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Between Wave- and Tide-Dominated Coasts: the Middle Ground Revisited

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ABSTRACT

Few of the world's coasts are devoid of wave action, such that waves are considered as the dominant agent of coastal change at short (hours to weeks) to medium (months to years) time scales, and can act as triggers via extreme events at the meso-scale (decades). Coasts where waves are absent or where wave energy is so important as to obliterate the tidal signal are the extremes recognised as tide- and wave-dominated coasts. The rest are inevitably mixed wave-and-tide-dominated (WTD) coasts that constitute a considerable proportion of the world's coasts. This is not a new idea, but recent advances in the understanding of such mixed-influence coasts impose a reconsideration in terms of a perspective that involves process signatures, sediment transport patterns and coastal morphologies. While tides show a regular predictable temporal cycle, wave conditions generally exhibit large temporal variability expressed by irregular, but short-term/seasonal variations in energy and period. As a result, the WTD spectrum is not constant in power level and is probably very irregular, characterised by a few key spikes. Examples include the well documented moderate wave-energy micro- to meso-tidal sand barriers with frequent tidal inlets such as those of the southeastern coast of the United States, and the much less well known macro- to mega-tidal beaches and their associated nearshore storm and tide-controlled ridges and banks, such as those of the eastern English Channel.

ADDITIONALINDEXWORDS: *Wave-tide interaction, tidal range, beach, shoreface.*

INTRODUCTION

Wave, Tides and the Coast

The combination of fetch and wind conditions at the scale of the world's ocean-facing coasts and of coasts in large enclosed seas such as the Mediterranean are such that few of these coasts are devoid of wave action. As a result waves are considered as the dominant agent of coastal change at short (hours to months) time scales. They can also act as triggers via extreme events at the meso-scale (years to decades) (ORFORD *et al*., 1999). It has been estimated that half of the energy budget of the world's coasts is provided by waves (INMAN and BRUSH, 1973). The rest must come essentially from tides. A considerable proportion of tidal energy is dissipated along the world's coasts, although the mechanisms of such dissipation are not as clearly known as those of waves (MINSTER, 1997).

A first question that may be asked is how to define mixed wave-tide-dominated (WTD) coasts. From first principles, tidal forces are felt universally on all coasts, although their effect is modulated by position. Waves are variable in time and space and as a result might mute, obliterate, modulate, amplify or dominate the tidal signal. Although tides show a regular periodicity, they might also similarly mute, modulate, or dominate the wave signal. Coasts where waves are absent are the extreme previously recognised as tide-dominated coasts, while coasts where waves obliterate the tidal signal are the extreme previously recognised as wave-dominated coasts. Inevitably, the rest must be mixed WTD coasts that constitute a considerable proportion of the world's coasts.

The recognition of such mixed WTD coasts is not a novelty. There have been a number of attempts at formalising the relationship between these two variables and the resultant coastal morphologies, notably those of HAYES (1979), and especially DAVIS and HAYES (1984), who used a graphic model displaying the spectrum of wave- to tide-dominated coasts based on mean wave height and mean tidal range. This spectrum was essentially concerned with certain barrier morphologies, notably in areas with numerous recurrent tidal inlets and/or moderately large tidal ranges. A useful finding of this work is that wave-dominated, mixed energy or tide-dominated morphologies may develop along any particular stretch of coastline with very little difference in tide and wave parameters.

Although beach studies have been overwhelming concerned with wave dynamics, the tidal perspective has not been neglected. Three decades ago KING (1972), probably out of her vast experience of British and northwest European coasts, emphasised the importance of tides in beach changes. Following WRIGHT *et al*. (1982), it has become clear, especially over the last decade, that beaches in areas with large tidal ranges are distinctly affected morphodynamically through tidal modulation of their hydrodynamics, sediment transport patterns and resultant morphology (SHORT, 1991; MASSELINK and TURNER, 1999; LEVOY *et al*., 2000). The interaction of waves and tides is embedded at two levels: (1) mean currents that jointly reflect time-averaged wave and tidal forcing, and (2) the effects the large vertical and horizontal tidal excursions have on wave processes.

