Architecture of very large submarine dunes influenced by tide- and wind-generated processes (Dover Strait, northern France)

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Abstract

A detailed seismic investigation of an extended field of very large dunes located in the central part of the Dover Strait (Southern North Sea) led to the recognition of three types of dune architecture. The diversity of architecture, also reflected in the dune morphology, is due to the balance between tide and wind-driven processes that occur in the study area. The results show that a study based on a geometrical description of internal structures only does not enable the reconstitution of ancient depositional environments. A discriminant criteria consists of the thickness of the second order sequences, although it is also strongly influenced by dune height.

1. Introduction

In tidal environments, several models of dune architectures have been proposed conceptually (Allen, 1980), from direct observations (Dalrymple,1984) or from seismic data and cores (Berné et al., 1988, 1993). Although they display strong geometrical similarities, the genetic processes proposed for the formation of the internal discontinuities and the global architecture are variable (tidal current asymmetry and instability, presence of superimposed dunes, seasonal non-tidal events).

On epicontinental shelves, wind-driven currents can play an important role, for example in the seasonal inversion of dune polarity (Harris, 1991; Thauront et al., 1996). In the Dover Strait, where large dunes display changing migration rates and directions according to the wind regime and the storm activity (Le Bot et al., 2000), we investigate the signature of tidal and wind-driven processes in the internal structure and external morphology of subtidal dunes.

The study of their internal structure enables to improve the knowledge of the formation and evolution mechanisms of sedimentary bedform. Recognition of present-day internal structures typical of specific hydro-sedimentary processes could enable the reconstitution of ancient depositional environments and processes. This would be of special interest in areas where deposits are scarse and thin or mainly concentrated in bedforms.

2. Studied area

The study area is located in the central part of The Dover Strait which corresponds to a shallow water continental shelf, where the seabed is essentially composed of a relict pebble-lag pavement, some tens of centimetres thick, mantled with a series of scarce sand and gravel bedforms (James et al., 2002). The tidal regime is semi-diurnal and characterised by a macrotidal range (2.5 to 6.5 m). Tidal currents are strong and present a marked alternating character. In mean tidal conditions, residual sediment transport pathways follows the asymmetry of tidal current phases on a long-term basis, but can be temporary reversed due to a change in the mean wind direction and stormy waves, without affecting long-term sediment transport pathways (Grochowski et al., 1993).

The study area consists in a field of 26 submarine dunes, located at the southern extremity of the South Falls sandbank. The water depths range from 20 m to 40 m (Fig. 1). They correspond to very large compound dunes which display heights of between 4 and 12.5 m and wavelengths ranging from 200 to

1100 m. Over the whole area, two sectors, termed A and B, comprise dunes that present various morphodynamic characteristics (Le Bot, 2001):

- In sector A, the dunes are typical of sand-rich environments characterised by low energy hydrodynamics. They consist of small to very large 2D dunes organised in a compact field. They are mainly made of a 0.35-mm medium sand (samples S1 and S2, Fig. 1), integrally covering the pebble lag. The dune migration is variable in direction and rate depending on the wind regime and the time-scale at which the observations are recorded.

- In sector B, the dunes are typical of sand-starved environments characterized by high energy hydrodynamic regimes. They comprise very large, isolated 3D dunes, frequently starved of superimposed smaller dunes. They are composed of a sediment made of flattened shelly gravels at the crest of the dune (sample S3, Fig. 1), associated with 0.35-mm medium sand on the dune flanks. Between the dunes, pebbles are associated with small volume of medium sand (sample S4, Fig. 1). The dunes migrate permanently towards the SW.

