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The morphodynamics of megatidal beaches in Normandy, France

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Abstract

The beaches on the west coast of Cotentin, on the Cherbourg Peninsula in Normandy, France, experience mean spring tidal ranges of 9.3–11.4 m. A study of the morphology, hydrodynamics and grain-size characteristics of these beaches was carried out in order to highlight the influence of large tidally induced water level fluctuations on their morphodynamics. These beaches are herein referred to as "megatidal", to differentiate them from macrotidal beaches with smaller tidal ranges. They are characterised by a wide and relatively shallow concave profile that lacks bar or ridge and runnel morphology. The typical profile exhibits three segments: a relatively steep ($\tan\beta = 0.07 - 0.12$) high tidal zone exhibiting medium to coarse sand, a mid-tidal zone with moderate slopes ($\tan\beta = 0.015 - 0.03$) and fine to medium sand, and a flat ($\tan\beta = 0.005$), featureless low tidal zone with fine sand. Statistical analyses of currents and wave data from several current meters and pressure sensors show that the incident wave heights and mean current velocities are strongly modulated by variations in water depth during the semi-diurnal tidal cycle. The mean current velocities increase downslope, with strong longshore currents in the low tidal zone driven by tides, storm waves and winds. However, wave orbital velocities are larger in the mid- and high tidal zones than in the low tidal zone. The joint variations in sediment size, slope, wave breaker height and tidally modulated water depth across the beach profile result in marked morphodynamic variability, as indexed by wave-sediment and surf parameters. In addition to the classic combination of a reflective upper beach and a dissipative lower beach exhibited by meso-macrotidal beaches, these megatidal beaches show, at low tide, an extremely dissipative low tidal zone characterised by very rapid breaker migration. Shoaling wave conditions prevail in this zone at high tide. This low tidal zone differs from sandy tidal flats dominated by tidal processes. Unlike the latter, which are generally not affected by waves, except during storms, the low tidal zone of these megatidal beaches is still a wave-dominated one, in addition to being subject to strong tidally driven longshore currents. The study adds a complementary, megatidal, dimension to meso-macrotidal beach classes defined in the literature from various parametric combinations of morphology, wave, sediment and tidal characteristics.

Keywords: Tidal range; Macrotidal beaches; Morphodynamics; Beach-surf zone parameters; Normandy; France

1. Introduction

The morphodynamics of microtidal beaches have been defined from a considerable amount of field work and occasional laboratory flume studies. This work has been integrated into beach state models covering such low tide-range environments (e.g. Wright and Short, 1984; Sunamura, 1988). Macrotidal beaches have attracted less attention, although there has been a spate of recent studies on such beaches, especially since the B-BAND programme (Russell et al., 1991). Large tidal ranges tend to 'tone down'

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sediment transport processes and morphodynamic changes, through both an increase in beach width and a decrease in the overall gradient of the beach profile across which waves and currents perform work. Tidal currents, generally of minor to moderate importance on wave-dominated microtidal beaches, may also play a significant role, especially on the lower beach and subtidal zone, as several studies have shown (Wright et al., 1982; Masselink and Hegge, 1995; Voulgaris et al., 1998; Sipka and Anthony, 1999; Masselink and Pattiaratchi, 2000). The spread of wave and tidally controlled processes over wider and shallower profiles on macrotidal beaches also implies greater cross-shore diversity in morphodynamics than on microtidal beaches. Overall, however, the present knowledge on the sediment response patterns on macrotidal beaches is still too fragmentary or restricted to enable elucidation of the morphodynamic signatures; hence the tentative and conceptual nature of the classifications proposed by Short (1991) and especially Masselink (1993) and Masselink and Short (1993). Masselink and Short (1993) proposed a beach state model based on a combination of the Ω parameter and of the relative tidal range parameter RTR. The parameter Ω, first introduced by Gourlay (1968), and later used by Wright and Short (1984) to discrimate between reflective, intermediate and dissipative beach states, is a dimensionless beach sediment fall velocity parameter computed from the breaker height, H_b, the particle fall velocity at high-tide level, w_s, and the wave period, T and is given by:

$$\Omega = H_b/w_sT \tag{1}$$

The RTR parameter proposed by Masselink and Short (1993) is calculated from the mean spring tidal range MSR, and from breaker height:

$$\mathrm{RTR} = \mathrm{MSR}/H_b \tag{2}$$

A few field experiments (Horn, 1993; Masselink and Hegge, 1995) have sought to improve these classifications and to specify the influence of the tide on morphodynamic changes. However, like most studies carried out so far on macrotidal beaches, these studies concern beaches with spring tidal ranges of <8 m. Studies on beaches with larger spring tidal ranges (>8 m) are much rarer. In this paper, we propose the term "megatidal" for these beaches in order to readily distinguish them from those with much lower tidal ranges but still falling within the macrotidal (spring tide range >4 m) domain (Davies, 1980). Megatidal conditions prevail along several coasts of the world (Fig. 1). While large tidal ranges commonly lead to tidal dominance and the prevalence of tidal flats associated with total dissipation of wave energy, some megatidal coasts are characterised by significant wave activity resulting in the development of sandy and gravelly beaches, especially where sufficiently deep offshore zones favour the inshore propagation of swell waves or where storm waves generated close to the coast propagate across shallow nearshore zones. An example of the former is Cable Beach in Australia (Wright et al., 1982; Masselink and Pattiaratchi, 2000), while examples of the latter line the Bristol Channel (Hawley, 1982; Jago and Hardisty, 1984; Russell et al., 1991; Russell, 1993; Fisher et al., 1997), and parts of the coast of northern France (e.g. Dolique, 1999).

The beaches of the west coast of Cotentin on the Cherbourg Peninsula, in Normandy, France (Fig. 2) fall into the megatidal category. From south to north along this coast, the mean spring tidal range on these beaches decreases from 11.4 m near Granville to 9.3 m near Barneville–Carteret (Fig. 2). Using an extensive field data base, the paper examines the effects of the important vertical range in tidal water level on wave height, and proposes a simple megatidal beach morphodynamic model that complements the earlier synthetic efforts of Masselink and Short (1993) and Masselink and Hegge (1995) on macrotidal beaches.

2. Study area

The west Cotentin coast is a low-lying rectilinear sandy coast bounding the Channel Islands embayment (Fig. 2). It is cut by several small estuaries locally called "havres". In the Channel Islands embayment, the tidal wave propagating eastward from the Atlantic Ocean is reflected by the north–south oriented coast of Cotentin, generating a standing tidal wave especially within the Mont-St.-Michel Bay (Fig. 2) where the maximum spring tidal range attains up to 15 m, among the highest in the world (Service Hydrographique et Océanographique de la Marine, 1953;

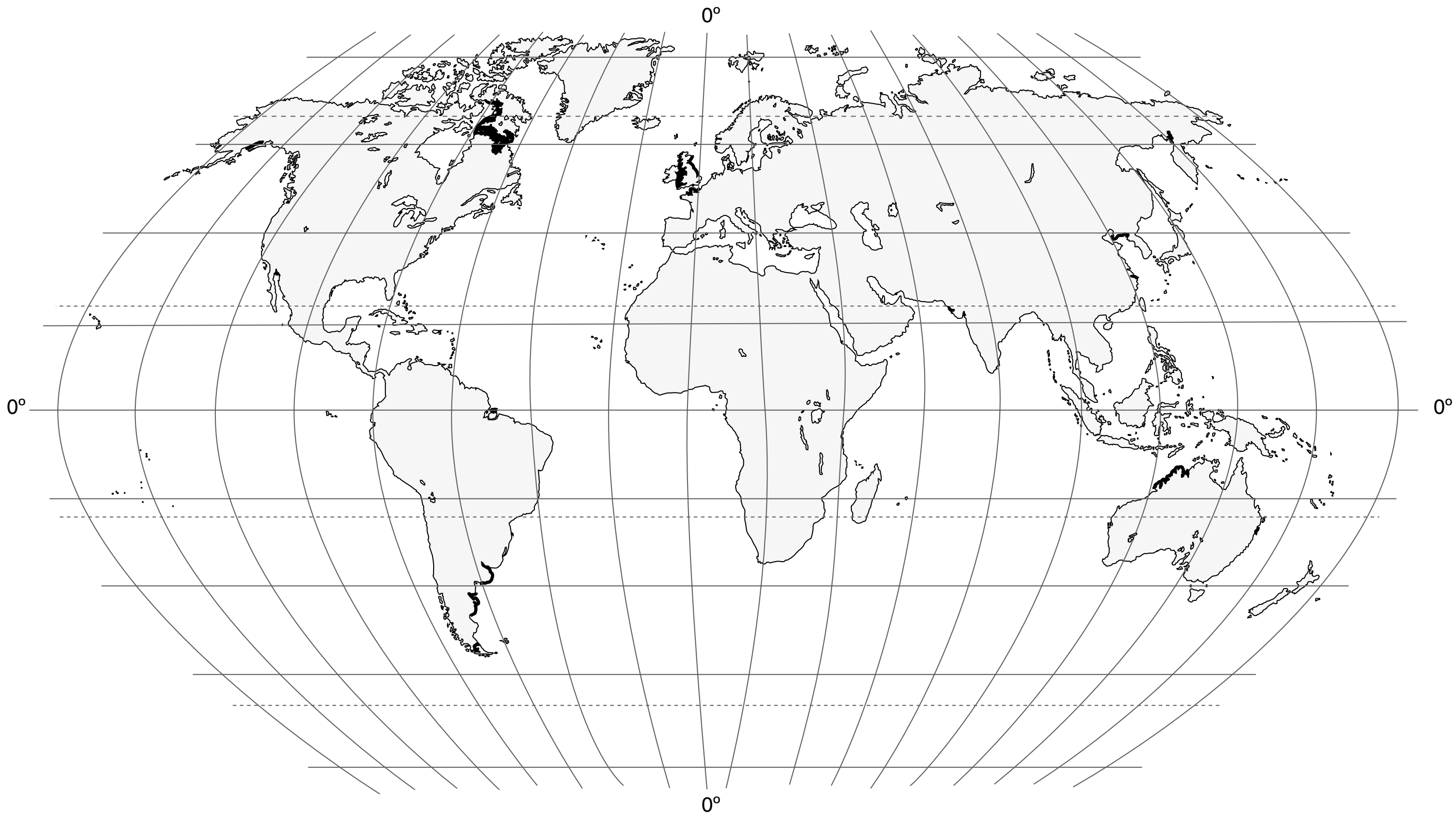

Fig. 1. World distribution of megatidal (mean spring tidal range >8 m) coasts (adapted from Dars et al., 1979).

