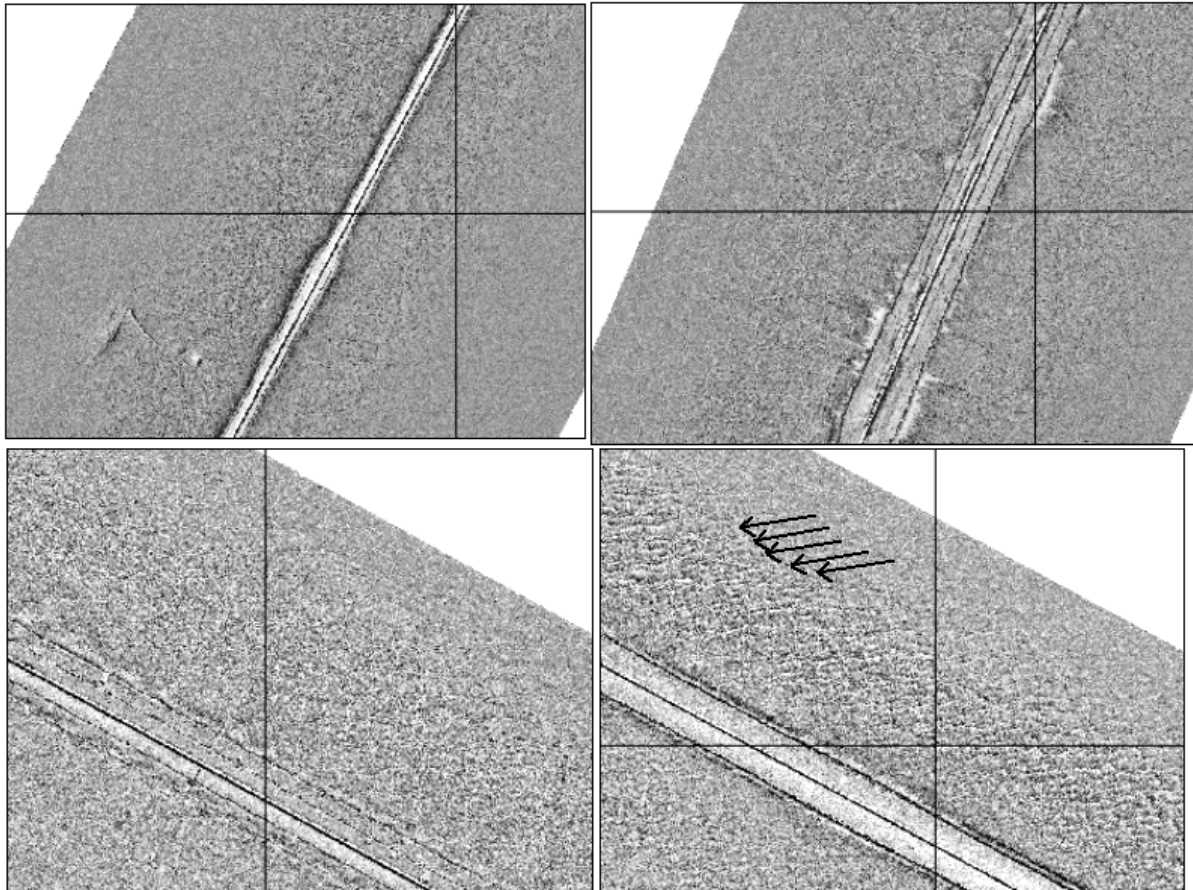


Fig. 3 – Sonar images of the middle-shoreface area (SANDPIT data) of 2 (top) and 8.5 km (bottom) offshore collected during the October 2002 post-storm conditions (left) and in February 2003 after fairweather conditions (right). The images represent areas of 300 m (top) and 200 m (bottom) wide. The line structure in the top-left image is one of the buoys plus anchors installed for protection of the benthic tripod. North is upward direction. The orientation and location of current-megaripple crests is indicated with arrows, but was not corrected for skewed orientation of the towed transducer due to tidal currents.