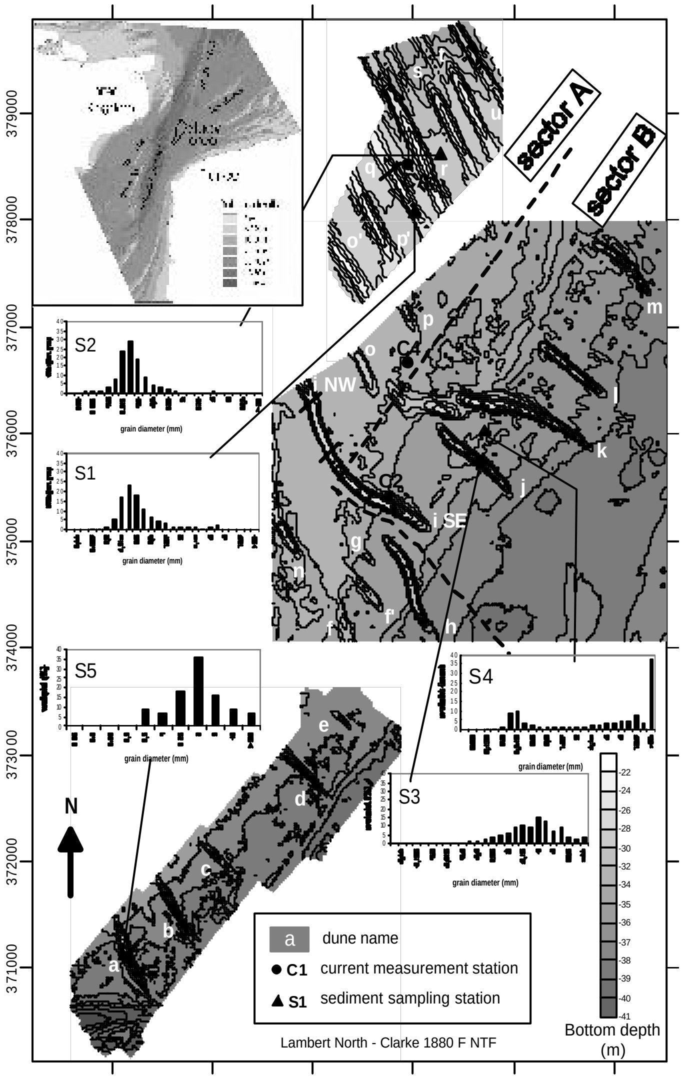

Fig. 1 – Study area.

Left: location of the submarine dune field in the Dover Strait (bathymetric map, from James et al., 2002). Right: Detailed bottom depth and location of dunes, current measurements, sediment samples with grain-size analysis presented in the paper.

3. Hydro-sedimentary processes

Complemented with results from dune migration analysis, current measurements, made in 1999 by SHOM (Hydrographic and Oceanographic Office of the French Navy), in the sector A (see location on Fig. 1), 1 m above the flat seabed, and hydrodynamic modeling simulations, realised by Idier and Astruc (in prep) in the Dover Strait, are used to characterize and quantify the hydro-sedimentary processes acting on the dunes. Special attention has been paid to instantaneous and residual sediment transport due to sole tidal currents and for combined tide- and wind-driven currents.

The tidal asymmetry is pronounced in favour of the ebb current phase in sector A, whereas it is negligible in sector B (about 0.03 m/s in favour of the flood current phase). Wind speeds required for the annulation and reversal of tidal currents are easier and more often reached in sector A than in sector B. In sector B, only strong wind-driven currents may modify the tidal hydrodynamic regime (e.g. storms combined with neap tides). Although sediment transport does not occur permanently, dune sediment is always transported towards the SW. In sector A, the tidal circulation is weak, nearly symmetrical and easily modified with winds of moderate speeds (a few m/s). In sector A, dune sediment is nearly permanently transported, and the transport is oriented towards the NE in case of no wind or SW winds, and towards the SW in case of NE winds.

4. Internal architecture and external morphology

4.1 Seismic data acquisition

A 3,5-kHz EDO-Western subbottom profiler has been deployed during the Ridens I (June 1996, 21 profiles, 88 km) and Ridens II (November 1998, 18 profiles, 90 km) surveys. The seismic system used allows an efficient penetration of about ten metres enabling the dune bodies, to be mostly insonified, with a vertical resolution of about 0.5 m. The data have not been post-processed and coring attempts for validation failed due to sediment coarseness and current velocity.