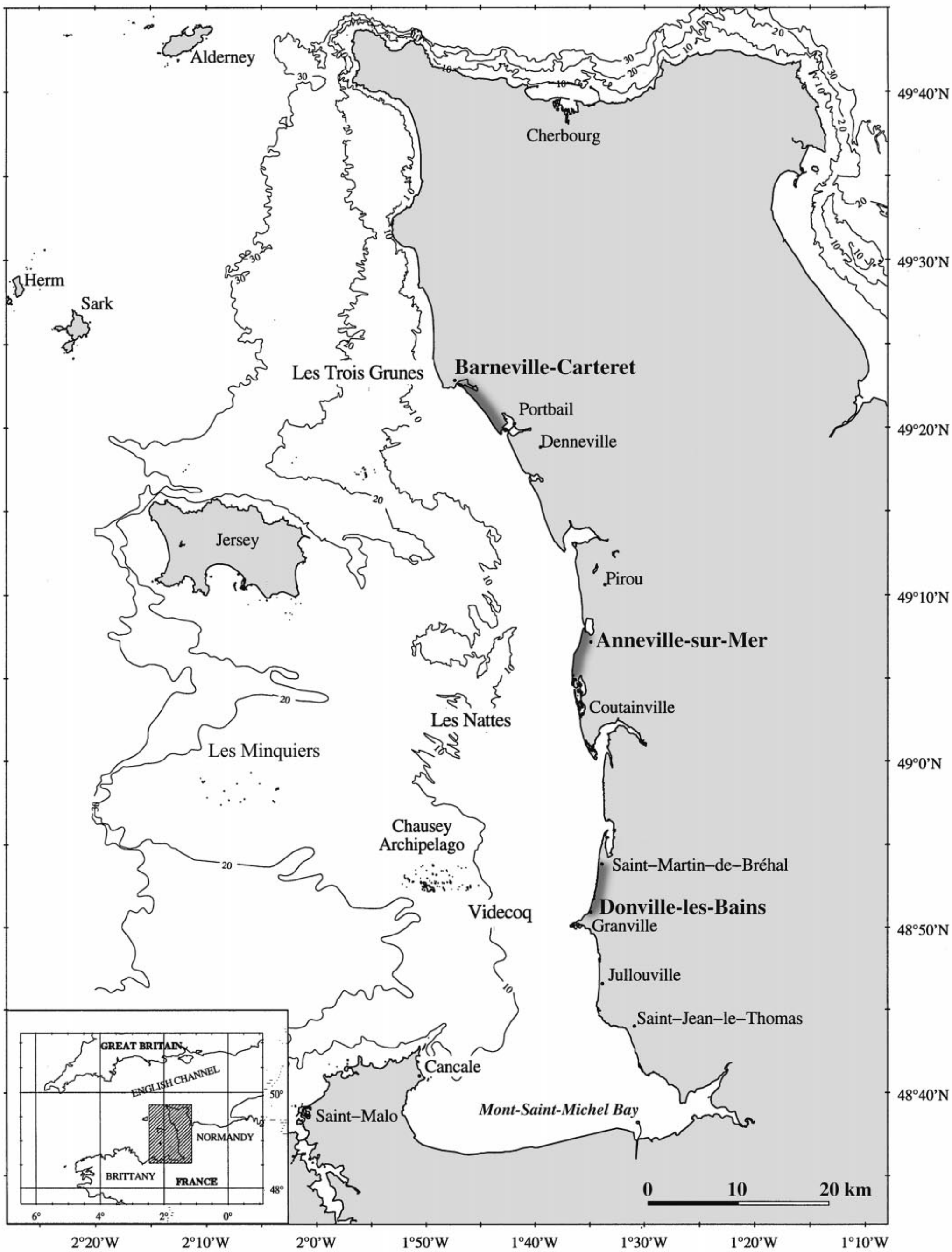

Fig. 2. The west Cotentin coast, Normandy, showing the beach study sites and nearshore zone.

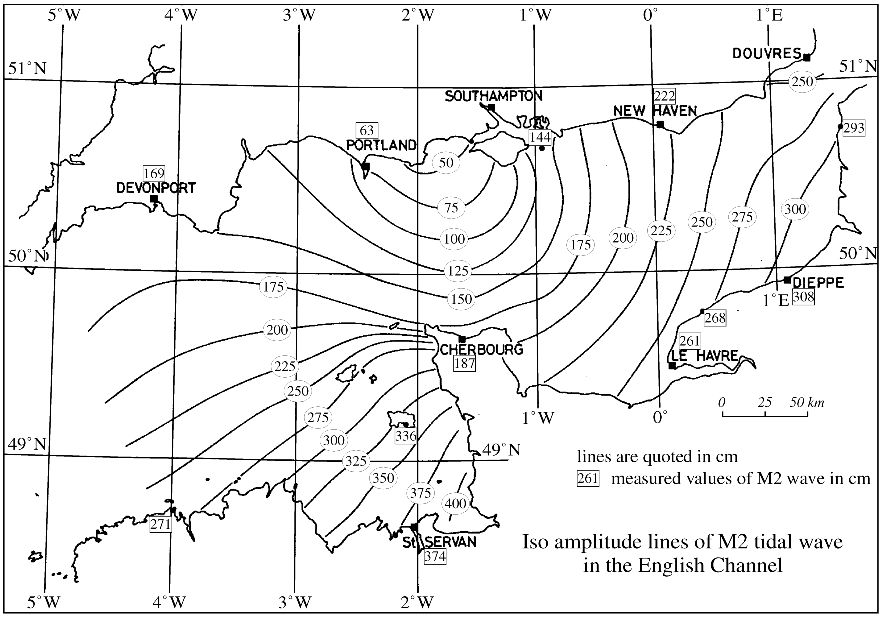

Fig. 3. Amplitude of the M2 constituent, the dominant tidal harmonic in the English Channel (from Chabert D'Hières, 1978).).

Bonnefille, 1968; Chabert D'Hières, 1978). Elsewhere along the west Cotentin coast, the tidal wave is progressive. The range decreases to 12 m towards the north (Fig. 3). The tidal wave is dominated by the M2 (semi-diurnal) harmonic whose amphidromic point is a virtual one located on land in southwest England (Pingree and Griffiths, 1979).

The central English Channel is an area of strong tidal current activity. In addition to currents due to the tidal wave, the tidal range differential between the south of the Channel Islands embayment and the north generates a strong slope current. On the whole, the mean offshore velocities can reach 1 ms^{-1} along the west Cotentin coast and up to 3 ms^{-1} in the mouths of the small estuaries in this area. On the beaches, the maximum velocities are observed at high tide and the main direction of the water movement is oriented towards the north, parallel to the coastline.

Offshore of the study area, the wave regime is bimodal (Fig. 4). Local southwesterly to northwesterly winds are active in winter and generate waves with periods of 4–6 s. These local-fetch waves coexist with north Atlantic swell with peak periods ranging from 8 to 12 s. Exceptional periods exceeding 20 s have been recorded. The propagation of Atlantic swell is complicated by the shallow shoreface bathymetry, and by various islands and shoals. The −20 m depth contour lies between 20 and 40 km offshore. Near the coast, rocky platforms and tidal deltas locally modify the wave propagation patterns. The Channel Islands embayment may be viewed as a very large dissipative embayment with a negative wave height gradient from north to south and from west to east (Fig. 5). The maximum annual significant wave height varies from 4.2 m at Les Trois Grunes to 2.8 m at Videcoq (Fig. 5).

