Morphodynamics of intertidal bars in wave-dominated coastal settings — A review

G. Masselink [a,*], A. Kroon [b], R.G.D. Davidson-Arnott [c]

[a] *School of Geography, Plymouth University, Plymouth, PL4 8AA, England*
[b] *Institute of Geography, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K., Denmark*
[c] *Department of Geography, University of Guelph, Guelph, Ontario, Canada N1G 2W1*

Abstract

Intertidal bar systems are ubiquitous features on wave-dominated beaches in coastal settings with a significant (>1 m) tidal range. Depending primarily on the wave conditions and the tidal range, and to a lesser extent on the nearshore gradient, they can assume a variety of forms. *Slip-face bars* represent the most pronounced and dynamic intertidal bar morphology, and are generally found on their own around the mean high tide level. They usually form low on the intertidal beach after storm-induced beach erosion and develop into a berm under prolonged calm wave conditions. *Low-amplitude ridges* and *sand waves* represent multiple bar morphologies. The bars occur across the entire intertidal profile and they remain present throughout the year. Multiple intertidal bars tend to be rather subdued and relatively static, especially sand waves, and their origin remains unclear.

The morphological response of intertidal bars to changing wave conditions is largely forced: bars build up and migrate onshore under calm waves, and are flattened and may migrate offshore during storms. The morphological response is, however, significantly affected by relaxation time effects and morphological feedback, particularly on beaches with multiple intertidal bars. Despite their morphological differences, the intertidal bar types exhibit pronounced similarities in their morphodynamics. Sediment transport processes and morphological response are principally controlled by the tidal water levels on the beach, because these, together with the offshore wave energy level and the beach morphology, determine the type, intensity and duration of the wave processes operating on the cross-shore profile.

It is the dominant importance of tidal water level variations and wave processes in shallow water depths (swash and surf zone bores), rather than wave height variability and deeper water wave processes (breaking and shoaling waves), that constitutes the main difference between intertidal and subtidal bar morphodynamics.
© 2005 Elsevier B.V. All rights reserved.

Keywords: Intertidal bars; Multiple bars; Beach morphology; Tide range; Morphodynamics

* Corresponding author. Tel.: +44 1752 233050; fax: +44 1752 233054.
E-mail addresses: gmasselink@plymouth.ac.uk (G. Masselink), ak@geogr.ku.dk (A. Kroon), rdarnott@uoguelph.ca (R.G.D. Davidson-Arnott).

1. Introduction

Intertidal bars are morphological highs situated between the mean low and high water spring levels on tidal beaches. They are aligned more or less parallel to the shore and may be dissected by rip channels at quasi-regular intervals. The depression onshore of the bar is the intertidal trough and collectively an intertidal bar and its associated trough are referred to as an *intertidal bar system*. The number of intertidal bars may vary from 1 to more than 10 and their associated vertical, cross-shore and longshore length scales are in the order of, respectively, 0.5, 20 and 100 m. Intertidal bar systems are ubiquitous features in coastal settings with a significant (>1 m) tidal range and various terms have been used to describe them, including *swash bar*, *ridge and runnel* and *sand waves*.

Intertidal bars have not received the same amount of attention in the coastal morphodynamic literature as their subtidal counterparts (Komar, 1998; Wijnberg and Kroon, 2002). This is somewhat surprising, because their accessibility during low tide allows morphological and sedimentological observations to be carried out very accurately. In addition, emergence of the bar morphology at low tide permits the deployment of instruments to measure hydrodynamic and sediment transport processes with relative ease. Understanding the dynamics of these bar systems is important, because, similar to subtidal bars, they play an important role for beach stability. Specifically, storm waves will break and dissipate their energy on the submerged intertidal bars, thereby reducing the amount of wave energy available to erode the subaerial beach and dunes. Insight into the dynamics of these bar systems therefore helps understanding coastal erosion.

The aims of this review are to identify the dominant morphodynamic processes governing intertidal bar systems and provide a conceptual framework with which these bars can be further investigated.

Three main intertidal bar types are defined and described first to provide a basis for our review (Section 2). This is followed by a consideration of the most important hydrodynamic and sediment transport processes affecting intertidal bar systems (Section 3). The response of intertidal bar morphology to changing wave/tide conditions is discussed next with reference to the effects of relaxation time and feedback (Section 4). A brief synthesis of intertidal bar morphodynamics is presented at the end of the paper (Section 5), followed by conclusions (Section 6).

2. Morphology

Several types of intertidal bar systems have been identified and reported in the literature (e.g. King, 1972; Greenwood and Davidson-Arnott, 1979; Carter, 1988; Wijnberg and Kroon, 2002). We recognize three main types and distinguish between them primarily on the basis of their morphology (Fig. 1). The terminology associated with intertidal bar morphology has been rather inconsistent, to say the least, and this has led to some confusion (cf. Orford and Wright, 1978; Orme and Orme, 1988). Not wishing to add to the plethora of generic and descriptive terms, existing terms are used to indicate the three main types of intertidal bar systems: *slip-face bars*, *low-amplitude ridges* and *sand waves*. The terminology is based on the final product of the morphological development and the scale of the morphological expression is implicit. So, slip-face bars have the largest amplitude, low-amplitude ridges represent rather subdued morphological forms and sand waves are relatively marginal repetitive features. When referring to the intertidal bar, ridge or sand wave in general terms, the word *bar* will be used from now on, irrespective of the intertidal bar type.

Slip-face bars are characterized by a well-defined, landward-facing slip-face (Fig. 2). They comprise the
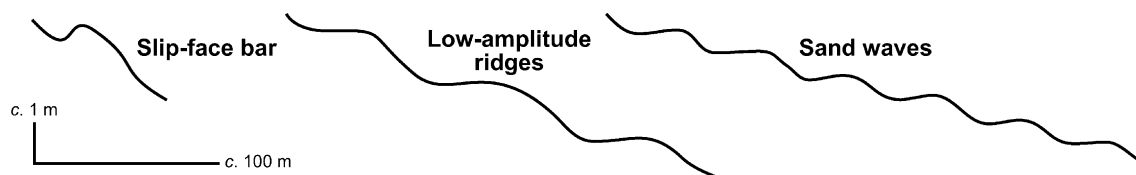