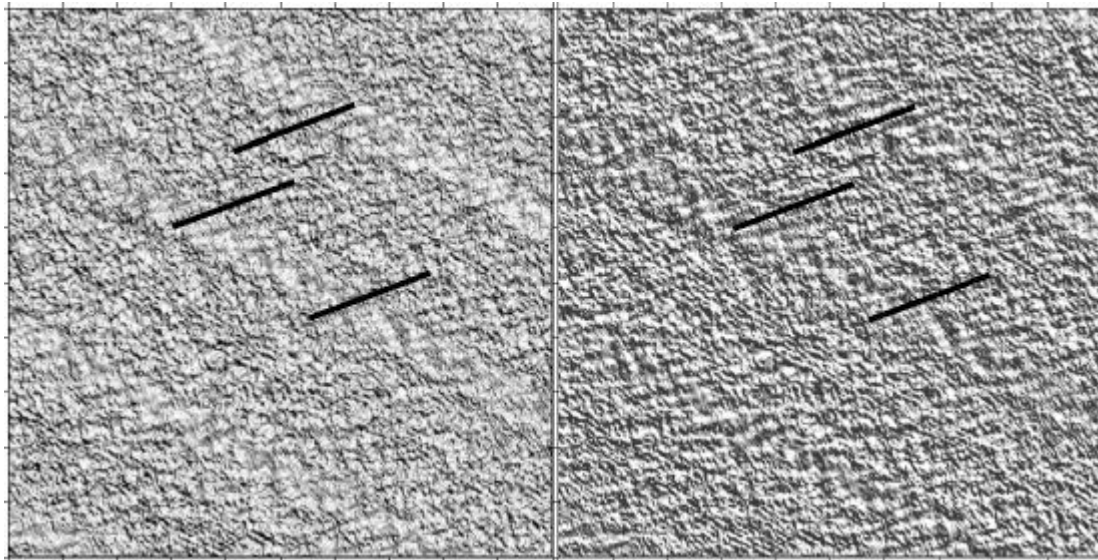


Fig. 4 – February 2003 multibeam image of the NW8.5 area, with illumination from two different angles above the bed ( $60^\circ$  for left and  $30^\circ$  for right) to simulate the effect of variation in sonar illumination angle with increasing distance from the sonar image axis. The most notable structure is striping due to slightly inaccurate overlap between multibeam tracks. The black lines indicate bedform crest orientation. The sides of the images are 100 m. North is upward direction.