3. Methods

Field work was carried out within the framework of the ROMIS programme (a French acronym for Field Observations and Measurement Systems) in Normandy aimed at providing a broad data base for the implementation of a coastal defence programme. The programme has involved monitoring of beaches, especially at Barneville–Carteret, Anneville-sur-Mer and Donville-les-Bains (Fig. 2), since 1990. Between 1990 and 1994, self-recording InterOcean S4DW electromagnetic current meters fitted with pressure sensors, moored about 0.4 m above the sea bed or

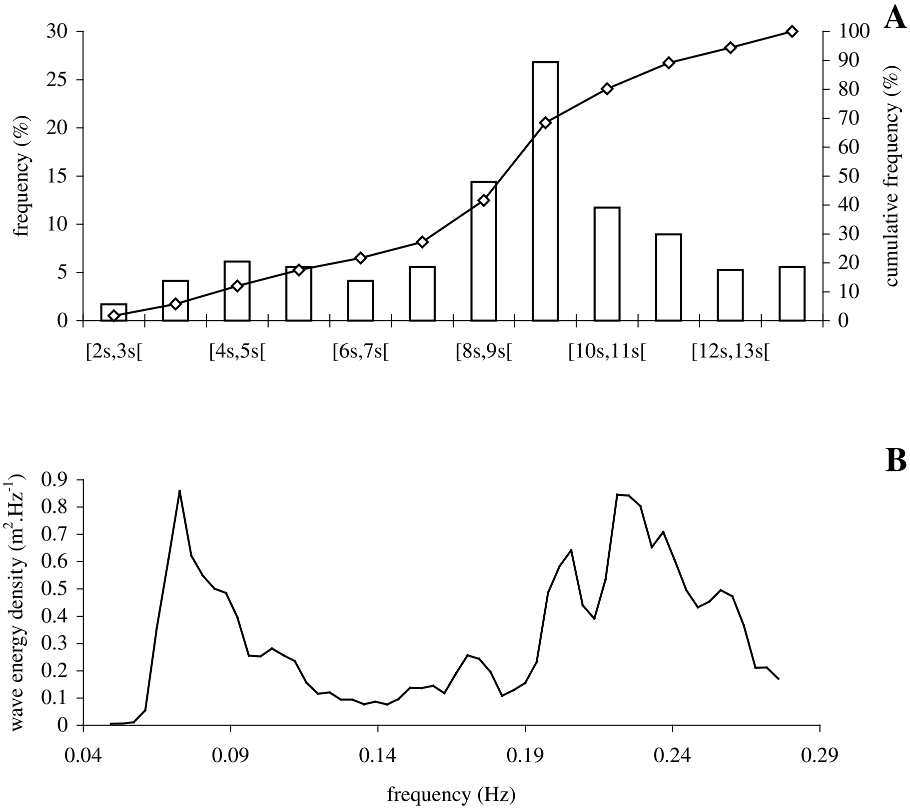

Fig. 4. (A) The bimodal distribution of the peak energy wave periods observed between March and September, 1992, at Les Minquiers (Fig. 2). (B) An example of the typical bimodal wave energy density spectrum observed on the west Cotentin beaches (Anneville-sur-Mer Beach, 10/06/1991).

the beach, were used to measure current velocities and directions, water level variations, and directional wave characteristics on these beaches as well as on various sites offshore (Fig. 2). The instruments deployed in the lower intertidal zone were programmed to record 18-min bursts of pressure and horizontal current fluctuations at a 2 Hz sampling frequency every 30 min. This 18-min burst sampling was chosen as a compromise between two opposite constraints. It had to be large enough to allow spectral analysis but short enough to ensure that the mean sea level observed during this period remained quasi-stationary. Instruments deployed on the shoreface recorded 9-min bursts of pressure and horizontal current fluctuations at the same sampling frequency every 4 h, a frequency dictated by the internal memory limitations of the current meters. The wave characteristics were obtained from the measured time series by spectral analysis using Fast Fourier Transforms. The Fourier coefficients of the free surface elevation fluctuations were obtained from the corresponding ones computed from the pressure time series. To this end, the frequency-dependent transfer function inferred from linear theory was used. To avoid electronic noise, we applied frequency cut-offs. There are no standard cut-off values and those we chose were retained after careful analysis of the data. These were taken as constant during the tidal cycle and fixed at 0.3 Hz for instrument deployments in the intertidal zone and at 0.2 Hz for deployments on the shoreface, where the water depth is larger. The cut-off used for data on the shoreface was based on a clear "talweg" identified at about 0.2 Hz. The energy above 0.2 Hz was considered as spurious and due to amplification of electronic noises. On the beaches, where the water depth is smaller, a similar analysis

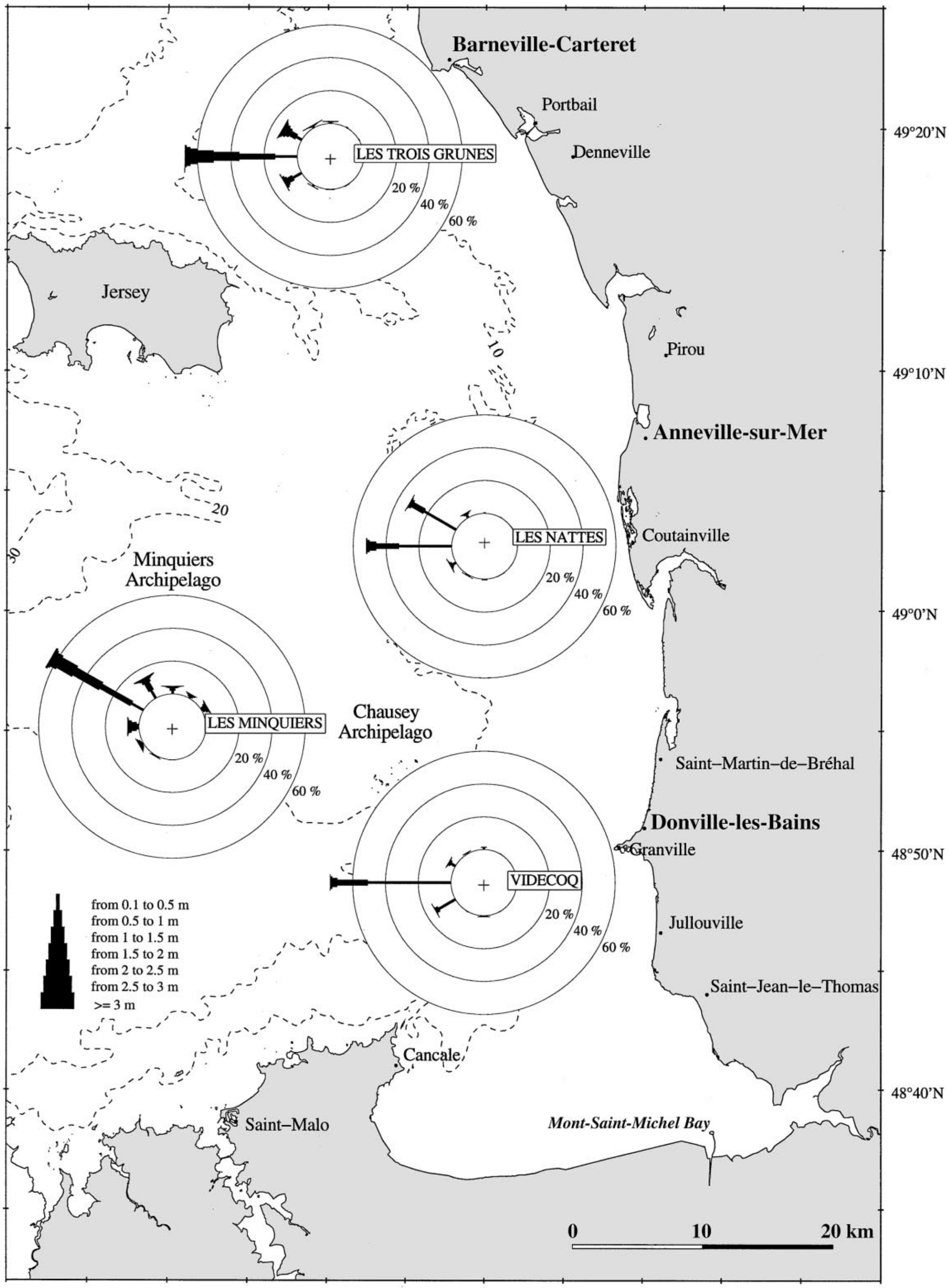

Fig. 5. Wave heights and directions off the west Cotentin coast.

showed that the amplification of electronic noise usually becomes important for frequencies larger than 0.3 Hz. The cut-off was therefore set at this frequency. Wind measurements near the current meter deployment sites were carried out with a portable weather station.

Since an important goal of the ROMIS beach programme was to monitor as precisely as possible wave breaker heights during the semi-diurnal tidal cycle, it was important to have a measurement system that was mobile between the mid- and upper beach. We measured breaker heights at the three beach sites (Fig. 2) from still photographs of a staff with 5 cm graduations using a little-known but efficient method proposed by Basinski (1989). The staff was fixed on a mobile frame that was tracted by a motorised vehicle, enabling it to be moved up the beach as the tide rose. This method circumvenes the problems of unstable staff-handling in the breaker zone. The mobile frame was placed at low tide halfway up the beach and the still photographs were taken during two to three 18-min runs covering the rising tide. Photography started as soon as the breaker zone was situated just behind the staff. Only the highest breaking waves were photographed, i.e. between 20 and 30 waves or about 10–20% of the waves in each run. We selected the higher 10% range of these breaker heights to calculate the mean breaker height per run. The precision of our measurements was about + or −2 cm relative to the upper and lower limits of the breakers. Interpolation of values from the graduated staff allowed an error margin of about ±5 cm on the height of each breaker. This simple technique enabled us to obtain relatively precise, statistically significant data at low cost on the wave breaker heights used in characterising beach morphodynamics. No wave breaker height measurements using this method were carried out on the lower beach because of logistic difficulties related to the traction of the mobile frame. We resorted to visual estimations for this part of the beach, and used the same procedure of breaker height analysis as for the mid- and upper beach.