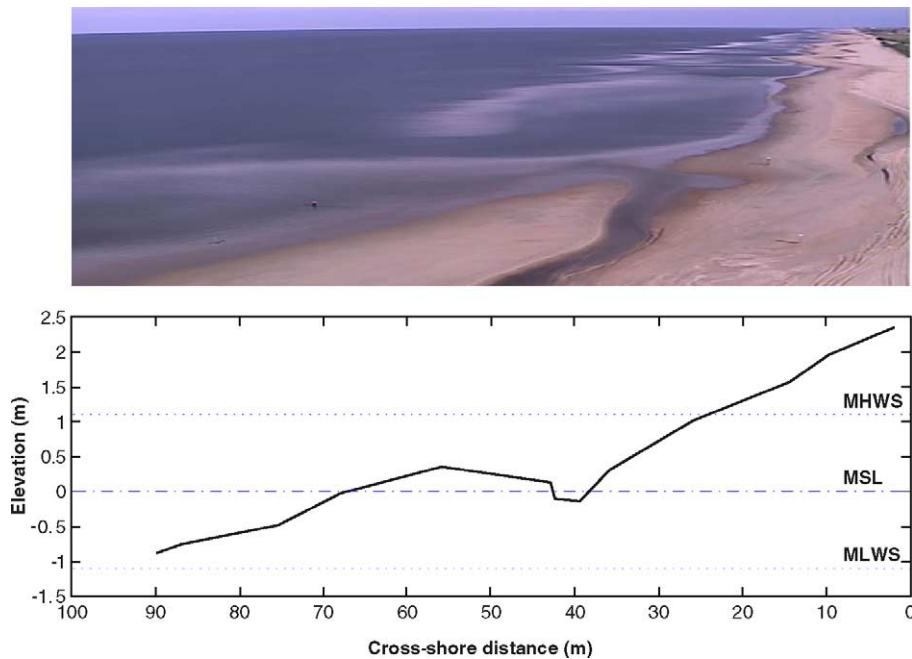Fig. 1. Diagram illustrating the three main intertidal bar types.

Fig. 2. Slip-face bars along the Holland coast near Egmond, The Netherlands: (top panel) ARGUS image showing intertidal beach with slip-face bar and trough and (bottom panel) beach profile. MHWS, MSL and MLWS refer to mean high water spring, mean sea level and mean low water spring, respectively.

Group II bars defined by Greenwood and Davidson-Arnott (1979), include the bar type occurring in the *ridge and runnel* beach state defined by Wright and Short (1984) and are referred to as *swash bars* by Carter (1988). Slip-face bars are quite pronounced with the elevation difference between the deepest part of the trough and the bar crest generally exceeding 1 m. The landward slope of these bars is very steep, often up to the angle of repose (30–35°), while the seaward slope is 3–6°. Rip channels dissect the bars approximately every 200 m, but it is noted that the rip spacing on all intertidal bar types is highly variable and certainly not a distinguishing factor. Slip-face bars generally occur on beaches with mild nearshore slopes (c. 2°) subjected to variable wave conditions and a micro- or mesotidal tide range (Davis et al., 1972). They may also be found along tideless shores, where small water level fluctuations related to wind set-up provide the mechanism for alternately exposing and subjecting emerged near-shore bars to swash and surf zone processes (Davis and Fox, 1972; Stewart and Davidson-Arnott, 1988). Slip-face bars are often fronted by a subtidal bar

system and they may be partially sheltered from the impact of storm waves (e.g. Aagaard et al., 1998a,b).

Low-amplitude ridges occur as a series of shore-parallel bars (2–6) that are dissected by shore-perpendicular drainage channels (Fig. 3). This type of intertidal bar morphology is the same as the *ridge and runnel* topography described by King and Williams (1949), includes the *Group I* bars defined by Greenwood and Davidson-Arnott (1979) and is a typical feature of *Group II* beaches identified by Short (1991) for intermediate wave energy, meso- and macrotidal beaches. The height of the intertidal bars (crest-to-trough elevation difference) rarely exceeds 1 m, while the spacing of the bars is approximately 100 m. The bars are generally asymmetric in the onshore direction and under prolonged calm conditions may develop a slip-face. The seaward slope of the bars (2–4°) is significantly steeper than the intertidal gradient (c. 1°) and the bars are distributed across the entire intertidal profile (Wright, 1976; Masselink and Anthony, 2001). Low-amplitude ridges occur on flat beaches subjected to low to medium wave energy
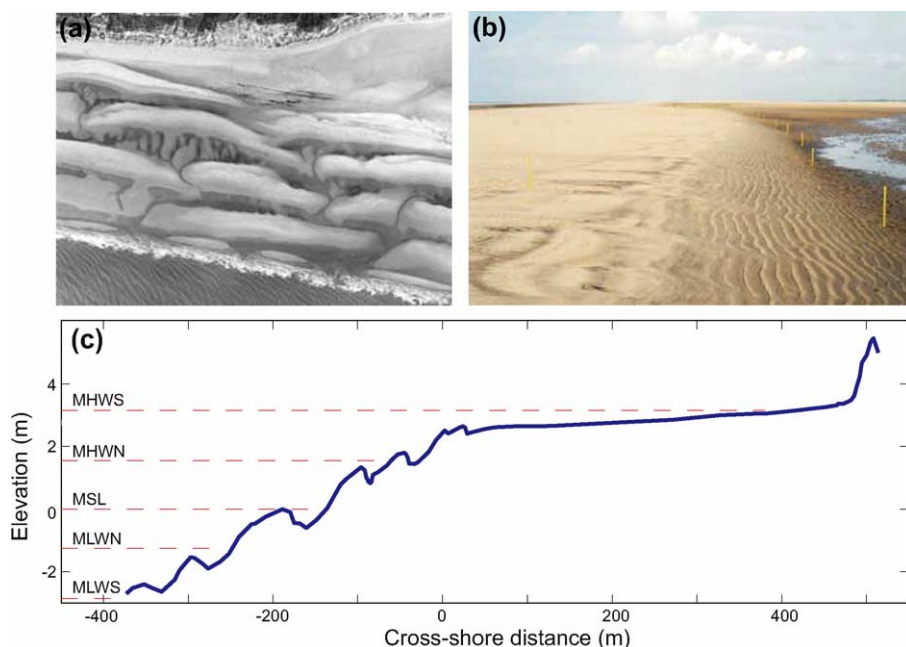
Fig. 3. Low-amplitude ridges along the north Lincolnshire coast, England: (a) aerial photograph showing exposed low-amplitude ridges and upper intertidal sand flat, (b) ground photograph and (c) beach profile. MHWS, MHWN, MSL, MLWN and MLWS refer to mean high water spring, mean high water neap, mean sea level, mean low water neap and mean low water spring, respectively.

conditions and a meso- or macrotidal regime (King, 1972).