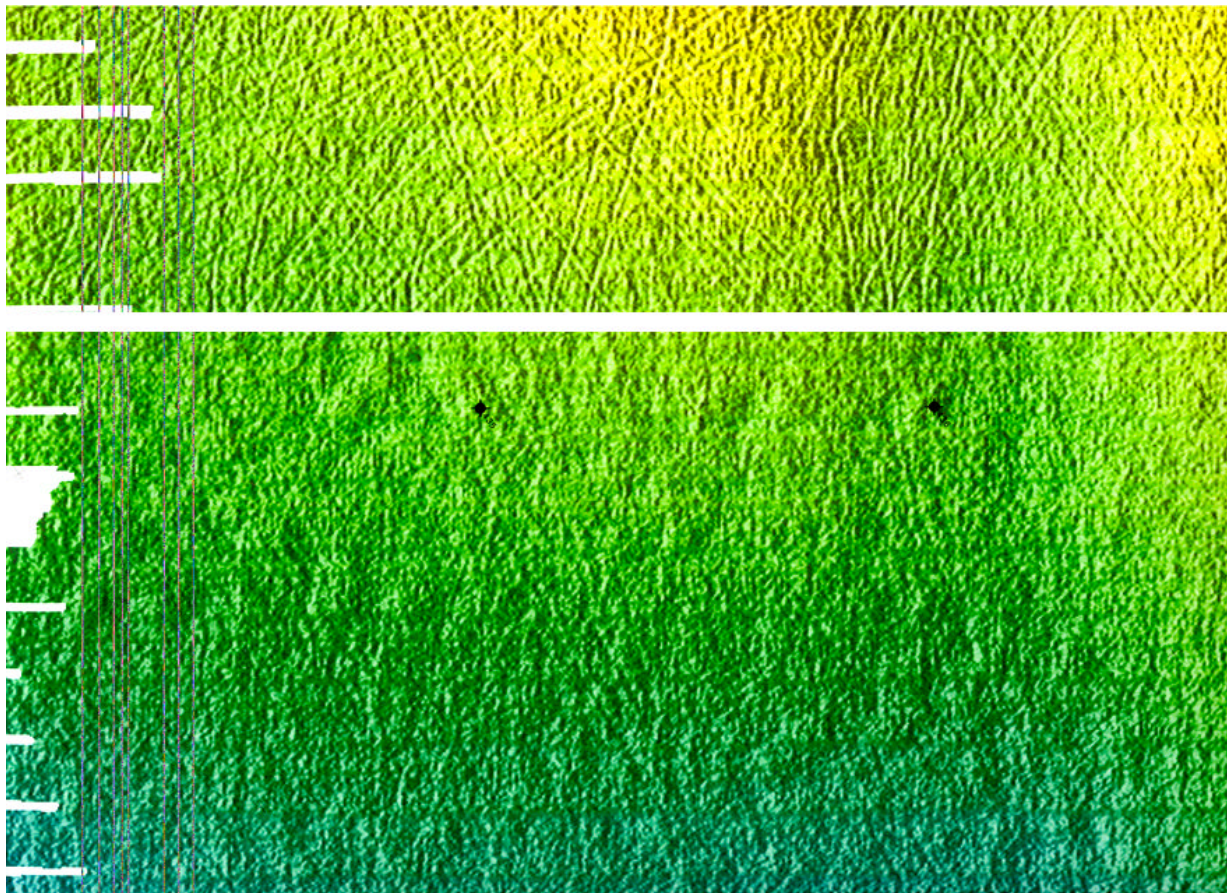


Fig. 5 – Multibeam image of NITG1 area, showing bedforms and fishing tracks before (above white line) and after (below) a gale ( $H_{sig} < 3\text{m}$ ). The north is to the right. The vertical sides of the image are 500 m.

The sonar images of the NW2 area in Fig. 3 indicate small three-dimensional ripples that are barely discernible. The sonar images of area NW8.5 indicate small three-dimensional bedforms immediately after the October 2002 storm and two-dimensional straight-crested bedforms after a fairweather period in February 2003. Both have wavelengths in the order of 5 m. Detailed multibeam digital elevation models of the NW8.5 area as in Fig. 4 were illuminated from different angles to simulate a sonar image. Two-dimensional bedforms (the same dimensions as visible on the sonar) are apparent although near the noise level, confirming the interpretation of the sonar image. The multibeam images of the NW2 area show a plain, seaward down-sloping bed with no structures above the noise level of 0.1 m, and therefore could not be used to map the bedforms indicated on the sonar images.

The multibeam data of the NITG1 area were collected partly before and partly after a gale (Fig. 5, Passchier & Kleinahns, this volume) and indicate reformation of well-defined three-dimensional bedforms with a wave length of 30-40 m. Since this must have occurred during the (waning?) gale, these bedforms are wave-generated. However, their wave length does not scale with the orbital diameter (~1.5 m).

The sedimentary structure of the bed immediately after storms demonstrates the nature of the observed hummocky bedforms. A typical example of a lacquer profile, from a boxcore taken 5 km offshore off Noordwijk is given in Fig. 6. Preliminary study of the lacquer profiles indicates that low-angle planar bedding, almost without bundles, interpreted as Hummocky Cross-Stratification of long hummocks, occurs in almost all profiles taken at 2, 5, 8.5 and 10 km offshore after the October 2002 storm and after the November 2003 storms. In fairweather periods some tidal signatures such as clay-drapes are found. In summer all flow-induced structures commonly are eradicated by bioturbation. After a storm most of the shells were broken and had been worked down to the base of the active layer of the storm. This active layer commonly is between 0.1 and 0.2 m thick (cf. Passchier & Kleinahns, this volume), and has a brownish color in contrast to the gray underlying sediment.