The premise of DAVIS and HAYES (1984) that consideration of coastal morphologies needs to be based on the relative effects of processes generated by waves and tides rather than on absolute wave height and tidal range has been taken further by MASSELINK and SHORT (1993). These workers proposed a non-dimensional parameter, the relative tide range parameter RTR, given by H/TR (where H is wave breaker height and TR is spring tidal range, in meters) to characterise beaches in terms of the effect of tidal range. RTR is a useful parameter, as it provides a framework for identifying a spectrum in wave-tide domination of the morphodynamics. However, it shows shortcomings when applied to parts of the spectrum characterised by either low wave breaking heights or very large tidal ranges (ANTHONY, 1998; LEVOY *et al*., 2000).

In this paper, the concept of mixed WTD coasts is revisited and the perspectives of these previous studies built on. WTD coasts are considered not just in terms of the beach, where our perspective is biased towards wave domination, but in terms of the net resultant coastal domain (beach and shoreface) that is a distinct reflection of the joint long-term wave-tidal mix. The paper also synthesises recent advances in understanding some aspects of the morphodynamic process framework of WTD coasts.

The Mixed Wave-and-Tide-Dominated Spectrum

The only explicit recognition and formalisation of the idea of WTD coasts in the literature is that of DAVIS and HAYES (1984) who identified such coasts with stubby barrier islands cut by numerous tidal inlets. These may be either fixed or migrating inlets linked to estuaries or lagoons. Alongshore migrating inlet systems associated with barriers occur along the whole spectrum of wave energy settings. They are especially active in areas with low tidal ranges favourable to barrier development, and are maintained in the face of low cross-barrier tidal flux. The tidal inlets may capture and store significant amounts of

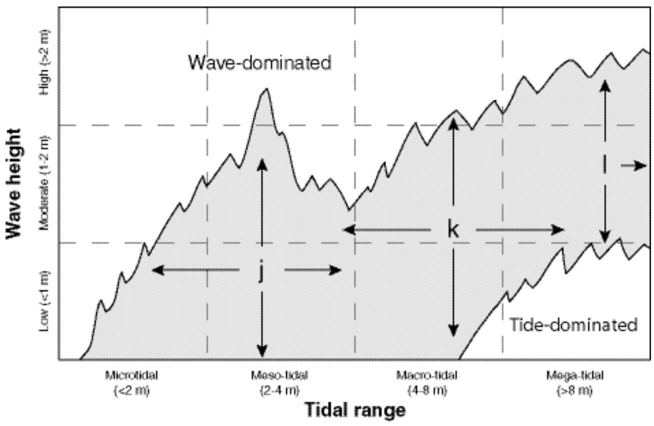

Figure 1. Simple schematic of the coastal energy spectrum. The stippled area shows the wave-tide-dominated part of this spectrum and a few key coastal types in terms of relative wave energy and tidal range. 1. Barrier coasts with migrating inlet systems. 2. Sandy-muddy coasts including low-latitude coasts subject to high seasonal mud inputs. 3. Sand-rich coasts with shallow shorefaces. Tidal range categories from DAVIES (1980) and LEVOY *et al.* (2000).

sand transported alongshore by wave-induced longshore drift as tidal inlet fill and flood tidal delta deposits. It is noteworthy that the sediment record of barrier coasts comprising inlets may exhibit important longshore sequences of wave-deposited barrier sand that overlies such tidal deposits (HAYES, 1980; REINSON, 1984).