Intertidal sand waves are straight to weakly sinuous features oriented parallel to the shoreline (Fig. 4). Morphologically and dynamically they are similar to subtidal bars described as *sand waves* by Zenkovich (1967) and comprise the *Group 3* multiple parallel bars defined by Greenwood and Davidson-Arnott (1979). The number of bars may range from 4 to 20 and the associated morphology is even more subdued than the low-amplitude ridges. The height of the bars is generally less than 0.5 m and their spacing is approximately 50 m. A symmetric cross-shore shape with slopes of 1–3° characterizes the bars. This type of intertidal bar morphology is typically found in low wave energy settings characterized by very gentle intertidal slopes (<0.5°). Often, the intertidal bars grade offshore into subtidal bars. Some uncertainty exists about the characteristic tidal range for this bar type. Greenwood and Davidson-Arnott (1979) suggest a small tidal range as the characteristic tidal setting, but Nilsson (1973) and Hale and McCann (1982) describe sand waves from mesotidal areas. Short (1991) observed that intertidal bars occurring on

wide, flat intertidal slopes of low wave energy, macrotidal beaches (*Group III* beaches) are morphologically similar to those occurring subtidally on low wave energy, microtidal beaches. Restricted wave energy combined with a low intertidal gradient appear to be the key control and sand waves may be found in a wide range of tidal settings.

The formation of the different intertidal bar types has been the subject of much speculation. The formation of slip-face bars is associated with storm activity and there are two hypotheses regarding their generation. According to Kroon (1994), the beach erodes during the storm and sediment is deposited in the low tide area or inner nearshore trough. In the days following the storm, a small ridge is formed around low tide level by swash processes, which subsequently develops into an intertidal bar. Other studies suggest that the bars are formed as breaker bars in the subtidal zone and migrate onshore into the intertidal zone (Hayes and Boothroyd, 1969; Davis et al., 1972; Aagaard et al., 2004). Whatever the exact mechanism, slip-face bars originate as breaker bars that develop due to the divergence of sediment transport resulting from off-
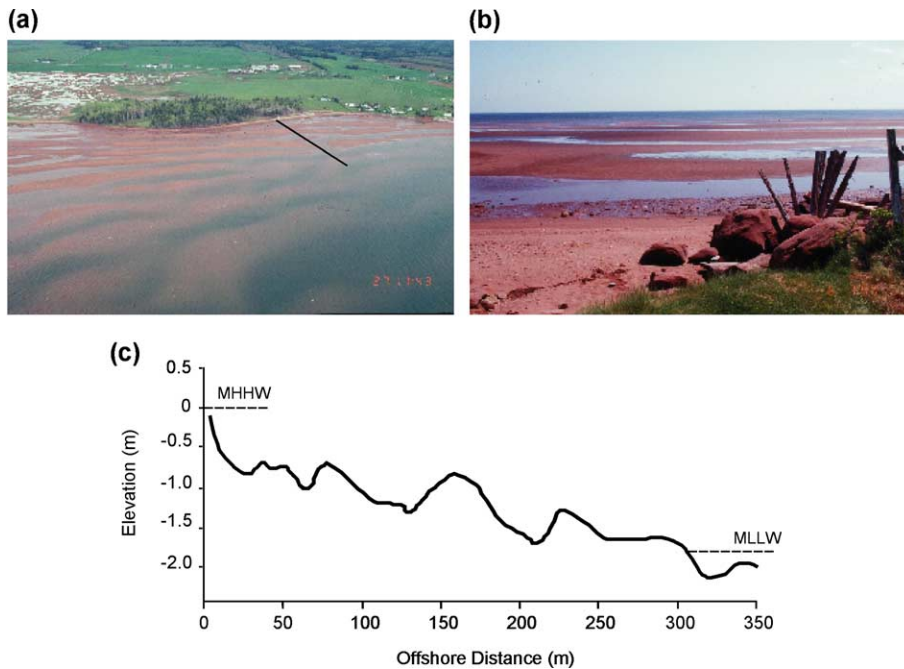
Fig. 4. Sand waves at Linden Beach, Gulf of St. Lawrence, Nova Scotia, Canada: (a) oblique aerial photograph showing exposed intertidal sand waves and subaqueous bars, (b) ground photograph and (c) beach profile (location of the profile is shown by straight line in aerial photograph). MHHW and MLLW refer to mean highest high water and mean lowest low water, respectively.

shore transport by the bed return flow and onshore transport due to wave asymmetry (Roelvink and Stive, 1989). The generation of low-amplitude ridges is less satisfactory explained. King and Williams (1949) and King (1972) suggest that their formation is related to the local process of beach gradient adjustment (i.e., steepening) by swash processes acting at temporary standstills of the water levels during low and high tide. There are indications of swash bar formation at the stationary tidal levels on beaches with low-amplitude ridges, but these bars tend to be less pronounced and more ephemeral than those occurring elsewhere on the profile (Anthony et al., 2004; Van Houwelingen, 2004). Most recent researchers (Carter, 1988; Short, 1991; Simmonds et al., 1996; Masselink and Anthony, 2001; Kroon and Masselink, 2002) favor a surf zone origin, and Masselink (2004) developed a numerical model capable of reproducing low-amplitude ridges solely as a result of surf zone processes. The formation of sand waves remains an enigma. Various authors have suggested that they are the result of multiple wave breaking and undertow development (Exon, 1975;

Dally and Dean, 1984; Dolan and Dean, 1985; Davidson-Arnott and McDonald, 1989), but other mechanisms have also been suggested, including standing infragravity waves (Bowen, 1980) and shoaling waves (Boczar-Karakiewicz and Davidson-Arnott, 1987).

The identified bar types are part of a continuum of intertidal bar morphologies and do not represent fundamentally different features. Kroon and Masselink (2002) showed that low-amplitude ridges on the upper part of the intertidal profile may develop a distinct slip-face under medium wave conditions and behave similar to slip-face bars. Hale and McCann (1982) investigated the morphology and processes of a series of bars located on a sub-horizontal intertidal platform. The relatively exposed bars at the edge of the platform were similar to low-amplitude ridges, whereas the more sheltered bars on the platform were akin sand waves. All three intertidal bar types may also have representation in the subtidal zone: slip-face bars can originate as a breaker bar in the subtidal zone during storms and develop into intertidal bars as a result of onshore bar migration (e.g. Davis et al., 1972); low-

amplitude ridges (e.g. Favas et al., 2000) and sand waves (e.g. Dawson et al., 2002) may smoothly grade into subtidal bars without any clear difference in morphology and/or process regime.