Fig. 6. Photograph of Anneville-sur-Mer Beach at low tide (May, 2000).

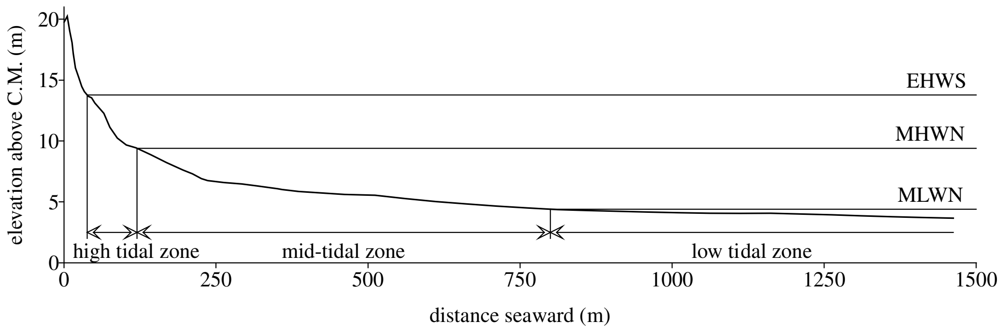

Fig. 7. An example of a west Cotentin beach profile showing the three tidal zones (Donville-les Bains Beach, November, 1998). CM (*Côte marine*) signifies level of the lowest astronomical tide.

Beach slopes were determined from topographic surveys at low tide using an electronic theodolite and infrared-ray distance meter. Sediment samples were taken along profiles where the current meters were deployed. Grain-size analyses were carried out using classical sieving methods.

4. Results

4.1. Beach profile characteristics

The typical west Cotentin beach profile (Fig. 6) is extremely wide and globally concave. On the basis of slope relative to tidal level, and of sediment characteristics, the beach profile may be divided into three zones: high tidal, mid-tidal and low tidal zones (Fig. 7). The beaches of west Normandy are backed by dunes or dune defences. They lack the "ridge and runnel" topography that characterises many of the beaches further east in the English Channel and the southern North Sea, or around the British Isles (e.g. Short, 1991; Mulrennan, 1992; Levoy et al., 1998; Voulgaris et al., 1998; Sipka and Anthony, 1999).

The beach slopes, expressed as tan β, vary from 0.07 to 0.12 for the high tidal zone, and from 0.015 to 0.03 for the mid-tidal zone. Beach cusps are sometimes observed in the high tidal zone but, as mentioned above, there are no parallel bars or ridges and runnels, excepting occasional and rather ephemeral swash bars, such as those described by Orford and Wright (1978). The sediment comprises a variable range of grain sizes from medium and coarse sand

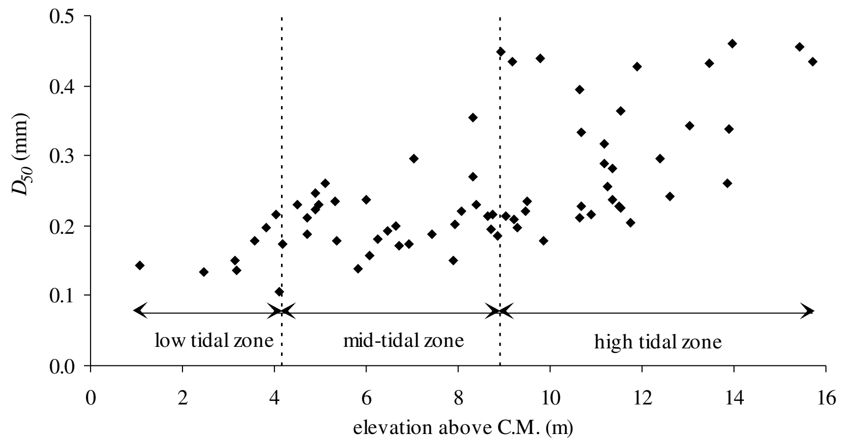

Fig. 8. Median (D_{50} mm) grain sizes of sediments from the three west Cotentin beaches.

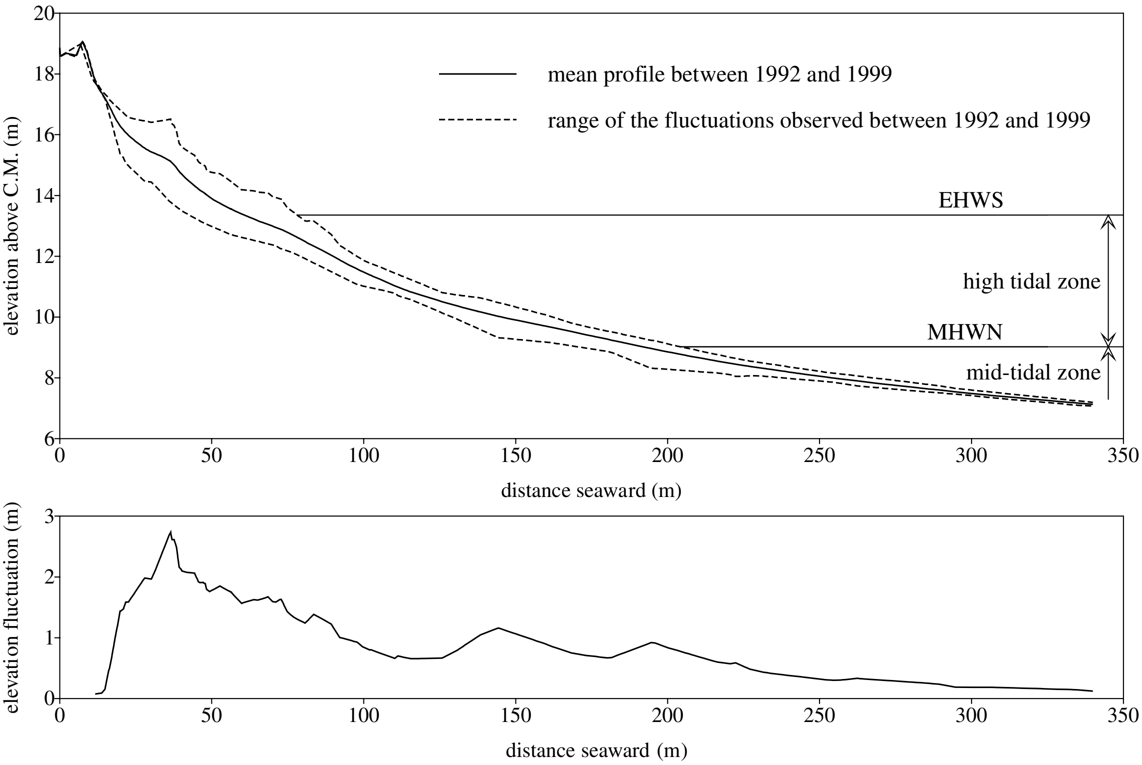

Fig. 9. Envelope of profile variations showing the marked downslope decrease in beach mobility (Anneville-sur-Mer Beach).

to gravel. The median diameter D_{50} on all the beaches ranges from 0.15 to 0.5 mm (Fig. 8). The finest sediments characterise the low tidal zone. The high tidal zone exhibits significant temporal variations in topography that tend to diminish downslope (Fig. 9). Storms can generate bed erosion of up to 2 m in the high tidal zone. In such cases, the re-establishment of the original beach profile may take several months. Both the high tidal and mid-tidal zones exhibit planar cross-beds with regular laminations due to wave activity. The low tidal zone differs markedly from the mid-tidal and high-tidal zones. It is flat, planar ($\tan \beta = 0.005$) and wet, due to cropping out of the water table. The beach surface exposed at low tide is commonly washed out and devoid of bedforms, excepting oscillatory ripples sometimes observed at low tide. Seasonal bed level variations are weak, generally less than 10 cm. At the offshore end of the intertidal profile, near the lowest tidal level, outcrops of bedrock are common.