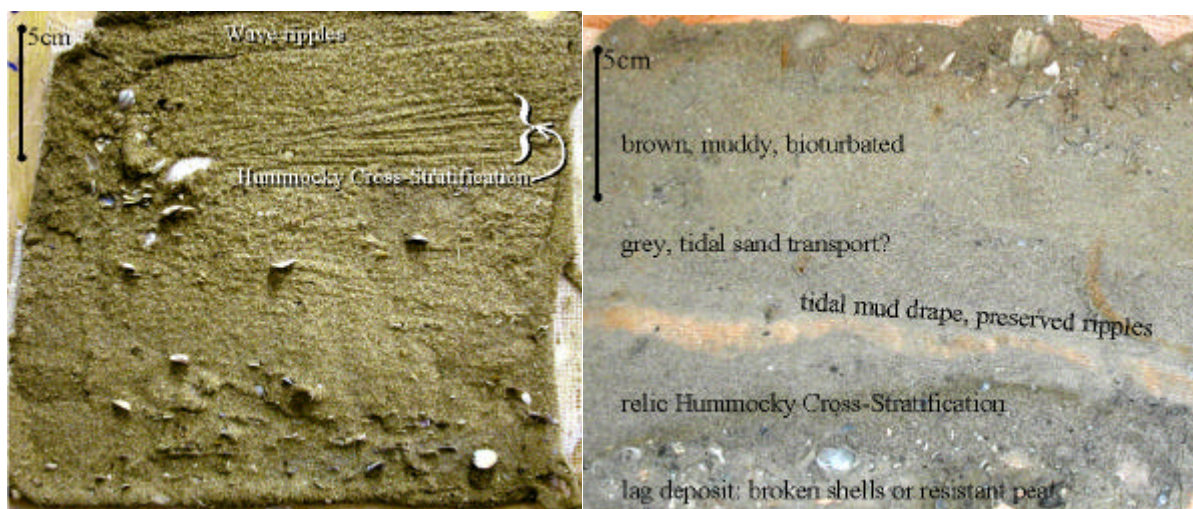


Fig. 6 – Lacquer profiles from boxcores taken on November 2002 (post-storm) at a water depth of 17 m (left) and on September 2003 (fairweather conditions) at 12 m water depth (right).

#### 4. Discussion

The two-dimensional bedforms observed after a fairweather period strongly resemble river dunes. ‘Megaripple’ is considered an alternative term for small dunes in a marine environment. Common variations in dune or current megaripple shapes are a source of confusion in attempts to infer the origin of the bedforms from their shapes in mixed wave and current conditions. From *in situ* bedload measurements it is clear that the sediment mobility is low and very close to immobility (Van de Meene et al. 1996, Kleinahns in prep.). In such low-energy conditions current related bedforms are commonly two-

dimensional. Moreover, the crest orientation is roughly perpendicular to the tidal current, so the observed forms in the NW8.5 area are clearly current-related.

From the observation of low-relief three-dimensional megaripples in the NITG1 area immediately after a gale it can be concluded that these bedforms are, at least partially, wave-generated. The observation of HCS immediately after storm strongly suggests that these megaripples are the same type of bedform as hummocks. Hummocks are known to be generated in wave-dominated conditions modified by a minor current (Swift et al. 1983), which agrees with the conditions characterising the study areas (although wind-driven currents may be significant during storms, which will be investigated in the near future with the SANDPIT data). From the comparison between the NW2 and NW8.5 sites, it is suggested that the size of the hummocks increases with increasing grain size, as expected from literature (Southard et al. 1990, Van Lancker 2000), whereas the wave length is  $O(10)$  larger than the significant orbital diameter. The thickness of sediment layers deposited as hummocks (HCS) is 0.1-0.3 m in the boxcores reported herein, which agrees with the estimated bedform height and with Swift et al. (1983). The hypothesis that one set of HCS is created in one event (Greenwood and Sherman 1986, Van de Meene et al. 1996, Amos et al. 1996) is corroborated with the present boxcores.