4.2 Internal discontinuities: typology, nature and origin

Seismic analysis of dune structure reveals a hierarchy of discontinuities of three different types, termed 1, 2, 3 on the seismic sections presented on Fig. 2. First-order reflectors correspond to sub-horizontal reflectors. They can be attributed to the progradational surface of the dunes above the pebble lag pavement at the dune base, and to the erosional surface generated by the overlapping of smaller superimposed dunes which have migrated faster than the host dune on the summital part. Third-order reflectors (25 to 30°) are considered to result from the alternation of avalanche phases and « sandy rainfalls» according to Berné et al. (1988). The dune master-bedding is constituted by second-order large erosive discontinuities, which dip with an angle of 9 to 11°, in a direction nearly perpendicular to the dune crest, and which reflect processes affecting either the progradating steep flank or the long flank of dunes. This type of discontinuities has been reported for other dunes located in shallow marine environments, and several hypothesis have been drawn concerning the origin of these discontinuities (action of the subordinate current, Allen, 1980 ; migration of superimposed dunes, Dalrymple, 1984 ; episodic combination of tidal and wave-generated currents, Berné, 1991).

In order to better constrain the erosive processes which give rise to these discontinuities, their formation periodicity has been estimated using the following formula :

$$T = S * \rho_s / q \qquad (1)$$

where T: formation periodicity of large erosive discontinuities

S: vertical surface of sediment trapped between 2 large successive large erosive discontinuities, estimated from seismic records.

ρ_s: sediment volumic weight, equal to 1600 kg/m^3 in case of a well sorted, medium sand (typical from sector A) or poorly sorted, coarse sand (typical from sector B).

q: bedload transport capacity, derived from current measurements realised in sector A.

The time elapsed between the formation of two large erosive discontinuities varies according to the dune types and hydrodynamic conditions. The formation periodicity is estimated as a minimum of 3.8 to 7.3 months (maximum 5.4 months in sector A) for a mean regime with combined tide and wind conditions. However, conditions with permanent wind-driven currents cannot realistically occur for the duration of such a long period. During the period concerned with the calculation (June 1996-November 1998) one violent stormy period has been identified per year in 1996 and 1997, and none in 1998 (Bessemoulin and Dreveton, 2003), revealing a good correlation between the occurrence of storm events and the formation periodicity of large erosive discontinuities. In sector A, the hydrodynamic conditions necessary for the temporary inversion of peak tidal current velocity asymmetry and transport are more often reached than in sector B, explaining the more frequent occurrence of large erosive discontinuities in sector A. In addition, dunes, which are smaller in this sector, adapt to less energetic and shorter inversions.

4.3 Types of architecture

Three main types of internal architecture have been recognised in the study area. They were previously reported by Berné et al. (1988, 1993) at diverse locations on the French continental shelf.

Asymetric dunes in cosets mostly correspond to the largest structures with heights greater than 6 m (Fig. 2, right panel). The superimposed dunes generally form a homogeneous pattern of 1 to 1.5-m high, but they can change into higher, more heterogenous shapes.

Asymmetric dunes in cosets are composed of a single megasequence which lays on the dune progradation surface and is truncated in its upper part by the progradation surface of superimposed dunes. Each sub-sequence limited by large erosive discontinuities are 2.5 to 4.85 m in dune i SE, 1.7 to 3.8 m in dune i NW and 1.7 to 2.1 m thick in dune j. Within small superimposed dunes the internal reflectors observed may dip in an opposite direction compared to the dipping of the master-bedding, but these reflectors are temporary and not long-term preserved. The external morphology of these dunes is characterised by a pronounced asymmetry. Their steep side is permanently oriented in the direction of large erosive discontinuities. The steepness of the steep flank varies therefore with time from this of large erosive discontinuities to the one of an avalanche surface.

Dunes in mega-chevrons display a wide range of heights, between 2.5 and 9 m (Fig. 2, left panel). Internal organisation of these dunes is complex. It consists of an up-piling of coset sequences with opposite progradation direction. The boundary between 2 successive sequences consists of a large erosive discontinuity which has affected the long flank of the dune. This second order discontinuity dips in the opposite direction compared to the underlying discontinuities. Sequences between 2 large erosive discontinuities are 1.5 to 3.1 m thick in the central part of dune i and 2.7 to 3.0 m thick in dune b. The complexity of the internal architecture is expressed in its external morphology, where symmetry or asymmetry is very little marked.