4.2. Currents

The numerous current measurements carried out on the west Cotentin beaches show an identical cross-shore gradient in current intensity, which diminishes from the low tidal zone to the high tidal zone. Mean currents (Fig. 10) show maximum velocities at high water, indicating a dominantly progressive tidal wave. Current strength increases significantly during the neap to spring tidal cycle by a factor of 1–3, attaining velocities of 0.2–0.6 $\mathrm{m\,s^{-1}}$ at about 40 cm above the bed. However, the most important variations in current intensity were due to storm waves, aided by wind forcing, which generate peak velocities of up to 1–1.2 $\mathrm{m\,s^{-1}}$. The strongest currents (0.4–0.6 $\mathrm{m\,s^{-1}}$) are dominantly longshore, especially at high water (Fig. 10D). Relatively weak (0.1 $\mathrm{m\,s^{-1}}$) cross-shore currents occur during both the rising and falling tide around the mid-tide level. The longshore current velocities, like the overall mean current, diminish from the low to the upper mid-tidal zone as shown by an

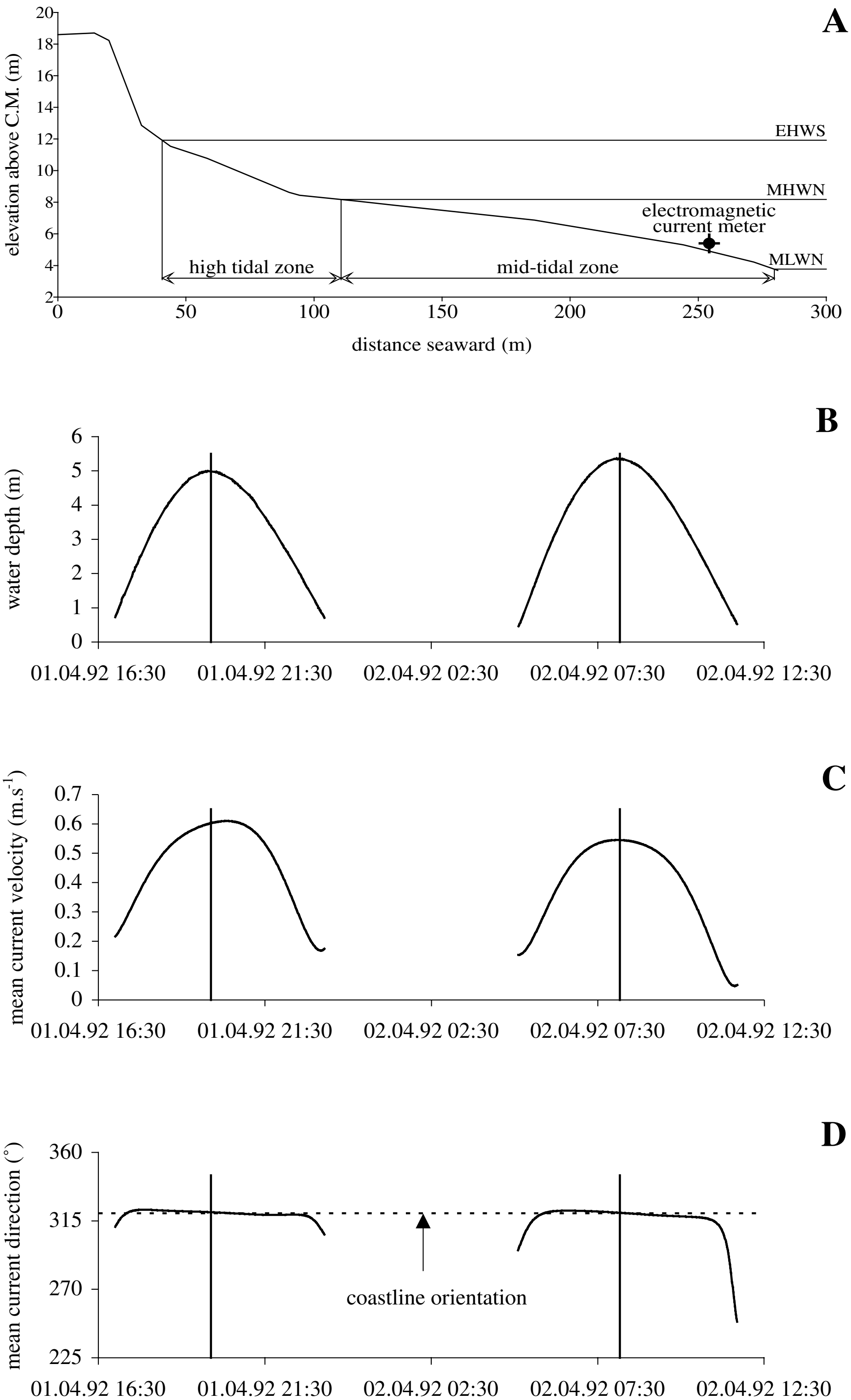

Fig. 10. Typical current data from the mid-tidal zone of Barneville-Carteret Beach for mean tidal range conditions (7.6–8 m).

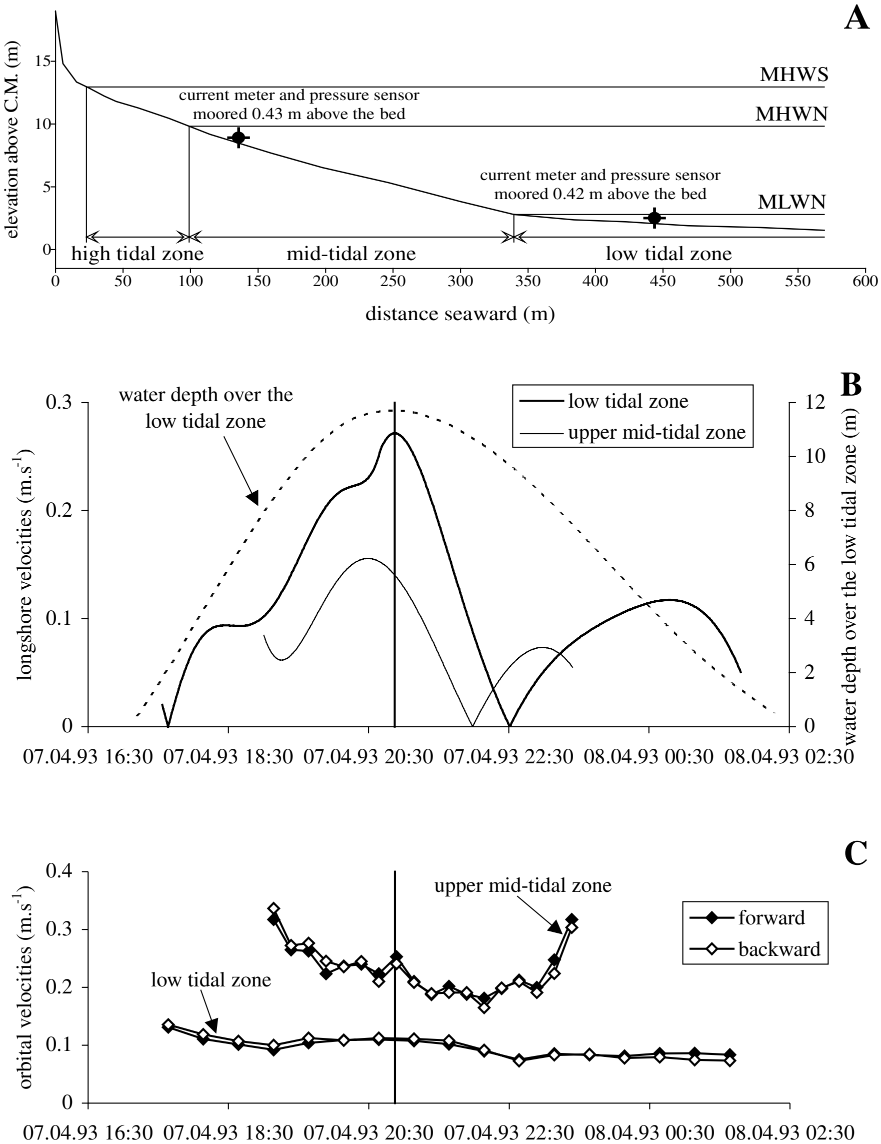

Fig. 11. (A) Instrument deployment locations, (B) mean longshore current velocities, and (C) peak wave orbital velocities in the low tidal and upper mid-tidal zones of Anneville-sur-Mer Beach.

example of data recorded from Anneville-sur-Mer beach (Fig. 11). The wind measurements near the beach on that day showed weak ($<5\ \mathrm{ms}^{-1}$) south-easterly offshore winds that had very little influence on the mean current, especially at 0.4 m above the bed. The mean current, dominated by the longshore component, was therefore due to the tide, with increasing tidal energy dissipation up the beach resulting in increasingly weaker longshore currents.

It appeared interesting to compare the wave orbital velocities with the currents, in order to evaluate the respective roles of waves (dominantly cross-shore influence) and tides (dominantly longshore) in moulding the beach morphology. In the mid-tidal zone, the orbital velocities are stronger throughout the tidal

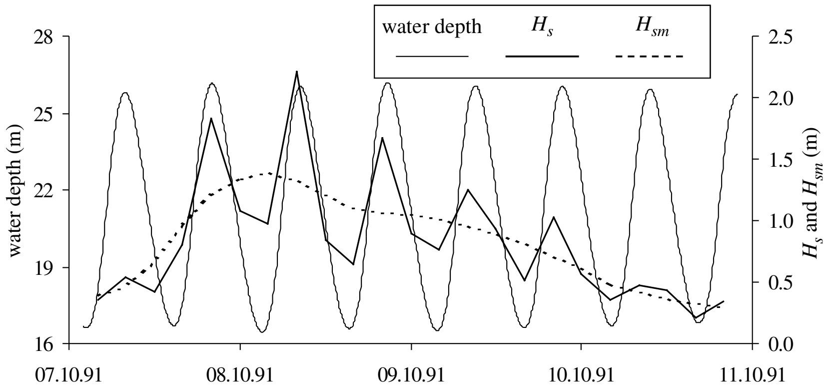

Fig. 12. Variation of the nearshore significant wave height (H_s) and moving average (H_{sm}) with water depth (d) at Les Trois Grunes during seven semi-diurnal tidal cycles. The figure also depicts the maximum H_s for stormy conditions between 08/10 and 09/10/91.

cycle than the current velocities (Fig. 11C). In the low tidal zone, orbital velocities are low, and weaker than the mean current velocities especially at high tide. They generally oscillate around 0.1 ms^{-1} throughout the tidal cycle (Fig. 11C). The variation, during the tidal cycle, of the near-bed wave orbital velocities reflects two opposite effects. The increase in water depth as the tide rises may result in a reduction of these velocities. However, this water depth increase also enhances a growth in wave height, with the consequent opposite effect of increasing these velocities. In the low tidal zone, these two effects apparently neutralise each other, resulting in the orbital velocities hardly varying with the tidally induced water depth variation (Fig. 11C). In the mid-tidal zone, the effects of water depth are more noticeable. The wave height in this zone is subject to lesser dissipation as shown below. The greater wave height in this zone explains the larger orbital velocities, especially on the rising and falling limbs of the tide. The lower orbital velocities at high water in this zone reflect the reduction in such velocities induced by greater water depth.