Following the bedform terminology of Jackson (1975), the intertidal bars discussed here are *macroforms* that are a reflection of the wave climate, rather than *mesoforms* that reflect wave/current-related boundary layer processes. The distinction between meso- and macroforms is not sharp, however, and it is possible that, with decreasing wave energy level and/or increasing tidal range, 'our' sand waves, which are wave-dominated macroforms, grade into Reineck and Singh's (1980) megaripples, which are current-dominated mesoforms.

3. Hydrodynamics and sediment transport processes

On beaches characterised by intertidal morphology the tidal range generally exceeds the modal height of the incident waves. The most important morphodynamic processes on intertidal bar systems are not related to the tide, however, but to the dissipation of incident wave energy. Waves propagating in shallow water to the shore undergo a number of transformations: (e.g. Aagaard and Masselink, 1999): symmetric shoaling waves $\rightarrow$ asymmetric shoaling waves $\rightarrow$ wave breaking $\rightarrow$ bores $\rightarrow$ swash. Each of these wave types is associated with a characteristic set of sediment transport and morphodynamic processes, and their occurrence can be linked to the relative wave height H/h, where H represents the significant wave height and h is the local water depth (Fig. 5). The hydrodynamic processes discussed here are common to all barred beaches, but the nature of these processes and their relative importance with respect to sediment transport varies significantly between intertidal and subtidal bar systems. Specifically, the relative wave height H/h across the crest and seaward slope of *subtidal* bars rarely exceeds 0.5 and the bars mainly experience wave shoaling and breaking processes (Plant et al., 1999). *Intertidal* bars, on the other hand, are exposed to the full range of wave processes with surf zone bores and, to a lesser extent, swash playing particularly significant morphody-

namic roles, especially on slip-face bars (Kroon and Masselink, 2002).

Shoaling waves operate seaward of the surf zone (H/h <0.3) and are characterized by larger onshore than offshore wave orbital velocities. As a result of this flow asymmetry, commonly referred to as *wave skewness*, the net cross-shore sediment transport under shoaling waves is generally directed in the onshore direction, with the transport rate increasing towards the wave breakpoint (Osborne and Greenwood, 1992a,b). Asymmetric shoaling waves can also occur in a trough located shoreward of a bar on which waves are breaking. Under such conditions, sediment transport may also be directed landward and this is testified by onshore asymmetric wave ripples typically found in troughs (Wright, 1976; Chauhan, 2000). Breaking waves are found on the crest and seaward slope of intertidal bars when H/h =0.3–0.5, and provide foci for wave-induced bed shear stresses (Favas et al., 2000). Several breakpoints may be present under energetic wave conditions on a beach with multiple bars, with the largest waves breaking furthest offshore and the breaker height progressively decreasing in the landward direction (Davidson-Arnott, 1981; Hardisty and Laver, 1989; Masselink, 2004). Cross-shore sediment transport under the breakers is determined by the relative contributions of onshore-directed transport due to wave skewness and offshore-directed transport by the bed return flow. The net transport direction depends mainly on the incident wave energy level with net onshore transport prevailing under calm wave conditions (Sunamura and Takeda, 1984), and net offshore transport occurring during storms (Russell and Huntley, 1999). Breaking waves rapidly transform in turbulent bores characterized by a saw-tooth shape and a large relative wave height (H/h =0.5–1). Streaming, Stokes drift and flow acceleration become important (Henderson et al., 2004), and bore-generated turbulence can directly influence local sediment suspension in shallow water depths (Puleo et al., 2000). The net transport direction may be onshore if the bore contribution bores exceeds that of the bed return flow and depends on the incident wave energy level (Elgar et al., 2001; Hoefel and Elgar, 2003). When surf zone bores 'collapse' on the beach they result in swash (H/h >1). Except under storm conditions, swash motion promotes net onshore sediment transport due to a
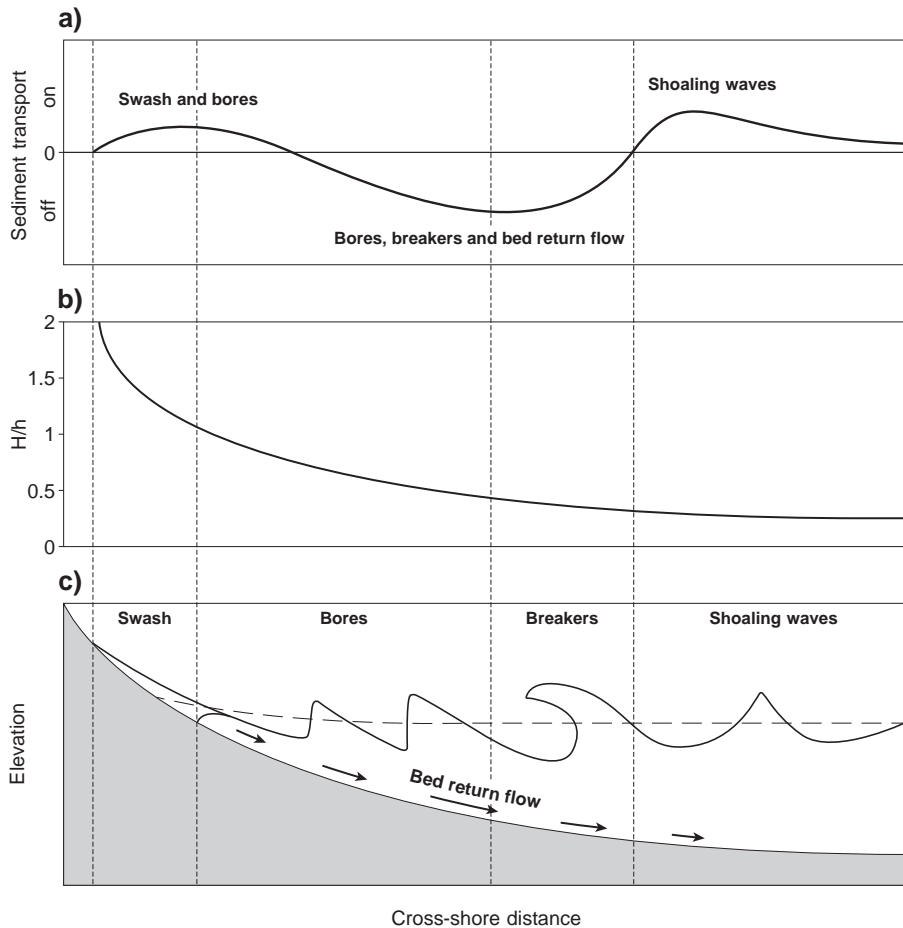
Fig. 5. Cross-shore definition sketch of wave-induced processes and cross-shore sediment transport over a flat sloping beach: (a) sediment transport rate and direction, (b) relative wave height H/h and (c) sloping beach and dominant wave-related processes. The dashed line in (c) represent the mean water surface profile (i.e., wave set-up profile).

range of factors, including flow asymmetry, bore turbulence, advection and infiltration effects (Masselink and Russell, submitted for publication).