WTD coasts are not however limited to barrier-and-inlet systems. What therefore is the range of WTD coasts? Between the wave- and the tide-dominated coastal extremes is a broad spectrum of WTD coasts that may span all wave energy and tidal range settings (Figure 1). While tides show a regular predictable cycle, wave conditions generally exhibit large variability expressed by irregular, but short-term (order of days to weeks), to seasonal variations in energy and period. As a result, the spectrum of joint wave-and-tide-domination is not constant in power level and is probably very irregular, with coasts fluctuating in the short-term (in addition to spatial, cross-shore variations discussed below) basis from wave domination to tide-domination. The fundamental process feature of WTD coasts which differentiates them from pure wave- or tide-dominated coasts is, however, the way the waves and the tides interact, via mutual muting, modulation, or amplification to give distinct process signatures, sediment transport patterns and coastal morphologies. Viewed in this way, most coasts, especially (and not exclusively) in areas subject to large tidal ranges, and in the more variable mid- to high latitudes where temporal wave energy variations are most marked,

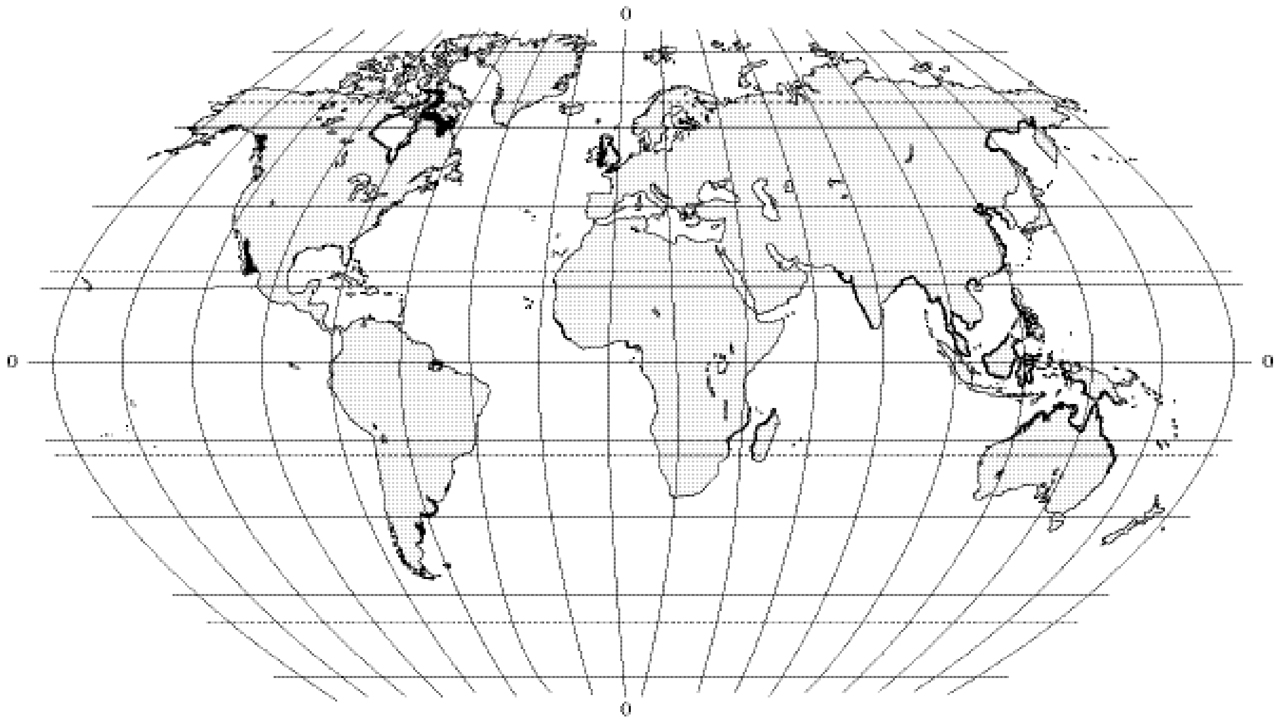

Figure 2. World distribution of wave-tide-dominated coasts. The distribution is based on a combination of tidal range and wave height characteristics. WTD coasts occupy essentially meso- to mega-tidal settings with significant wave heights of 0 to 2 m 50% of the time. Coasts with migrating barrier-inlet systems have also been identified as WTD. Wave data from YOUNG and HOLLAND (1996) and tidal range from DAVIES (1980).