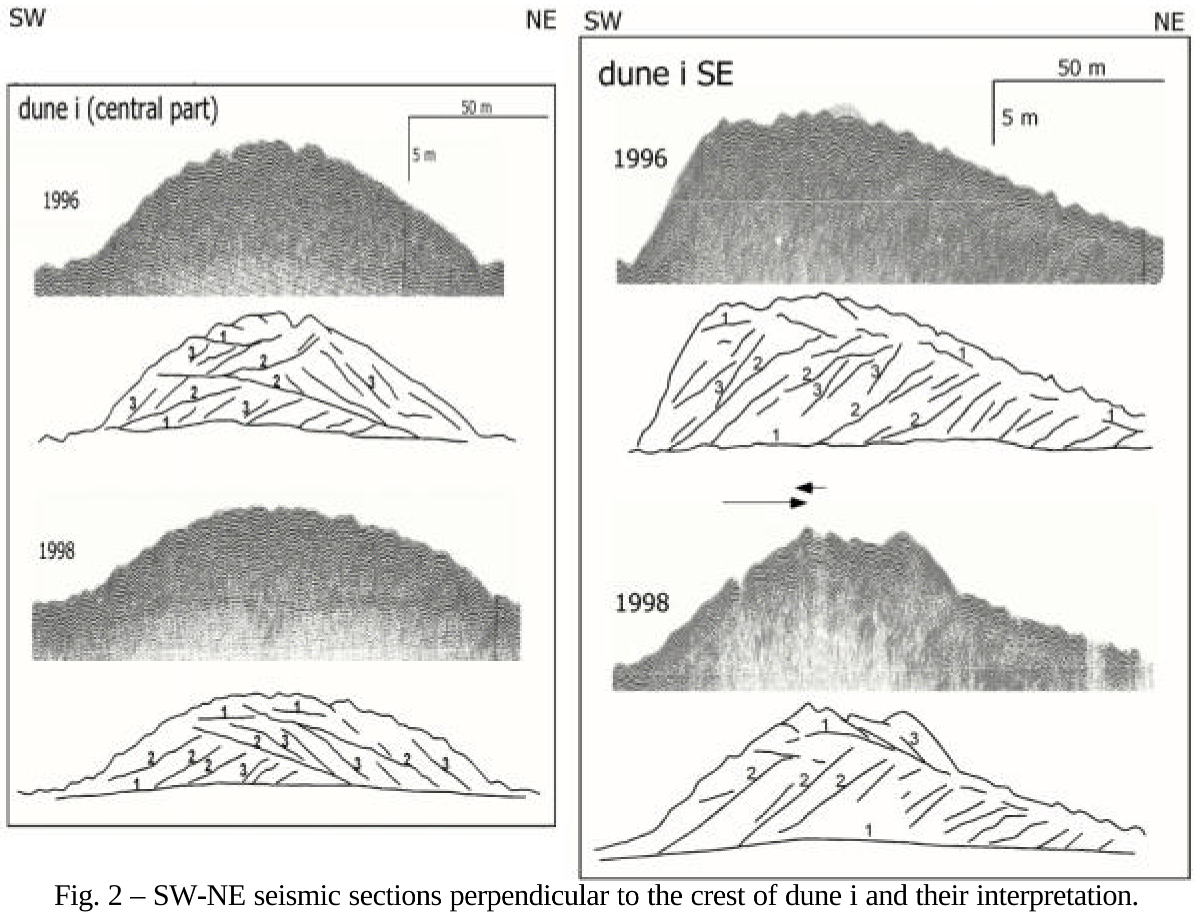

Fig. 2 – SW-NE seismic sections perpendicular to the crest of dune i and their interpretation.
Left: architecture in mega-chevrons in the central part.
Right: asymmetric architecture in cosets in the southwestern part.