Sediment transport on beaches with intertidal bar morphology is not only caused by cross-shore processes. Longshore currents, and hence longshore sediment transport, in intertidal troughs are driven by a combination of waves and tides, with the importance of wave forcing increasing with the incident wave energy level. Tide-driven currents are often reversing and occur when the bar seaward of the trough experiences shoaling waves (Sipka and Anthony, 1999; Kroon and Masselink, 2002). These currents can be substantial in megatidal settings, especially when the longshore current is reinforced by strong winds

(Anthony et al., 2005). When wave breaking occurs on the seaward bar, the longshore current in the trough is mainly wave-driven, and the current strength and direction depend primarily on the height and angle of the waves. When the relative wave height over the bar crest is high ($H/h > 0.5$; i.e. the trough is relatively shallow), the longshore current is fed by the discharge of propagating bores and swashes (Kroon and De Boer, 2001). In this case, the direction of the current in the trough is solely dictated by the intertidal bar-trough morphology, with the current generally flowing towards the nearest rip channel draining the trough (Chauhan, 2000). Overall, the morphodynamic role of currents in the trough region is limited, but may be significant. Specifically, the currents restrict the move-

ment of sand across the trough, causing the troughs to serve as effective sediment transport barriers (Parker, 1975). Under certain conditions (strong winds and large tides), the longshore sediment transport in the troughs may be substantial and significantly contribute to the overall sediment budget (Anthony et al., 2004, 2005). Moreover, long-term monitoring of beaches with low-amplitude ridges along the east coast of England has revealed that the intertidal bar configuration migrates alongshore due to longshore sediment transport (King and Barnes, 1964; Van Houwelingen et al., in press).

Tides do not directly affect wave-driven hydrodynamic processes, because the associated timescales are very different (hours as opposed to seconds) and the tide-driven current velocities are relatively modest. The tide nevertheless plays an important morphodynamic role by shifting wave processes up and down the beach profile, and determining the position and duration of distinct wave processes (Masselink and Turner, 1999). On a beach with a series of intertidal bars, most bars will experience a mixture of swash, surf zone (bores and breakers) and shoaling wave processes over a neap-spring tidal cycle, but the relative importance of each of these hydrodynamic processes will be different (Wright et al., 1982). Generally, the importance of swash and surf zone processes increases in the landward direction toward the spring high tide level (Masselink, 1993). In addi-

tion, spring tides induce a large spatial variation in water lines and small residence times for distinct processes, while neap tides narrow the intertidal area and increase the time for certain processes to work on the sediment at one location (Kroon and Masselink, 2002). There is, therefore, more potential for morphological change during neap tides than during spring tides. The variability in wave processes introduced by the neap-spring tidal variation is especially significant under persistent calm wave conditions, but is obliterated by highly variable wave energy levels.

The tide-induced migration of the different hydrodynamic zones across the beach profile reduces the amount of time that certain wave processes are allowed to act, but may also cause changes in the cross-shore sediment transport rate and direction over a tidal cycle. In Fig. 5a, the distribution in the cross-shore sediment transport rate across the nearshore zone, referred to as the *shape function* (Foote et al., 1994), was shown schematically for medium wave energy conditions. The shape function is expected to vary with incident wave conditions; for example, sediment transport during a storm is likely to be off-shore-directed throughout the surf and swash zone (Russell and Huntley, 1999). Under most conditions, however, there is likely to be a change in the sediment transport direction across the nearshore zone, resulting in either sediment transport divergence or convergence, whether in the vicinity of the water line, or
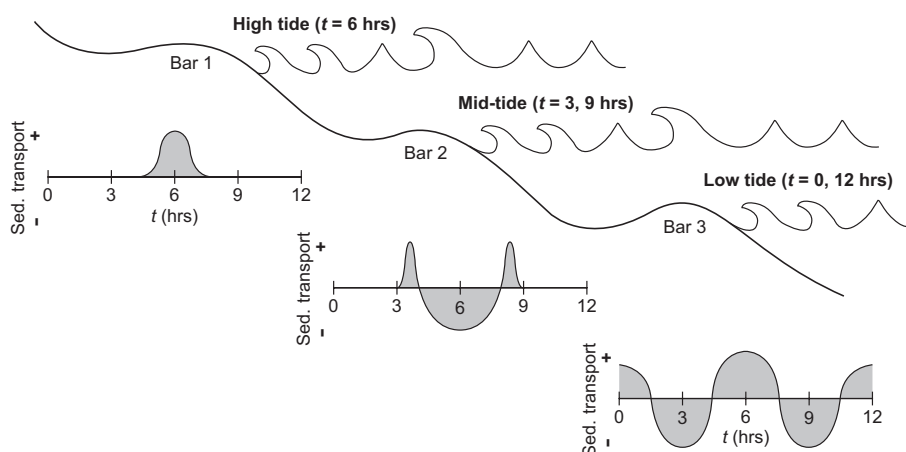

Fig. 6. Variation in the cross-shore sediment transport rate and direction over a single tidal cycle (assumed to last for 12 h) for three different intertidal bar systems obtained by advecting the 'shape function' of Fig. 5a across the intertidal profile. The wave patterns represent the variation in wave type at the different stages in the tidal cycle with breaking waves on the bar crest, wave transformation in the trough and bores on the beachface.

near the wave breakpoint. As water levels rise and fall during a tidal cycle, the shape function is advected up and down the beach (Fisher and O'Hare, 1996; Fisher et al., 1997; Masselink, 2004), potentially causing temporal changes in the cross-shore transport direction at any location on the intertidal profile (Fig. 6). Such changes are expected to be particularly significant in the lower intertidal zone. For example, the sediment transport direction on an intertidal bar located around low tide level may switch during a single tidal cycle from onshore by swash and bores, to offshore due to bed return flow in the surf zone, to onshore by shoaling waves during high tide; and back again to offshore in the surf zone, and to onshore by swash and bores (refer to sediment transport for Bar 3 in Fig. 6).