are part of the wave-tide-dominated spectrum (Figure 2). Strong tidal currents associated with large tidal ranges commonly characterise shallow seas and wide, low-gradient shelves. Both settings favour tidal amplification. Wave generation conditions and fetch may also become restricted in semi-enclosed coastal seas, while shallow shelf seas favour wave energy dissipation. The combination of these wave and tidal conditions would lead to a wave-tide-dominated coastal spectrum. However, this spectrum would exhibit a few key spikes associated with certain distinct coastal types that may be considered as stable manifestations reflecting a long-term balance between wave and tide domination (Figure 1). Examples include the aforementioned stubby sand barrier coasts with frequent tidal inlets, sandy-muddy tropical coasts in areas of moderate to large tidal ranges and low to moderate wave energy, and sandy coasts in areas with large tidal ranges and low to high wave energy whose shorefaces are characterised by storm wave-and tidally moulded sand banks and ridges. These constitute a significant proportion of the world's coasts.

The Morphology of Mixed Wave-Tide-Dominated Coasts

To what extent do WTD coasts differ in terms of morphology from pure wave- or tide-dominated coasts? DAVIS and HAYES (1984) state that (p. 324): "There can be no disagreement with the basic premise that straight and smooth coasts, characterized by well-developed beaches are the result of physical conditions dominated by waves and wave-generated currents." This premise is based neither on process interactions, nor on tidal modulation of coastal hydrodynamic conditions but purely on visual morphological associations. The coasts bounding much of the eastern English Channel, and many other mixed wave-tide dominated coasts, are straight, smooth and characterised by well developed beaches (Figure 3), but in no way can they be considered as being products of simple wave domination, or tidal domination for that matter.

WTD coasts would be expected to show stable large-scale morphological and sedimentary patterns that are quite distinct from those of pure wave-dominated and tide-dominated coasts, being a mix of the two. These differ first in terms of shoreline width and gradient as well as in profile characteristics. On some sandy-muddy tropical coasts, the

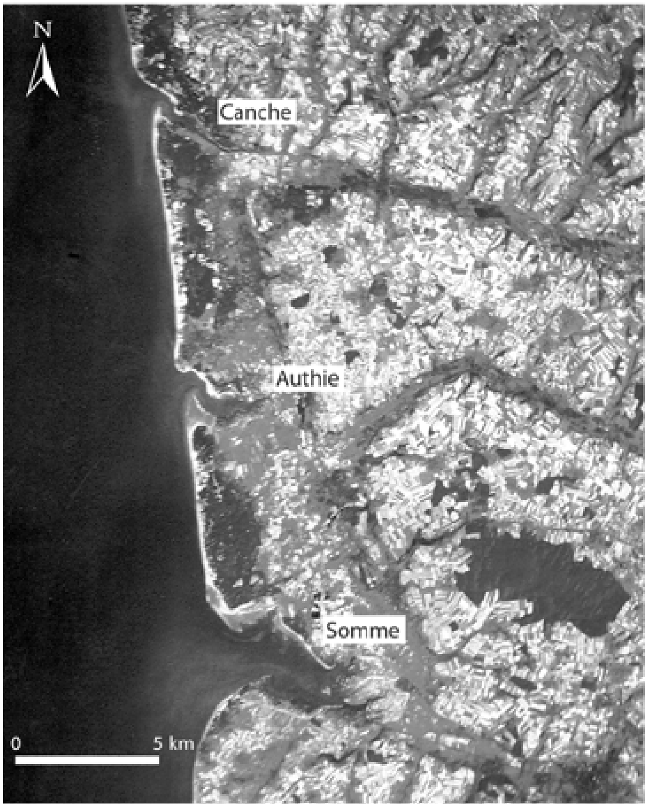

Figure 3. A SPOT image of part of the coast of northern France near the Dover Strait. Although the characteristics of a long, straight coast are those deemed as most typical of wave-dominated coasts, this is, in fact, a fine example of a WTD coast characterised by ridge and runnel beaches, macro-tidal estuaries subject to strong tidal currents and significant wave action, and a storm- and tide-dominated shoreface of sand banks (see Figure 4 for a typical cross-shore profile of this coast).