Dunes with megaripple bedding sequences are observed in sand-rich sectors in dunes with moderate heights (5-6 m). These dunes consist generally of 2 sequences. A basal sequence typical of asymmetric dunes in cosets or typical of dunes in megachevrons is truncated along a horizontal reflector by an upper sequence composed of a complex assemblage of beds which dip successively in opposite directions. The thickness of the complex beds is similar to the heights of superimposed dunes indicating that these deposits are controlled by superimposed dunes. This mixed architecture is not permanent in time. Like the internal architecture, the external morphology is composite. The flanks of the basal sequence present an asymmetry orientated in the direction of internal discontinuity dipping. In the upper sequence of megaripple bedding, the external morphology is symmetrical.

4.4 Spatial distribution of the types of architecture

In the present study, the particularity is that the three types of architecture are observed within a single dune field, and even sometimes within a single dune.

- Distribution within sectors A and B

In sector B dune architecture is homogeneous and constant. It consists of dunes in cosets with a SW asymmetry. Large erosive discontinuities dip towards the SW in the direction of dune migration. At the boundary between the two sectors, dunes portions (mainly dune extremities) present an architecture in mega-chevrons. In sector A, complex time-varying architectures are observed: (1) in the western part, dunes in cosets are the most frequently observed features with an asymmetry generally oriented towards the NE, in agreement with the dipping of internal discontinuities and the direction of long-term dune migration. However, some dunes present typical symmetrical sequences with megaripple bedding which give evidence of the great density of superimposed dunes in this sand-rich area. However, in time, both architectures can be observed within a given dune ; (2) dunes f, f' and g present an architecture in mega-chevrons. Sometimes they are asymmetric and made of cosets with a SW (1996) or NE (1998) progradational direction, implying that the dunes have been totally rebuilt during this period ; (3) dunes a to e are composed of mega-chevrons indicating a NE-SW alternating migration.

- Dune i: a combination of the different architecture types

Dune i partly belongs to sector A and sector B. Its SE part is located in sector B and displays the architecture that is characteristic from this sector: it has a strong SW asymmetry coupled with an internal architecture in cosets dipping in this direction (Fig. 2, right panel). In the NW part of dune i, the architecture is of the same type, but the dune is symmetrical and internal discontinuities dip towards the NE. In the central part of dune i, the architecture is typical of a mega-chevrons shaped symmetrical dune (Fig. 2, left panel).

5. Effects of the balance between tide- and wind-generated processes in the dune architecture and morphology

The diversity of dune internal architecture and external morphology reveals the variable hydrodynamic and sediment transport conditions that occur in the study area.

5.1 Influence of the asymmetry of tidal currents

In sector B, tidal currents are fast and their asymmetry is pronounced in favour of the ebb current phase. Large erosive discontinuities within the megasequences are oriented towards the SW, in the direction of the dominant ebb current, the sediment transport and the dune migration.

In sector A, tidal velocity asymmetry is low to negligible. The slope of large erosive discontinuities is mainly oriented in the direction of the slightly dominant flood current (i.e. the NE), and dunes generally correspond to asymmetrical dunes in cosets. Dunes a to g which are located in a gyre show the predominance of mega-chevrons architectures with complex external morphologies, indicating no preferred progradational direction.

5.2 Influence of wind-driven currents

In sector B moderate SW winds induce the decrease of SW tidal residual sediment transport but no reversal of sediment transport direction. Dunes display the same internal architecture and external morphology as in absence of wind, but the depositional sequences will be temporarily thinner and/or less frequently formed. Migration of the dunes will also slow down (scheme b, Fig. 3). If moderate NE winds are established, the SW tidal residual transport will be enhanced, resulting in thicker and/or more frequently formed depositional sequences (scheme e, Fig. 3). In case of a stormy winds, dune architecture and asymmetry are not modified, but the steep and long flanks of the dune and its top are somewhat affected (scheme k, Fig. 3). The steep flank of the dunes is eroded, forming a new large erosive discontinuity (e.g dune i SE in 1998). Eroded sediment contributes to the feeding and migration of superimposed dunes towards the NE. Once the event stops, superimposed dunes recover their tidal polarity and the slope of the steep flank is increased again. Dune migration is stopped, or slightly reversed towards the NE in its top part. In case of NE stormy winds, the steep flank constitutes an avalanche surface, the migration accelerates and the depositional sequence thickens and/or forms more frequently (scheme h, Fig. 3).