4.3. Wave height fluctuations during the tidal cycle

The study of wave propagation between the shoreface and the beach is central to the question of the influence of tidal range on the wave field. Wave heights were computed by spectral analysis for Les Trois Grunes, 8 km off Barneville–Carteret (Fig. 2). The data highlight a relationship between gravity wave height and water level (Fig. 12). Maximum wave heights are more commonly observed at high tide, while minimum heights are more likely to be observed at low tide. Nevertheless, the direct correlation between water level and significant wave height is very poor. This is because wave height on the shoreface is subordinate to wind conditions, as well as to dissipation due to bottom friction, the latter varying, during the tidal cycle, with the water depth. At Les Trois Grunes, even the shortest waves taken into account (with periods of 5 s) experience bottom influence.

In order to analyse the effect of water depth variations on the significant wave height at any one specific location on the shoreface, we rendered the water depth d at Les Trois Grunes non-dimensional. We used the water depths observed for exceptional spring tide conditions at high tide and at low tide, respectively, d_{MaxHWS} and d_{MaxLWS}, to obtain this non-dimensional relationship β_{d}:

$$\beta_{\mathrm{d}} = \frac{(d - d_{\mathrm{MaxLWS}})}{(d_{\mathrm{MaxHWS}} - d_{\mathrm{MaxLWS}})} \tag{3}$$

The significant wave height H_s, was also expressed as a non-dimensional parameter β_s:

$$\beta_{\mathrm{s}} = \frac{H_{\mathrm{s}}}{H_{\mathrm{sm}}} \tag{4}$$

The height H_{sm} in relation (4) represents computed moving averages of the values of H_s over 12 h periods. This duration was chosen because of its similarity to the local tidal cycle duration and its compatibility with the selected data acquisition frequency. The

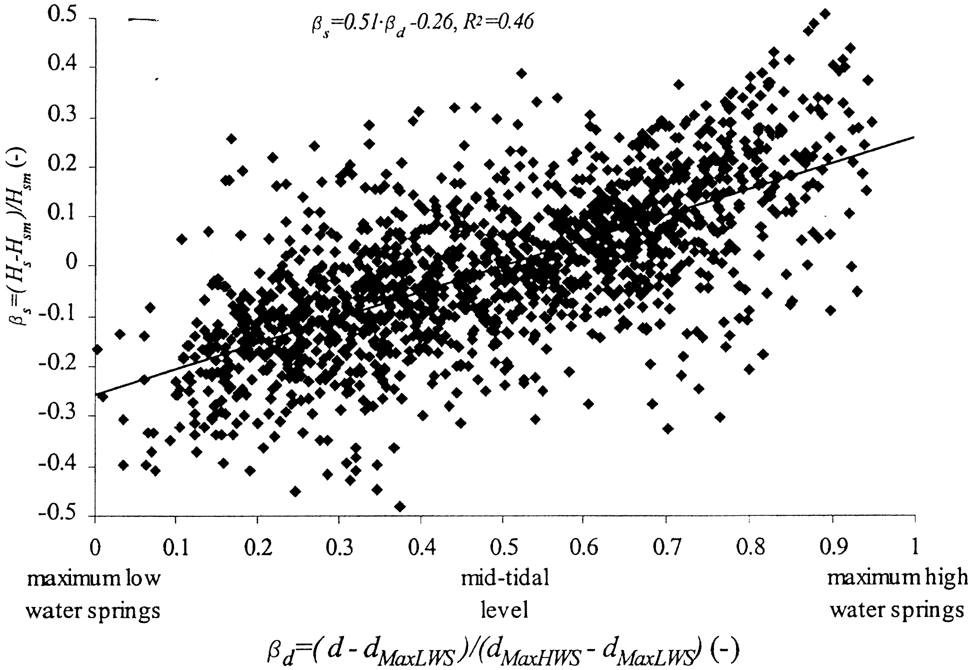

Fig. 13. A statistical relationship depicting the influence of non-dimensional water depth (β_d) on non-dimensional significant wave height (β_s) for the whole data set from Les Trois Grunes.

calculated value of H_{sm} during a storm event in October 1991 is also shown in Fig. 12. The H_{sm} value is quite independent of the tidal water level fluctuations, but it nevertheless allowed us to take into account the major trends in wave height variations.

Fig. 13 shows the variations of β_s as a function of β_d. It highlights a good-fit relation between the two parameters that is expressed as:

$$\beta_s = 0.51\beta_d - 0.26 \tag{5}$$

This relation, significant at the 0.01 confidence level, describes the increases and decreases in wave heights relative to the mean value of H_{sm} due to the tidal water level fluctuations.

Following relations (3) to (5), for a storm event characterised by a constant value of H_{sm} and a mean spring tidal range, the significant wave height at high tide ($d = 26$ m, $\beta_d = 0.89$) will be 1.5 times the significant height at low tide ($d = 17$ m, $\beta_d = 0.11$). The significant wave height observed at high tide for exceptional spring tide conditions ($d = 27$ m, $\beta_d = 1.00$) should be 15% larger than the value observed for mean neap tide conditions ($d = 23$ m, $\beta_d = 0.68$) for the same storm event. It appears that for all wave periods greater than 5 s, and heights at Les Trois Grunes, the variation in significant wave height between high and low tide is larger than that between the high tide values observed for neap and spring tide conditions. The obtained relationship is, of course, site-dependent, as it is hinged on the conditions of propagation (distance, bathymetry) between the region where the waves are generated and the location of the measurements.

4.4. Wave periods

A large set of values for water depths, between 1 and 11 m, and wave peak periods between 4 and 22 s, was covered by the field investigations. The shortest wave periods were obtained from the beach, using the 0.3 Hz frequency cut-off. The wave data indicate, as expected, that peak period, T_p, does not vary with water depth during the tidal cycle. Whatever the water depth, nearly all the range of the peak periods was observed.

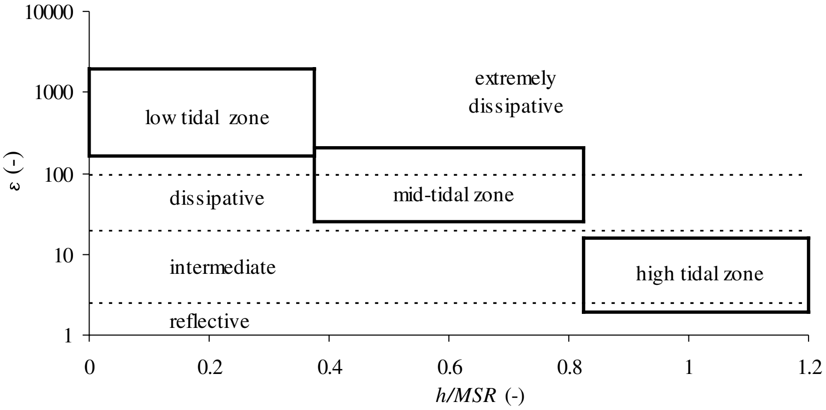

Fig. 14. Range of the surf-scaling parameter ε for the three profile zones of west Cotentin beaches. Horizontal axis shows the ratio of the water column h, above the lowest astronomical tide CM (*Côte marine*), to mean spring tidal range *MSR*.

4.5. Morphodynamic domains

Macrotidal beaches differ basically from microtidal ones in that they commonly exhibit wide shallow profiles comprising a significant dissipative component, especially on the lower beach, and an upper beach that may show dissipative to reflective morphodynamic signatures, depending on waves and tidal stage (e.g. Masselink and Hegge, 1995). To distinguish morphodynamically between reflective and dissipative beaches, a surf zone index such as the surf-scaling parameter ε (Guza and Inman, 1975) is commonly used:

$$\varepsilon = \frac{0.5H\sigma^2}{g\tan^2\beta} \tag{6}$$

where H is the incident breaking wave height, σ the wave radian frequency ($2\pi/T$ where T is the wave period), g the gravitational constant and $\tan\beta$ the beach gradient. Extremely shallow profiles characterizing the lower beach may be "ultra-dissipative", with ε values ranging from 5 to 30 at high tide and exceeding 30 at low tide as Masselink and Hegge (1995) have shown for the megatidal Cable Beach in Australia.