profile may reflect seasonal changes from wave-tide domination to tide domination that are hinged on seasonal variations in wave energy. The coast may exhibit tide-controlled muddy slopes or mud-draped beaches when wave energy is low to nil. This mud may become dispersed by waves during the high-energy season, resulting in a profile that reflects mixed domination, as described below. Such swings in energy regime are typical of coasts exposed to seasonal trade wind-generated waves, such as parts of the west coast of India and the Guinea coast of West Africa. In some of these muddy settings, the formation of cheniers is dependent on such seasonal changes in wave energy.

Generally, when sediment supply conditions are favourable, coasts that are permanently in the WTD spectrum adjust, over the long term, to the vertical tidal excursion by building out a beach and shoreface whose width and gradient are closely hinged on both waves and tidal range. The larger the range, the more important the intertidal volume of sand or gravel, and the higher the wave energy levels required in order for large-scale morphological changes to occur. As a result, the rates of sediment transport and beach morphological change are retarded on beaches with large tidal ranges and lower modal wave energy. Daily wave reworking of beach morphology in such cases may become limited to minor changes in bed forms that are themselves strongly hinged on the tidal cycle. In storm wave settings, such as those of northwestern Europe, this tidal influence alternates temporally from effective muting, modulation, or domination of the wave signature during more or less long periods (days to months, depending on the season) to wave muting or even domination of the tidal signal during storms lasting a few days. Over the large, low-gradient profile, there is thus an irregular temporal framework of mutual modulation determined essentially by the irregularity of changes in wave energy.

In considering a typical cross-shore profile, the joint work of waves and tides is generally expressed by the same concave type of profile as that of wave-dominated coasts. Sediment conditions being equal, this concavity, which concerns the beach, no doubt expresses wave dominance of the mixed process spectrum on this part of the coast, as on wave-dominated coasts. However, tidal dominance not only appears further downslope, but tidal modulation of the wave hydrodynamics also occurs (Figure 4). As tidal action increases, the shallow shoreface and inner shelf topography may, where abundant loose sediment is available, be characterised by numerous banks and ridges that are typical of a tide-dominated process signature, such as in the eastern English Channel, southern North Sea and the Huanghai

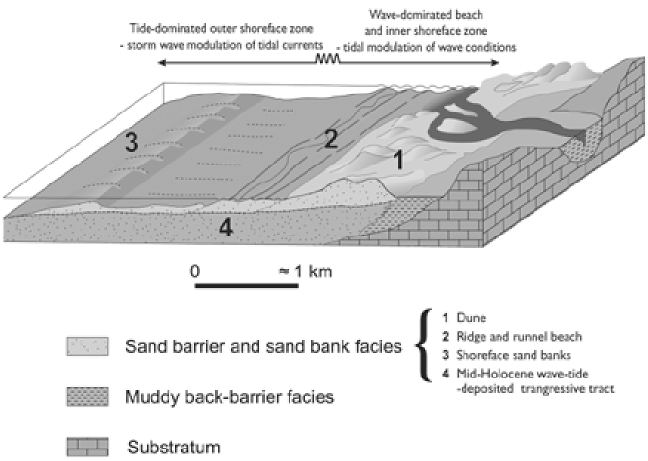

Figure 4. Cross-shore variations in wave and tidal activity on a typical sand-rich WTD coast. The beach may be of sand or gravel (adapted from ANTHONY, 2000).