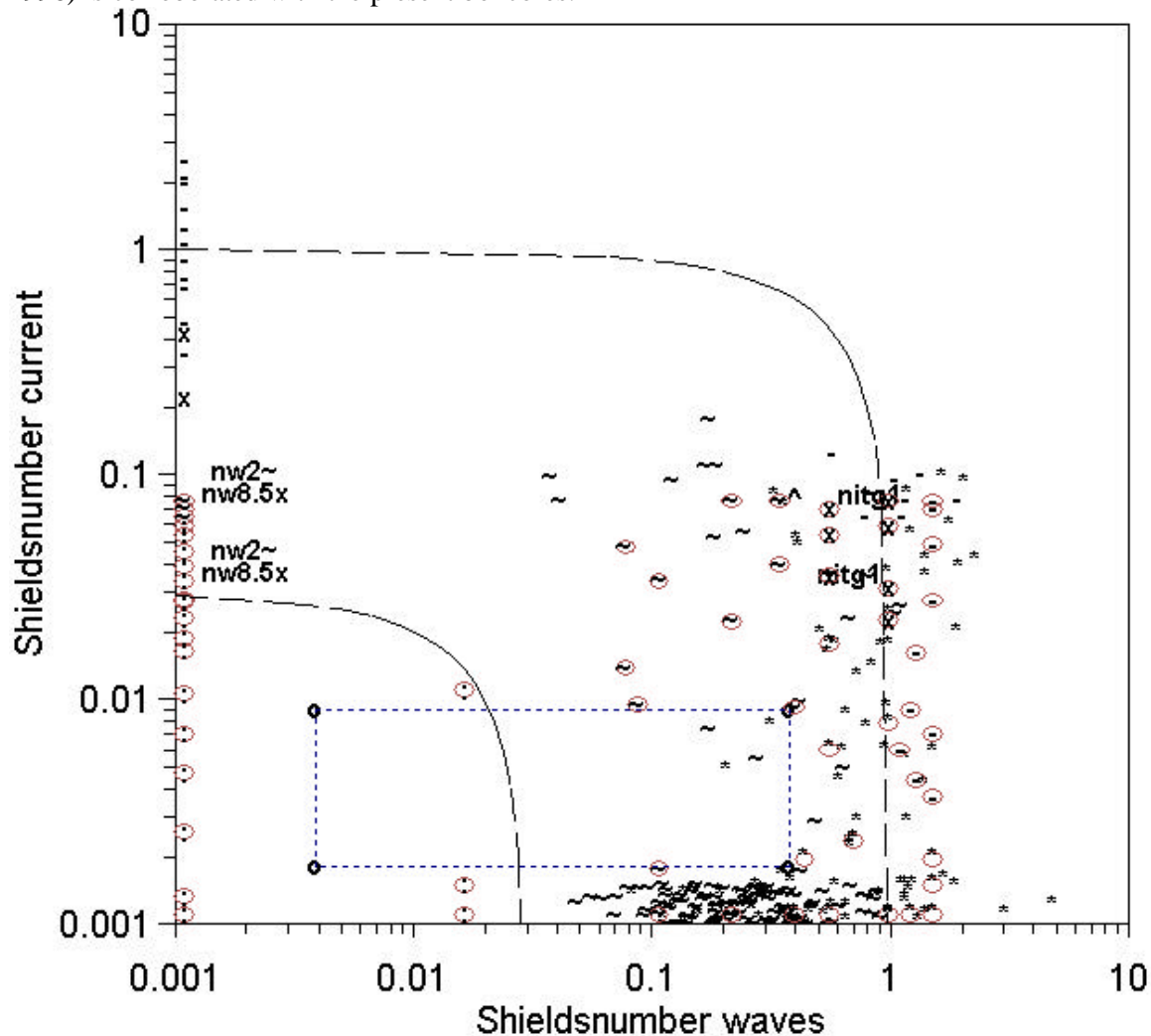


Fig. 7 – Bedform-stability diagram. ---:  $\theta_{waves} + \theta_{current} = 0.03$  and 1.0 (thresholds for motion and sheet-flow), :=no motion, ~:=ripples, x:=dunes/megaripples, \*:=LWR/hummocks, -:=upper plane bed/sheet-flow, o--o denotes range of Traykovski ripples. Encircled points are laboratory data from Arnott and Southard.

The data are plotted in a bedform stability diagram. The dimensionless (Shields) shear stress parameter is straightforwardly computed, ignoring their different directions:  $\theta = \tau / [(\rho_{\text{sed}} - \rho_{\text{water}})gD_{50}]$ , with  $\tau = \rho_{\text{water}}g[u_{\text{cur}}/18 \log(12h/2.5D_{50})]^2$  for currents and  $\tau = \rho_{\text{water}}u_{\text{orb, sig}}^2 \exp[5.213(2.5D_{50}/A_{\text{orb, sig}})^{0.194} - 5.977]$  for waves, with  $\tau$ =shear stress,  $g=9.81 \text{ m s}^{-2}$ ,  $h$ =local water depth,  $u$ =significant orbital velocity,  $D_{50}$ =local median sediment diameter,  $A$ =orbital diameter from linear theory and significant wave height  $H_{\text{sig}}$  and period  $T_p$  from the Meetpost Noordwijk. The parameters relating to the images collected immediately after storm are computed for the peak wave height of that storm, and for tidal currents the flood spring-tide peak and the neap ebb-tide peak are given as extremes. Data from the literature are: current dunes on the sand banks of Belgium (Van Lancker et al. 2000); short and long wave ripples on the inner shoreface of Duck, USA (Hanes et al. 2001); long and short wave ripples plus small current in the surfzone of Egmond, The Netherlands (Grasmeijer 2002); inner shelf wave ripples (Traykovski et al. 1999, clustered); wave ripples, hummocks and sheet-flow formed under waves on a shelf (Li and Amos 