The morphodynamic implications of the twice-daily sweep of the tide across the intertidal profile are more pronounced as the tidal range increases. Similarly, an increase in the relative importance of tide-related processes is also anticipated when the wave height decreases. The ratio between tide range and wave height, referred to as the *relative tide range*, is a useful parameter to quantify these tidal effects (Masselink, 1993; Masselink and Short, 1993). The larger the relative tide range, the shorter the residence times for swash and surf zone processes, the more important shoaling wave processes, and the more likely the occurrence of changes in the cross-shore sediment transport direction over a tidal cycle.

4. Morphological response

Intertidal bar morphologies are to a large extent forcing-dominated systems, characterised by a reasonably clear relation between the forcing signal and the morphologic response (Wijnberg and Kroon, 2002). Both single (e.g. Owens and Frobel, 1977) and multiple intertidal bars (e.g. King, 1972) build up and migrate onshore under fair-weather conditions, and they become less pronounced and/or migrate offshore during storms. As an example, Fig. 7 shows the morphological development of low-amplitude ridge morphology under the influence of calm wave conditions (H_s <0.5 m), resulting in an increase in bar relief and onshore bar migration, and its response to a storm event (H_s >1 m), when the prominence of the bar

morphology is reduced due to infilling of the troughs. A second example is provided in Fig. 8, which illustrates the morphological development of a slip-face bar in response to wave and water level forcing over several months. In this case also, calm wave conditions cause bar build-up and onshore bar migration (e.g. Phase III), whereas energetic waves and high water levels result in reduced bar relief and offshore bar migration (e.g. Phase II).

Shoaling waves may contribute to onshore bar migration when the bar is located just outside the surf zone, such as described by Plant et al. (1999) for subtidal bars, but their role can only be significant on lower bars associated with multiple bar morphologies. Surf zone processes can push intertidal bars onshore when the crest of the bar and its seaward slope are subjected to low to medium energy breaking waves and bores (Sunamura and Takeda, 1984; Kroon and Masselink, 2002). Swash-induced onshore bar migration is, however, most frequently mentioned in the literature (Wijnberg and Kroon, 2002). According to this mechanism, sediment is entrained at the seaward slope of the bar by breaking waves, bores and/or swash action; when the sediment-laden uprush overtops the bar crest, the efficiency of the backwash is greatly reduced, and sediment is deposited landward of the bar crest (Owens and Frobel, 1977; Dabrio and Polo, 1981). Sedimentary structures show that the migration is a coherent progradation of the entire slip-face (Davis et al., 1972; Dabrio and Polo, 1981). Swash processes are most effective in causing onshore bar migration when the elevation of the bar crest is just above high tide level, ensuring that a large number swash events will overtop the bar crest around high tide.

Bar morphological change during storms mainly occurs when the bars are in the surf zone and subjected to the action of breaking waves and energetic bores. Offshore bar migration occurs when the significant breaker height over the crest of the bar and its seaward slope exceeds 0.4 m (Kroon, 1994; Houser and Greenwood, 2003). Analogous to the storm response of subtidal bar systems, it is inferred that the offshore sediment transport is carried out by the bed return flow (e.g. Thornton et al., 1996; Gallagher et al., 1998), which is particularly strong around the bar crest region (Garcez Faria et al., 2000). However, when intertidal bar morphology is three-dimensional,
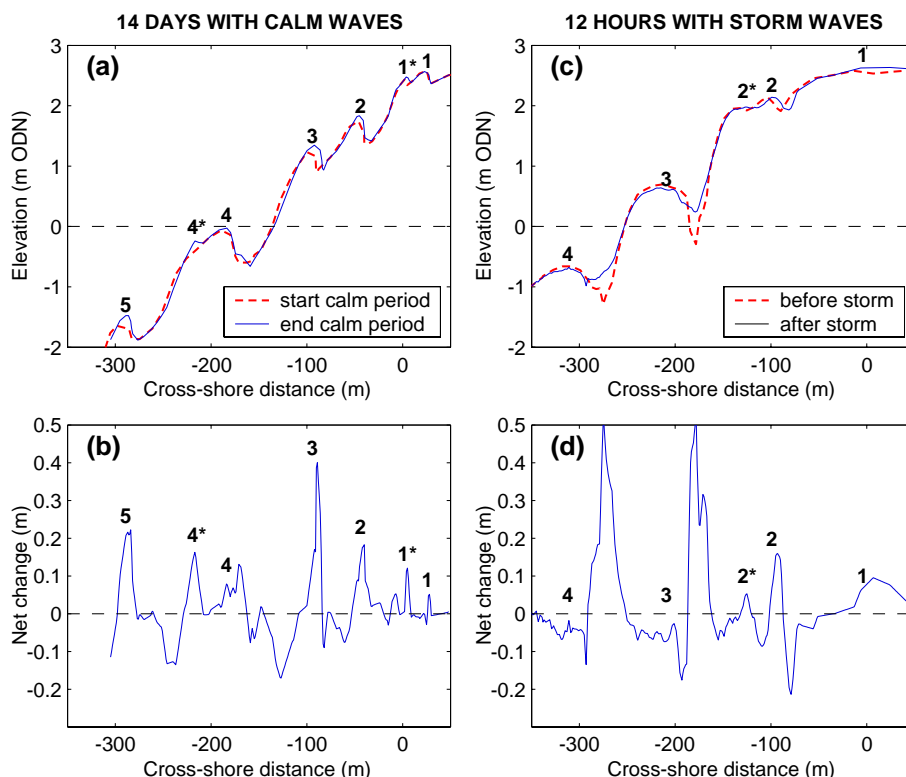
Fig. 7. Response of low-amplitude ridge morphology to 14 days of calm wave conditions (a and b) and 12 h of storm waves. The data were collected along the north Lincolnshire coast, England (Van Houwelingen, 2004).

onshore-directed mean currents may prevail over the bar crest and intertidal bars may migrate onshore even during storm conditions (Aagaard et al., 1998a,b).