(Yellow Sea). The sediment cover and bedform suite on such shorefaces may show spatial variations that are strongly hinged on bed shear stress gradients due to tidal currents (BELDERSON *et al*., 1982; JOHNSON *et al*., 1982; DYER and HUNTLEY, 1999). These bedforms range, as shear stress decreases, from gravel waves, through sand banks, when sand is abundant, and down to rippled beds and sand patches. This tide-dominated offshore part of the coastal slope may, however, be more or less significantly influenced by waves, depending on power levels. It is noteworthy that such shallow sand-rich shorefaces are generally considered as tide-dominated (BELDERSON *et al*., 1982; JOHNSON *et al*., 1982; BERNÉ *et al*., 1998; DYER and HUNTLEY, 1999), while the shoreline, on coasts subject to waves, may be considered as wave-dominated by beach specialists. Indeed, our perception of coastal processes has been very strongly hinged on beach studies that are mainly concerned with the area of coast between modal wave base and the limits of swash run-up, this being a definition of the beach (SHORT, 1999). As SHORT (1999) has recently stated, between these limits is where ‘waves and beaches reign supreme’.

Mixed Wave-Tide-Dominated Processes: A General Overview

General morphological patterns associated with meso- to macro-tidal beaches have been synthesized in a beach classification framework (MASSELINK and SHORT, 1993). LEVOY *et al*. (2000) have complemented this work by examining beaches with mega-tidal tidal ranges. The large beach volume and the important horizontal tidal translation imply a reduction in overall beach gradient. As a result, the various wave zones migrate rapidly across the wide, low-gradient profile during the tide, resulting in significant cross-shore variations in the hydrodynamics and resulting morphology (Figure 5). Although waves tend to dominate tides on this part of the shoreline, the wave influence is toned down because the sum of energy spent per unit area over time is much less than on beaches with low tidal ranges or no tides. While entrainment thresholds are the same, the volume of sediment transport is thus much less on beaches with large tidal ranges. Holding beach sediment volume and slope constant, then the larger the tidal range, the greater the variations in morphodynamic behaviour between the lower beach and the upper beach. On sandy mega-tidal beaches, the morphodynamic domains may range from extremely dissipative at low tide on the lower beach to moderately reflective on the upper beach at high tide (WRIGHT and SHORT, 1983; LEVOY *et al*., 2000). At high tide, the extreme lower beach is subject to a combination of shoaling waves and strong longshore tidal currents. LEVOY *et al*. (2001) have suggested that such beaches may be termed as ‘wave-tide-dominated beaches’.