1999); sheet-flow in currents (rivers) (Julien and Raslan 1998) and laboratory duct data (Arnott and Southard 1990, encircled symbols). Below  $\theta_{\text{waves}} + \theta_{\text{current}} = 0.03$  most observations are no motion, which agrees with the Shields criterion, and around  $\theta_{\text{waves}} + \theta_{\text{current}} = 1.0$  most of the points representing hummocks, dunes, megaripples, LWR and sheet-flow are clustered which demonstrates that these bedforms are formed at equal shear stresses. Some overlap between bedform types may reflect superposition in reality, uncertainties related to the shear stress computation method and effects of relic forms, on water depth and wave versus current directions, and to a certain grain size dependence of hummocks (results herein), current dunes (Van Lancker et al. 2000) and LWR (Hanes et al. 2001).

## 5. Concluding remarks

The hypotheses in section 1.2 have been evaluated with field data on the shoreface and inner shelf of the North Sea off Holland. In specific:

1. Three-dimensional wave megaripples after storm have hummocky cross-stratification. These bedforms are mostly wave-generated but with a small current component and are probably genetically related to hummocks. Two-dimensional megaripples after a quiet period are probably current-generated and are formed at equal shear stresses as river dunes.
2. The pattern of data in the bedform stability field suggests that the various bedform classes as described herein and in literature are part of a continuum of bedform types in varying contributions of wave and current flows. This indicates that a applicable bedform stability diagram (based on data) is feasible if the continuum of bedform type classes is properly reflected.

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