Calculations of the surf scaling parameter for the megatidal beaches of west Cotentin show very strong gradients between the low- and the high-tidal zones (Fig. 14). In order to standardise the tidal elevation range for each tidal zone on these megatidal beaches, the x-axis in Fig. 14 is shown as a non-dimensional expression of the ratio between water column depth h, above the lowest astronomic tide (CM), and the mean spring tidal range, MSR along the beach profile. The zonal variations in ε are due to marked variations in both slope and tidally modulated incident wave breaker heights. Values range from 2 to 15–20 in the high tidal zone, from 20–25 to 150–200 in the mid-tidal zone and to extreme values that range from over 200 to 2000 in the low tidal zone. High-tide conditions in the high tidal zone may vary from reflective to intermediate depending on breaker height. Low to moderate breaker height conditions (H_b of 0.2–0.5 m) and the moderately steep slopes ($\tan\beta$ of 0.07–0.12) result in reflective conditions that are manifested by plunging breakers and episodic cusp formation. These conditions are generally met during the spring-to-neap tidal cycle, as decreasing water depths increasingly affect the breaker heights. As breaker heights increase, during storm episodes or near spring high water, conditions become more dissipative, but breakers remain dominantly plunging, except during moderate spring tides when spilling breakers may occasionally prevail in the lower part of the high tidal zone. These dissipative conditions associated with spilling breakers are more commonly met in the mid-tidal zone.

Whatever the tidal stage and the wave regime, strongly dissipative conditions prevail in the low tidal zone, although the degree of dissipation is hinged on the tidally modulated breaker heights which vary during the tidal cycle. The most dissipative conditions

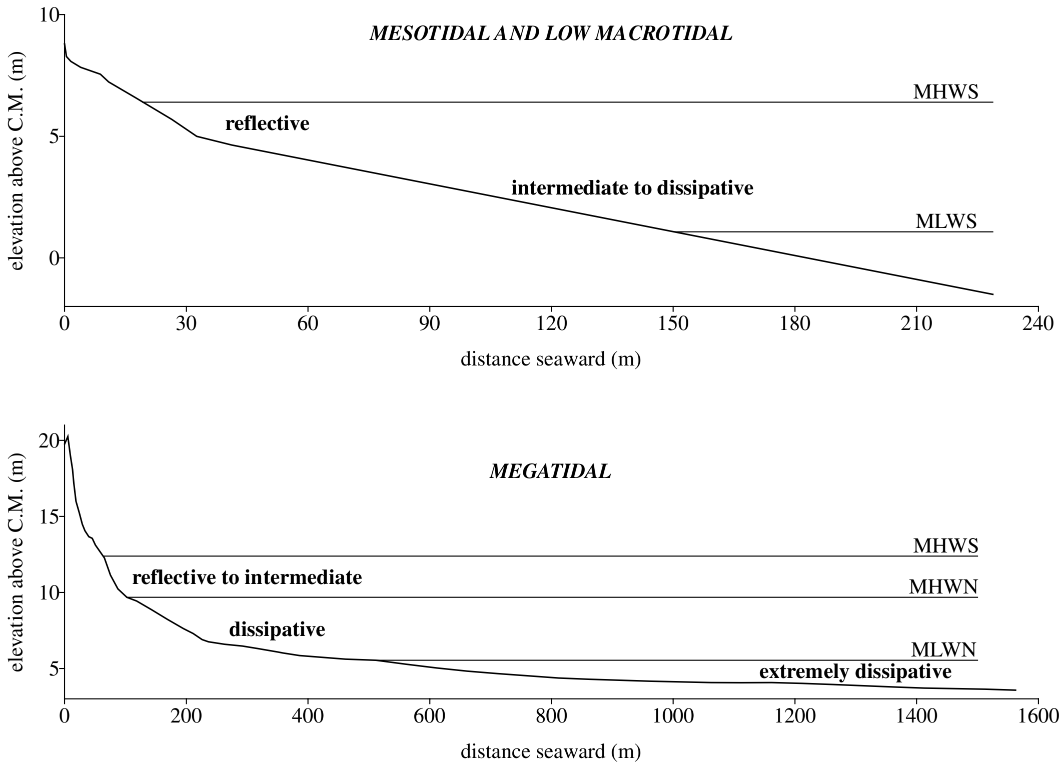

Fig. 15. Schematic morphodynamic segmentation of meso-macrotidal and megatidal beach profiles.

are attained, as expected, at low tide, notwithstanding the fact that the effect of the very low slopes (tan β of 0.005) is offset by low breaking waves (H_b of 0.05–0.15).

5. Discussion

Several significant features relating to the morphodynamics of the megatidal beaches of Normandy are highlighted by the data. These include: (1) the marked difference in slope characteristics between, on the one hand, the mid- and high-tidal zones and their wave-formed structures and bedforms, and, on the other, the flat, featureless low-tide beach; (2) significant cross-shore variability in grain sizes; (3) a marked diminution in tidal current strength from the low tidal to the high tidal zone; (4) a correlative dominance of wave orbital velocities in the mid- and high-tidal zones, and dominantly longshore currents in the low tidal zone; (5) important variations in offshore wave heights and breaker heights due to changes in water level induced by the very large tidal ranges; and (6) marked cross-shore variations in morphodynamic domains. We emphasise the role of tide-induced variations in wave height in explaining the morphodynamics of these megatidal beaches.

Using purely statistical analyses of the data rather than theoretical computations of variations in dissipation caused by bottom friction, we have shown that this tidal modulation affects waves throughout the zone of bottom influence from the shoreface to the breaker zone. Considering only the most significant waves in terms of energy, the extreme difference in wave heights between high and low tide reflects the aforementioned wave energy dissipation by bottom friction during the falling tide. This condition also highlights the influence of the rather shallow bathymetry of the Channel Islands embayment. It may therefore not be a general feature of megatidal beaches elsewhere, although very large tidal ranges are expectedly generated by very shallow offshore

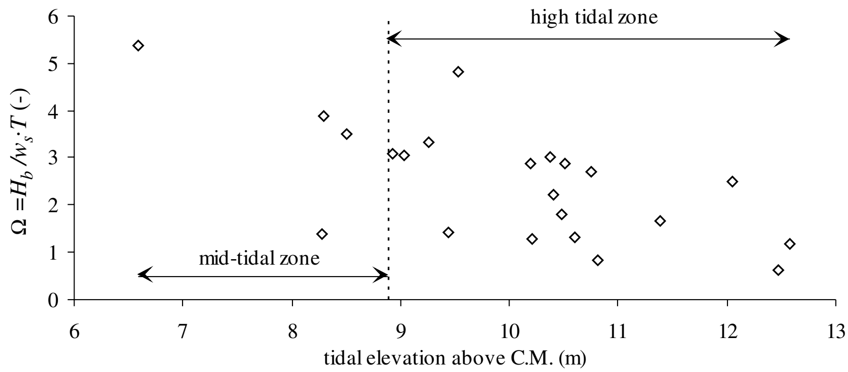

Fig. 16. Calculated values of the parameter Ω for the mid- and high-tidal zones of the megatidal beaches of west Cotentin.

bathymetry on wide shelves (Cram, 1979; Clarke and Battisti, 1981).

The extreme difference in morphodynamics between the high- and low-tidal zones constitutes the major difference between macrotidal and megatidal beaches (Fig. 15). The former are generally characterised by a high-tide reflective beach and a low-tide intermediate-dissipative beach, as several studies have suggested (e.g. Jago and Hardisty, 1984; Horn, 1993; Masselink and Hegge, 1995). The west Cotentin beaches exhibit a concave beach profile characterised by a marked slope difference between on the one hand the mid- and high tidal zones, and, on the other, the low tidal zone (Fig. 7). The first two zones conform to the general morphodynamic model of macrotidal beaches as summarised recently by Masselink and Hegge (1995) and are wave-dominated zones subject to significant changes in bed level (Fig. 9) caused essentially by storm wave reworking of the profile. Sand winnowed out from this zone is injected seaward by undertow or shoreward by winds into the aeolian dune systems capping the high tidal beach zone.

The extreme dissipation in the low tidal zone goes with the formation of a beach segment akin to a sandy tidal flat. The flat planar morphology of this low tidal zone is devoid of wave-formed structures other than very shallow-water oscillation ripples, indicating low energy swash action as the tidal excursion occurs. At high tide, this zone is dominated by the combined action of longshore currents due to tides and, sometimes, wind stress (e.g. Anthony et al., 1999), and by shoaling wave conditions. This low tidal beach zone is similar to the "ultra-dissipative" megatidal beach type (Masselink and Hegge, 1995). These workers proposed the example of Cable Beach (Wright et al., 1982), whose low tidal zone shows more marked evidence of wave action than the west Cotentin beaches because of a more energetic wave regime. Because of the negligible slope, the low tidal zone of west Cotentin beaches is one of extremely rapid migration of the surf and swash zones, leaving little scope for wave reworking of the bed; hence the rather weak bed level changes observed in this zone, even after storms. These conditions of rapid migration of the wave domains may also be responsible, together with the extremely dissipative character of this zone, for the absence of bar morphology, as Short (1991) has speculated for meso-macrotidal beaches.