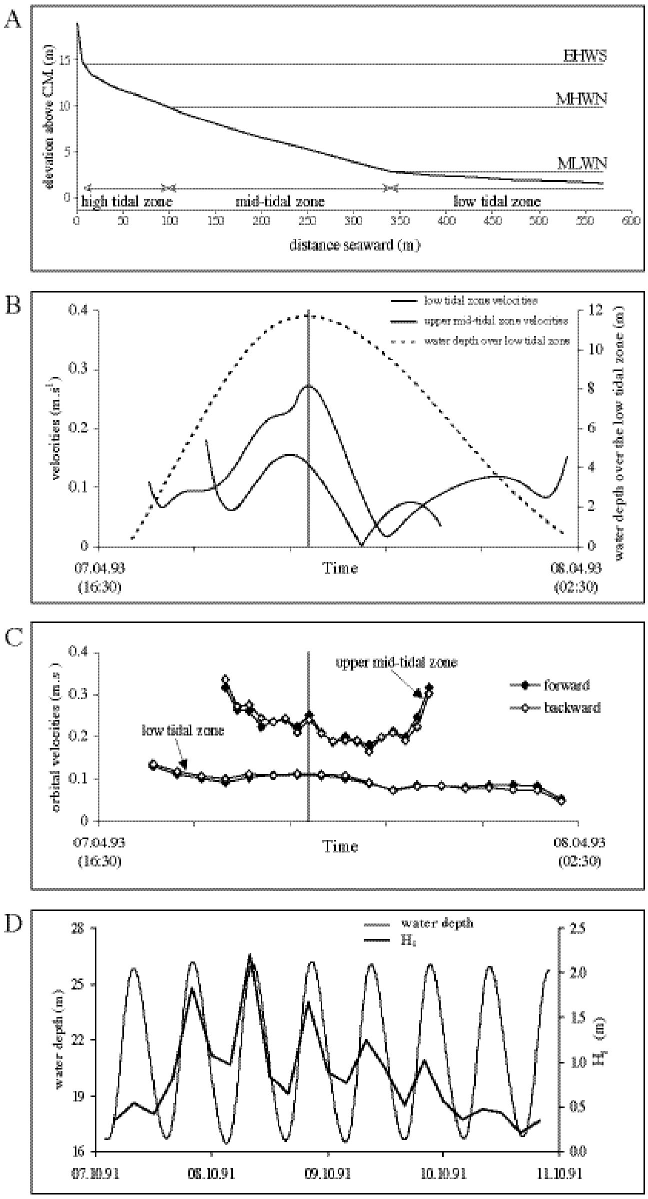

Figure 5. Tidal current characteristics and tidal modulation of wave characteristics on a mega-tidal beach and shoreface in Normandy, France (adapted from LEVOY *et al*., 2000). A. Beach profile. B. Mean current velocities on the lower beach (low tidal zone) and mid-beach (upper mid-tidal zone). C. Orbital velocity variations for the same beach zones (note the weaker velocities on the lower beach). D. Significant wave height (Hs) variations with tidally-modulated water depth on the shoreface. C.M.: Côte Marine (local sea-level datum); EHWS: exceptional high water springs; MHWN and MLWN: mean high and low water neaps.

A similar pattern prevails on mixed gravel and sand beaches in settings with large tidal ranges. It is interesting to note that on many Atlantic coast gravel beaches where the tidal range exceeds 3-4 m, there is often an outer-dissipative, wave-tide-dominated low-tide terrace of sand fronting the gravel beach. On such beaches, the upper gravel beach is extremely reflective and may be dominated by subharmonic gravity wave motions while the highly dissipative lower beach may show infragravity edge wave motions as well as strong, tidally-induced longshore currents (DOLIQUE, 1999). Where wind, sand size and supply conditions are favourable, wide, low-gradient beaches associated with large tidal ranges may provide significant surfaces for aeolian reworking of beach sand into coastal dune fields (Figure 4). These wide beaches are also commonly characterised by strong groundwater table fluctuations that are strongly hinged on the tidal fluctuations and that may actively affect beach face hydrodynamic conditions, potential for aeolian sediment transport and hence beach stability (TURNER, 1993; MASSELINK and TURNER, 1999).

Apart from morphodynamic classification frameworks, much of the work carried out so far on the wave-tide relationship on such beaches has focused on instantaneous to short-term wave-tide sediment mobilisation patterns. These studies are still few, and some of their results may be considered as site-specific at this stage. However, certain general patterns may be identified. Wave orbital velocities and wave breaking processes induce sediment suspension while transport is by combined wave and strong tidal currents (DAVIDSON *et al*., 1993; MASSELINK and PATTIARATCHI, 2000), although the most active tidal phase appears to differ on different beaches, depending on the effects of friction and on whether the tidal wave is progressive or standing. DAVIDSON *et al*. (1993) and MASSELINK and PATTIARATCHI (2000) have monitored strong net offshore sediment transport during the ebbing tide compared to little net transport during the flooding tide. They attributed this to the destruction, during the falling tide, of high-tide ripples formed by waves. On French sandy beaches in the eastern English Channel, the progressive tidal wave is associated with strong longshore currents at high water that are highly effective in terms of sand transport because they coincide with higher high-tide waves that lead to suspension of fine sand. In such situations, both the tidal and wave signatures mutually amplify each other. The longshore currents are always directed northwards or eastwards, and are therefore very important in terms of the net long-term bedload and suspended sediment (including pollutants) transport in these directions. On these beaches, at low tide, waves and tidal currents on the lower beaches are generally much weaker, muting each other mutually. These modulations are due to the fact that the shallower water imposed by the tide results in enhanced wave dissipation (Figure 5), while tidal retardation probably occurs through increased bed friction, the tidal current strength being generally greater seaward in deeper water LEVOY *et al*., 2001). On other beaches in settings with large tidal ranges, the large tidal flux may impose cell circulation towards low tide (MASSELINK and HEGGE, 1995). Ridge and runnel beaches often exhibit channel flows at low tide that are due to the concentration of the flow of both the ebbing tide and swash bores breaking over the ridges (SIPKAand ANTHONY, 1999).