Slip-face bars migrate onshore at relatively fast rates, commonly exceeding 1 m per day (Owens and Frobel, 1977; Kroon, 1994; Aagaard et al., 1998a), and may eventually weld to the upper beach and develop into a berm (Kroon, 1994; Houser and Greenwood, 2003; Borrelli and Wells, 2003; Aagaard et al., 2004). Onshore bar migration rates associated with low-amplitude ridges are more modest, generally ranging between 1 and 10 m per month (Mulrennan, 1992; Levoy et al., 1998; Sipka and Anthony, 1999; Stepanian and Levoy, 2003; Van Houwelingen et al., in press), and only under optimal wave/tide conditions can they move onshore more than 1 m during a single tidal cycle (Voulgaris et al., 1996, 1998; Kroon and Masselink, 2002). Sand waves do not appear to migrate consistently in any direction at all; rather, they oscillate landward and seaward about a mean

point in response to waves generated by storms of varying intensity (Davidson-Arnott and Pember, 1980; Davidson-Arnott, 1981; Dawson et al., 2002). During extreme storms, slip-face bars are generally destroyed (Kroon, 1994; Houser and Greenwood, 2003), but multiple intertidal bar morphologies tend to survive destruction, albeit with much reduced relief (King, 1972; Mulrennan, 1992; Navas et al., 2001).

The variation in the rate of morphological response between the different intertidal bar types is attributed to relaxation time effects, resulting from the finite time required for morphological change to occur (De Boer, 1992). Generally, the relaxation time depends on the size of the morphological feature, the extent to which the morphology deviates from equilibrium, and the energy level of the hydrodynamic processes (Cowell and Thom, 1994). But an additional factor is of fundamental importance for intertidal bar morphology: the amount of time that sediment transporting processes – mainly breaking waves and surf zone
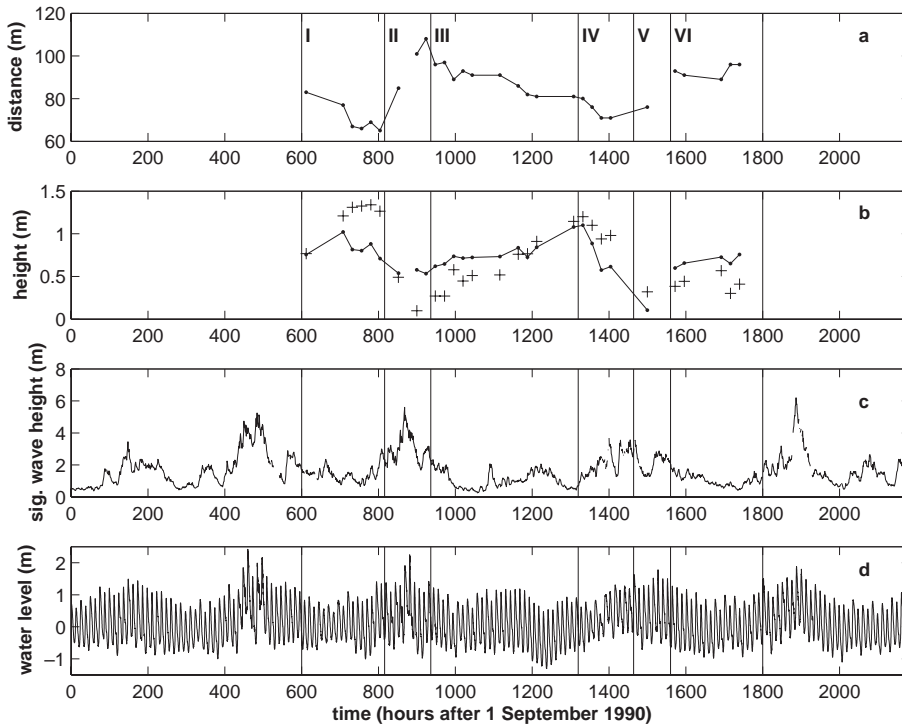
Fig. 8. Response of slip-face bar system to changing wave and water level conditions: (a) bar crest position, (b) bar height (line) and elevation relative to MSL (crosses), (c) offshore significant wave height and (d) mean water level relative to MSL. The data were collected near Egmond, the Netherlands (Kroon, 1994).

bores, but also shoaling waves and swash – operate across the crest and seaward slope of the bar. For any given bar, this amount of time increases with wave height and decreases with tide range; in other words, it increases with decreasing relative tide range (Masselink, 1993; Kroon and Masselink, 2002). Therefore, on some beaches with intertidal bar morphology the bars are completely eroded and/or moved into the subtidal zone during storms (slip-face bars in energetic, microtidal environments), while in other settings the bars only undergo minor modifications (sand waves in low-energy, macrotidal environments). Relaxation time effects are also responsible for the negative correlation between onshore bar migration rates and tidal range (Davis et al., 1972), and the difference in permanency of intertidal bar morphology in low and high tidal settings (Van den Berg, 1977). Relaxation time effects vary across the same beach due to the variable exposure time to hydrodynamic processes; therefore, some intertidal bars may be greatly affected by storm

waves, while other bars present on the same beach are hardly modified.

Intertidal bars are also characterised by morphodynamic feedback, which weakens the correlation between the forcing signal and the morphologic response (Wijnberg and Kroon, 2002). The feedback causes the morphology to play an active part in its evolution, rather than merely responding to changing hydrodynamic conditions. On intertidal bars not fronted by other bars, the local wave conditions are representative of the offshore wave climate. In this case, the feedback between morphology and hydrodynamics is mainly local. Examples of such morphodynamic feedback include the control of the local bed slope on swash asymmetry (Hardisty, 1986) and breaker type (Battjes, 1974), the influence of the bar crest elevation on the frequency of overtopping, and the effect of abrupt changes in the slope in causing steep hydrodynamic process gradients (Anthony et al., 2004). Alongshore variation in the overall slope of the intertidal beach (coupled to horn/embayment features)

can also induce alongshore changes in the intertidal bar response under similar offshore storm conditions due to feedback (Aagaard et al., 2005). On intertidal bars fronted by other bar systems, however, non-local morphodynamic feedback which affects the entire intertidal zone becomes also important (Short and Aagaard, 1993). Wave breaking on the outer bar(s) reduces the wave energy level on the inner bar(s) and protects the upper part of the beach from storm wave action. The dynamics of the upper bars can therefore not be considered in isolation from those of the lower bars and the interactions between the different bar systems may even dominate the morphological response (Wijnberg and Kroon, 2002). Well-documented examples of feedback-dominated subtidal bar systems are the Dutch coast (Ruessink and Kroon, 1994; Wijnberg and Terwindt, 1995) and Duck in North Carolina (Plant et al., 2001), but feedback effects are expected to be equally, if not more, important on multiple intertidal bar systems (Van Houwelingen, 2004).