In sector A fluctuations in the wind direction are directly correlated with fluctuations of sediment transport direction and rate. Most dunes may progradate temporarily in the direction of the tidal current phase reinforced by wind-driven currents (schemes a and c, Fig. 3). In the western part, dune migration is merely stopped than reversed. The abundant superimposed dunes react immediately to current fluctuations, and an upper symmetrical sequence with megaripple bedding is formed (scheme d, Fig. 3). In the case of SW stormy winds, dune migration strongly intensifies and thicker and/or more numerous depositional sequences are formed (schemes f and g, Fig. 3). In the case of NE stormy winds, the progradational direction of dunes (schemes I and j, Fig. 3) is reversed, leading to the formation of a new depositional sequence dipping towards the opposite (SW) direction and to an architecture in mega-chevrons.

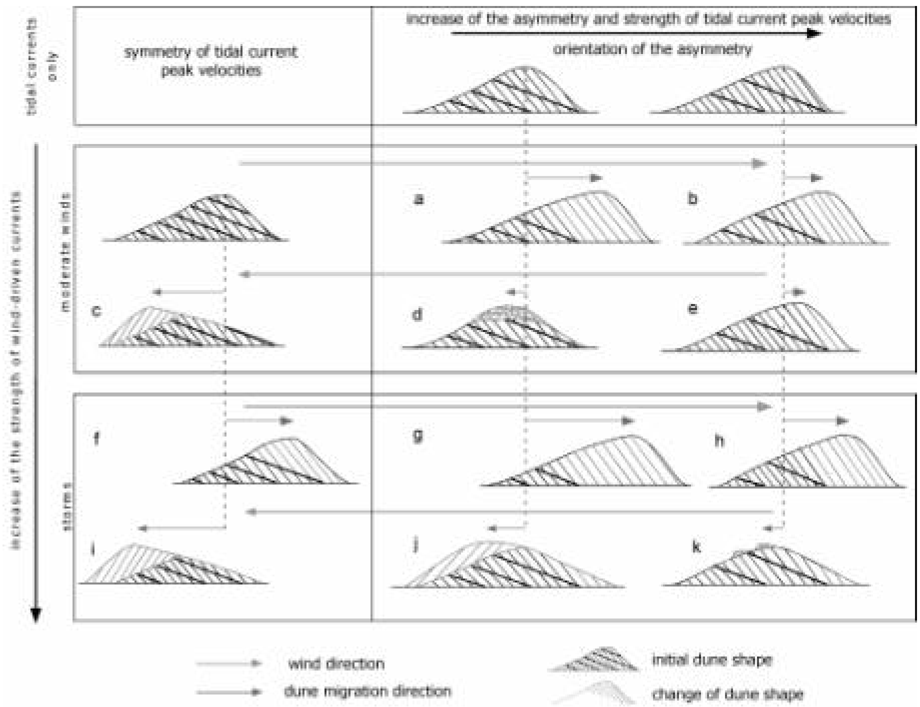

Fig. 3 - Types of internal structure and external morphology of submarine dunes as a function of tidal peak current asymmetry (horizontal axis) and wind-driven current strength (vertical axis). Types c, f and i are similar to dunes of the southern part of sector A and dunes located at the boundary between sectors A and B; types a, d, g and j are similar to dunes of the western part of sector A; types b, e, h and k are similar to dunes of sector B.

5.3 Illustration from the modifications observed between 1996 and 1998

Between 1996 and 1998, observed architectural modifications consisted either in the formation of NE dipping second and/or third order discontinuities (sector A) or in the erosion of dune structures located on the SW sides of dunes (sector B). Compared to previous periods, the wind regime between 1996 and 1998 was characterized by an increase in SW winds. This variation in wind regime has induced longer and more frequent periods of NE orientated currents during the 1996-1998 period and NE dune migration (sector A) or decreased SW dune migration (sector B), responsible for the architecture modifications observed.