Wave-tide interaction also prevails over the generally tide-dominated shoreface. On sand-rich shorefaces, the organisation of tidal current ridges may be hinged on a long-term balance reflecting the joint action of strong background tidal currents and the imprint of periodic storm waves. The linear current ridges and dunes are generally oriented more or less parallel to the shoreline in response to the longshore tidal currents. From detailed monitoring of sand dunes off the Belgian coast, VAN LANCKER (1999) showed a vertical pattern of wave-and-tide reworking. Dune mobility in shallow depths (< 5 m), whatever the distance offshore, was dominated by wave action while deeper water mobility was dominated by tides. In these shallow epicontinental seas of the eastern English Channel and southern North Sea, storm waves tend to drive dunes and ridges inshore, a process that sometimes tends to be countered by the longshore tidal currents. This may result in stretching and eventually division of the ridges (TESSIER *et al*., 1999). Ridges that do get close inshore may eventually become attached to the beach, leading to significant accretion (ANTHONY, 2000) and onshore feeding of aeolian dunes. On coastal sectors where the morphodynamic balance is such that the ridges maintain self-stability and do not move inshore, this may eventually deprive beaches and aeolian dunes of sand, in spite of the abundant nearshore sand stocks.

Tidal flow asymmetry on coasts may also determine preferential sediment transport patterns and directions. On many WTD coasts, especially in the mid- and high latitudes, the nearshore residual tidal current signature may become strengthened or weakened by synoptic winds, thus supporting the differentiation of tidal asymmetry patterns that determine medium to long (order of tens to hundreds of years) term sediment transport. These ebb or flood-dominated flows lead to well-defined sand transport pathways such as those that run along both the French and English coasts in the eastern Channel and Dover Straits (BECK *et al*., 1991; GROCHOWSKI *et al*., 1993). They may also be responsible, together with strong bed shear stress gradients, for the creation of zones of bedload parting and convergence (JOHNSON *et al*., 1982; HARRIS *et al*., 1995; DYER and HUNTLEY, 1999). As a result of various hydrodynamic conditions, notably orientation of the synoptic wind field and Coriolis deflection of the water mass, tides are larger on the French coast and the mixed wave-tide-dominated sand transport pathway on this coast has been much more active than that on the English side. It has been suggested (ANTHONY, 2000) that this sand-rich pathway has fed the large Holocene aeolian dune fields on the French coast via storm reworking of the nearshore sand stocks, and shoreward transport by winds over the wide dissipative beaches. Such a UK-regional starvation of sand has led to an enhancement of the gravel component as the major beach constituent along the English side of the Channel.

SYNTHESIS

The concept of WTD coasts is not a novelty. However, it appears to have been limited mainly to sandy barrier coasts cut by tidal inlets. In this paper, an attempt has been made to show that the WTD spectrum encompasses a wider range of coasts than this. A particularly significant range of coasts that fall within this spectrum is that of meso- to mega-tidal coasts wherein the beaches have been considered essentially in terms of wave-dominated features that are influenced to varying degrees by the tide. A different position is adopted in this paper by considering the coastal profile in terms of one subject to a mixed influence wherein wave domination on the upper, beach, part of the profile gives way to tide-domination in the offshore part of the profile as strong tidal currents determine the sediment transport patterns, and impose bedform development suites and morphological features, when abundant reworkable sand-sized sediment is available. These offshore areas of coasts subject to significant tidal ranges have commonly been considered as tide-dominated shorefaces by workers not concerned with the wave-dominated element of the upper profile. WTD coasts are more than a hybrid, rather they should be considered as a major focus of coastal attention, given their widespread occurrence.

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