Both the wave-dominated mid- and high-tidal zones conform to the classic morphodynamic scheme identified by various workers. The high-tidal zone exhibits a reflective morphodynamic signature (Fig. 14) over significant periods of time, as attested by the cusps that sometimes form in this zone. The impact of waves is particularly evident during storms in the high tidal zone, where the influence of tidal currents is insignificant, in spite of the large tidal range.

The parameter Ω shows a wide range of values for the mid- and high-tidal zones (Fig. 16). Determination of both the Ω and RTR parameters requires modal values of breaker height, sediment fall velocity and wave period. Modal values of H_b are very difficult to define, especially in settings with variable wave regimes such as the English Channel (Anthony, 1998). From our field experience and wave data

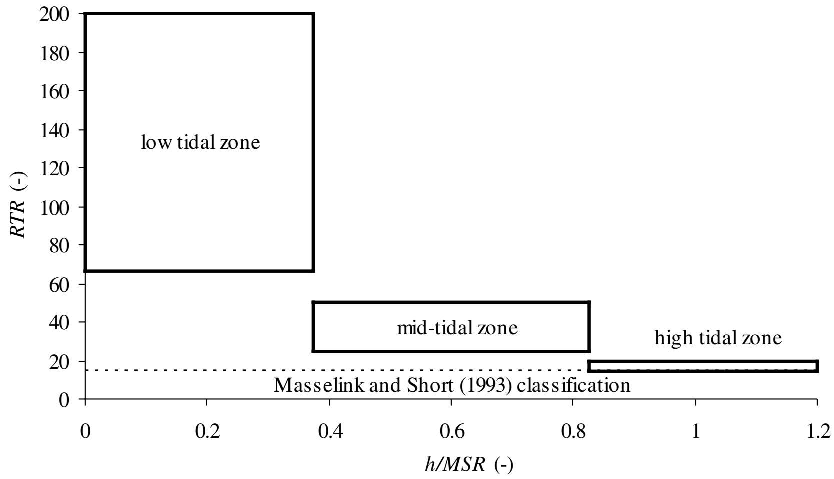

Fig. 17. RTR values for the profile zones of the megatidal beaches of west Cotentin.

base, we deduce that the modal breaker height on the Cotentin coast between Barneville–Carteret and Granville is greater than 0.5 m. In experiments during storm conditions, breaker heights at high tide ranged from 0.8 and 1.2 m, and the modal value would probably have been close to 0.5–0.6 m. Calculated values of the Ω parameter based on the high tidal beach sediment fall velocity are very large and are clearly variable as a function of the water level during a tidal cycle. The values range from 1 to 2.3 in the high-tidal zone ($H_b = 0.5$ to 0.6 m, $w_s = 0.07$, $T = 3$–4 s and 8–9 s) and from 0.2 to 1 in the low tidal zone ($H_b =$ 0.1 to 0.2 m). The mean RTR value could have been close to 20 (MSR of 9.3 m in the northern sector of the study area and 11.4 m in the south) at high tide, but must be considered as higher at mid-tide or near the low water level (between 60 and 200 with a modal value of H_b smaller than about 0.05–0.15 most of the time on the low tidal zone).

The Ω values for the west Cotentin beaches suggest that the entire beach profile falls in the reflective or intermediate domains, following the classification of Masselink and Short (1993). This is clearly not the case for the mid-tidal and low-tidal zones. In these zones, the low wave breaker heights, especially at low tide, induce reflective Ω values comprised between 0 and 2. Only during major storms (but these do not represent modal conditions), and on the upper part of the low-tide beach as well as on the mid-tide beach does Ω attain values of 4.5, and exceptionally 6–7.

These conditions also suggest a need to refine the RTR values applicable to megatidal beaches. Masselink and Short (1993) proposed an RTR value ranging from 7 to 15 for a macrotidal "low-tide terrace" beach or an "ultra-dissipative" beach. The moderate breaker heights induce very large RTR values for the megatidal beaches of west Cotentin (Fig. 17). Although the tidal range is very large on these beaches, absolute wave height is still sufficient at low tide to maintain a beach environment, rather than a tidal flat environment. In essence, this means that high values of the RTR index (Fig. 17) may be attained without necessarily shifting from beach to tidal flat. Megatidal beaches may therefore have very large RTR values that may overlap with those of 'true' tidal flat environments. However, values such as those identified for the beaches in the study area are probably not far from defining transitional states towards such tidal flat environments and tidal dominance of the morphodynamics, such as in neighbouring Mont-Saint-Michel Bay (Fig. 2). At this level, there is need for a clearer distinction between beach and sandy tidal flat. Morphology, especially the influence of slope, is one criterion in such a distinction. Tidal flats in megatidal settings most likely exhibit flatter and wider slopes than the low tidal zone of beaches in the same tidal settings. This distinction would need to be backed by a clear definition of the hydrodynamics, notably the role of tides and tidal currents vis-à-vis waves in sediment transport, bedform development

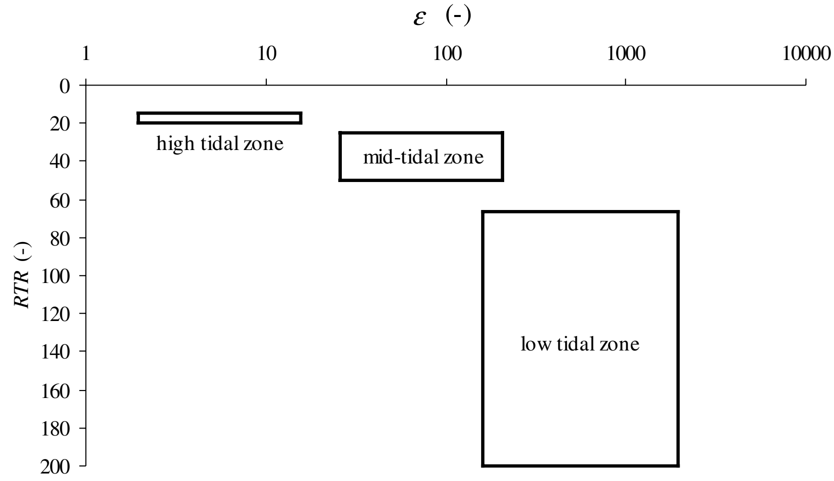

Fig. 18. RTR and ε ranges for the megatidal beaches of west Cotentin.

and moulding of the morphology. Good indicators of sandy tidal flats in macro-megatidal settings are strong cross-shore channelled flows in large (meters to tens of meters wide), shallow (0.1–1 m deep) and anastomosing drains, the absence of waves at low tide (although storm waves may episodically affect the flats), and the presence of vegetation on the high-tide slopes.

Finally, the foregoing observations suggest that while RTR is a relatively simple and adequate index for characterizing megatidal beaches, Ω fails to convey the cross-shore variability of megatidal beaches. This is because low levels of H_b lead to a bias towards reflective values in spite of the prevalence of extremely dissipative conditions, as in the low tidal zone. Slope appears to be a better indicator of cross-shore variations on wide macro-megatidal beaches than a combination of breaker height and sediment fall velocity (Anthony, 1998). As a consequence, the parameter ε, enables, together with RTR, better differentiation of such cross-shore morphodynamic variations. Fig. 18 proposes a simple framework of megatidal beach zone characterization on the basis of these two parameters.

6. Conclusions

Megatidal tidal range conditions have been set to mean spring tidal ranges >8 m, in order to distinguish them from macrotidal conditions associated with lower tidal ranges. Analyses of the morphology, grain-size and hydrodynamics of the megatidal beaches of Normandy show strong tidal modulation of wave heights and cross-profile variations in breaker height, slope and sediment size that result in significant morphodynamic variability. Three beach segments have been defined from the whole data base. These are the low tidal, mid-tidal and high tidal zones. The mid-tidal and high tidal zones correspond, respectively, to the intermediate-dissipative lower beach and the reflective upper beach segments classically associated with meso-macrotidal beaches. Megatidal beaches basically differ from the latter in that they exhibit a flat, featureless and extremely dissipative low-tide beach characterised by very rapid cross-shore breaker migration during the vertical tidal excursion. This results in little swash and surf activity. At high tide, this low tidal zone is characterised by shoaling conditions and by strong longshore currents due to both tides and storm wave activity.

West Cotentin beaches are morphologically similar to the "ultra-dissipative" macrotidal beach state identified by Masselink and Hegge (1995) using the example of Cable Beach in Australia, but they differ from the latter, high-energy example in terms of their low to moderate breaker heights. These low to moderate breakers result in an extremely dissipative morphodynamic signature and large values (>20) of the RTR parameter in the low tidal zone. These values largely overlap with those to be expected from sandy tidal flats, dominated by channelled cross-shore tidal flows and subject to hardly any wave activity at low tide other than during storm wave conditions. The presence of low breaker heights sweeping across the low tidal zone twice daily during the semi-diurnal tidal cycle is a basic factor that differentiates these low-tide beach segments from classic sandy tidal flats. The study provides data and observations that enable upgrading of the meso-macrotidal beach classification proposed by Masselink and Short (1993) to include a megatidal beach type from a modally low-to-moderate energy setting affected by dissipated swell waves and periodic local-fetch storm waves. The data also suggest that the surf-scaling parameter ε is a better predictor of cross-profile morphodynamic variations on these wide megatidal beaches than the sediment-wave parameter Ω.

Acknowledgements

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