6. Geometrical criteria to help defining ancient depositional environments. Comparison with dunes from other shelf areas.

In the study area, the architecture types are typical of combined tide- and wind-driven processes. As the internal discontinuities, the different types of dune architectures display strong geometrical similarities with structures observed in dunes from other shelf environments, where the processes and the dune dimensions can differ (Allen, 1980 ; Berné et al., 1988, 1993). This implies that a study based on a geometrical description of internal structures only does not enable to determine the hydrodynamic environment where dunes occur. This could be an important point for the reconstitution of ancient depositional environments.

A more discriminant criteria consists of the large erosive discontinuities. Their formation periodicity and the thickness of sequences bounded by 2 large erosive discontinuities are typical of specific hydrodynamic agents and resulting genetic processes, and also of dune dimensions. Sequences are 1.5-4.85 m thick in the present study (2.65 m on average) and 5-10 m thick in Berné et al. (1988) for very large dunes (3-7.5 m high), 0.1-1 m thick in Allen (1980) for intertidal ripples and 1.19-0.77 m thick in Dalrymple (1984) for medium intertidal dunes (0.81 m high on average). In the present study, as in the literature, the most clear relationship is observed between the maximum thickness of sequences and the height of dunes. The higher the dune, the thicker the second order sequences. In the study area, the thickness of sequences is larger in asymmetric dunes in cosets than in dunes in mega-chevrons, and in sector B than in sector A, indicating that tidal asymmetry is the main parameter influencing the thickness of second order sequences. In the Surtainville area, where the tidal asymmetry is similar, the larger thicknesses of sequences are due to less frequent sediment transport reversal and discontinuity formation induced by processes with equinox cyclicities (Berné et al., 1988). In purely tidal environments, the smaller thicknesses are due to shorter, semi-diurnal cyclicities.

Conclusions

(1) In the study area, winds can lead to the reversal of sediment transport, occuring when moderate winds blow (from 5 m/s in neap conditions) in sectors with neglictible tidal asymmetry (some cm/s) whereas stormy winds combined with neap tides are required in sectors with strong tidal asymmetry (some tens of cm/s).

(2) Dune master-bedding consists in large erosive discontinuities, with 9-11° slopes, which are formed during storms. These discontinuities form sequences of 1.5 to 4.85 m thick (2.65 m on average).

(3) Three main types of dune architecture are recognised, within which internal structure and external morphology display a strong linkage. “Purely” asymmetrical dunes consist of a single megasequence formed by cosets dipping in the direction of external asymmetry and dune migration. Other dunes display a complex external morphology, and are made of an up-piling of mega-chevrons, each one having an opposite progradational direction. In sand-rich sectors, dunes may have a temporary summital megaripple bedding sequence due to the dynamics of the superimposed dunes.

(4) Dune architecture types reflect the balance between tide- and wind-generated processes that occur in the study area. Tidal current asymmetry and the relative strength of wind-driven currents are the parameters which have the most important influence on dune architecture. Asymmetrical dunes in cosets, observed where the tidal current asymmetry is strong, are modified only in case of storm-induced currents, which lead to the erosion of the steep flank. Dunes in mega-chevrons occur in areas where the tidal current asymmetry is negligible and reversed each time moderate winds blows, leading to frequent erosion of the dune steep and long flanks and reversal of dune asymmetry and migration. In the same tidal conditions, dunes with a summital sequence of megaripple bedding are temporary encountered when abundant superimposed small to medium dunes are observed, which reversed their migration at each rapid current fluctuation.

(5) Dune architectures observed in the study area display strong geometrical similarities with structures observed in dunes from other shelf environments where processes can differ. This implies that a study based on a geometrical description of internal structures only does not enable to determine the

hydrodynamic environment where dunes occur. A discriminant criteria which could help for the reconstitution of ancient depositional environments consists of the thickness of the sequences bounded by 2 large erosive discontinuities. It is largely influenced by the dune height, but is also typical of specific hydro-sedimentary processes and resulting transport capacities.

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