5. Synthesis

Depending primarily on the wave conditions and the tidal range, and to a lesser extent on the nearshore gradient, intertidal bar morphology can assume a variety of forms. Three main intertidal bar types are identified primarily on the basis of their morphology: slip-face bars, low-amplitude ridges and sand waves. An overview of the characteristics and dynamics of the three bar types is given in Table 1, and a conceptual diagram summarising the intertidal bar morphodynamic system and its local and non-local forcing is provided in Fig. 9.

At any time during a tidal cycle, the morphological response of an intertidal bar is determined by the type and intensity of the wave processes acting on its crest and seaward slope. These can be parameterised by the relative wave height and the local wave height, respectively, and depend primarily on the incident wave conditions, the (tide-controlled) water depth over the bar and the offshore (bar) morphology. The relief of the bar in question is also important and the steeper its offshore slope, the more energetic the wave processes are (e.g. plunging versus spilling breakers), and the more important the role of swash processes is.

Low to medium wave energy swash and surf zone bores, and shoaling waves under any wave energy condition cause bar build up and/or onshore bar migration (Sunamura and Takeda, 1984), whereas high wave energy swash and surf zone processes induce bar flattening and/or offshore bar migration (Gallagher et al., 1998). Over a longer time period, such as over a tidal cycle, the movement of the tidal water level gives rise to a third factor controlling intertidal bar response: the duration of the different wave processes. The amount of time that certain wave processes are allowed to operate on the bar is mainly a function of the tide range (Wright et al., 1982) and decreases from spring to neap tides, and from micro-to macrotidal ranges. Tidal residence times also depend on the relief of the bar morphology, because a large trough-to-crest height and/or a steep seaward slope reduce tidal migration rates and prolong the amount of time that certain wave processes can act on the bar surface. The limited duration of wave processes due to changes in the water level gives rise to relaxation time effects, which slow down the morphological response (Davis et al., 1972).

The variation in the type, intensity and duration of the wave processes acting on the cross-shore profile accounts for the main difference in morphological behaviour between intertidal and subtidal bars. The latter bars are not usually affected by swash and inner surf zone bores, and are more commonly exposed to deeper water processes, such as wave breaking and shoaling waves. The morphological response of subtidal bars is determined by the location of the bar relative to its 'equilibrium' location near the wave breakpoint (Plant et al., 1999): bars located outside the surf zone will be pushed onshore by shoaling waves, whereas bars inside the surf zone will be pushed offshore by the bed return flow. Over periods of days to weeks, therefore, subtidal bar morphology responds primarily to wave height variability. Intertidal bars are subjected to the same fundamental wave-driven sediment transport processes as subtidal bars; however, their longer-term development is largely controlled by tidal water level variations and changes in the incident wave conditions play a secondary, albeit significant role (Kroon and Masselink, 2002).

The formation of multiple intertidal bars has not been resolved (refer to Section 2) and warrants further

Table 1
Overview of intertidal bar morphodynamics

	SLIP-FACE BARS (Owens and Frobel, 1977)	LOW-AMPLITUDE RIDGES (King and Williams, 1949)	SAND WAVES (Hale and McCann, 1982)
MORPHOLOGY			
Intertidal slope	Gentle (c. 2°)	Very gentle (c. 1°)	Sub-horizontal (<0.5°)
Seaward slope of bars	Steep (3–6°)	Intermediate (2–4°)	Gentle (1–3°)
Relief	Pronounced (>1 m)	Intermediate (0.5–1 m)	Subdued (<0.5 m)
Cross-shore shape	Strongly asymmetric	Weakly asymmetric	Symmetric
Slip-face	Common	Occasional	Rare
Number of intertidal bars	1	2–6	May exceed 10
Bar spacing	c. 200 m	c. 100 m	c. 50 m
Permanency	Transient features	Permanent features	Permanent features
Subtidal expression	Intertidal bar may be fronted by subtidal bar(s)	Intertidal morphology may extend into subtidal zone	Intertidal morphology may extend into subtidal zone
OCEANOGRAPHIC SETTING			
Waves	Medium to high wave energy ($H \approx$ 1–2 m)	Low to medium wave energy ($H=0.5$–1 m)	Low wave energy ($H=0$–0.5 m)
Tides	Low tidal (MSR<3 m)	High tidal (MSR>3 m)	High tidal (MSR>3 m)
Relative tide range (H/MSR)	RTR <5	RTR=5–15	RTR >15
HYDRODYNAMICS			
Relative roles of swash and surf	Surf and swash are both important	Surf is dominant, but swash can be significant	Surf is dominant and swash is insignificant
Swash and surf conditions	Intermediate	Dissipative	Extremely dissipative
MORPHOLOGICAL RESPONSE			
Type of response	Mainly forcing-dominated, relaxation time and feedback effects significant	Combination of forcing-, relaxation time- and feedback-dominated	Mainly relaxation time- and feedback-dominated, forcing effects significant stationary
Onshore migration rates	1–10 m per day	0–1 m per day	
Response to calm conditions	Onshore bar migration	Onshore bar migration and bar build-up	Bar build-up
Response to storm conditions	Bar erosion, possibly destruction, offshore bar migration	Morphology becomes more subdued, offshore bar migration	Morphology becomes more subdued
Bar formation	Probably breaker origin	Unknown; mixture of flow-field mechanism (swash, breaking waves and infragravity waves) and self-organisation	Unknown; mixture of flow-field mechanism (breaking, shoaling and infragravity waves) and self-organisation

discussion in light of our current understanding of intertidal bar morphodynamics. We envisage a bar generation model whereby the convergence of sediment transport during stationary tide conditions – by whatever wave process: swash bar or breakpoint bar – results in the development of local accumulations of sediment. Positive feedback between these incipient bar features and the tidally modulated hydrodynamic processes (e.g. increase in tidal residence time and swash importance with increase in bar relief) during subsequent tidal cycles may result in the growth of

these features into mature intertidal bars. Critical factors in deciding whether a sediment accumulation will be allowed to grow during subsequent tides, or will be eliminated, include the size of the incipient bar, its location on the intertidal profile, the intertidal morphology and, most importantly, the subsequent wave/tide conditions. Once an intertidal bar is well developed, the long relaxation time and the potential sheltering provided by any bars to the seaward, will promote their preservation, even under extreme storm conditions.
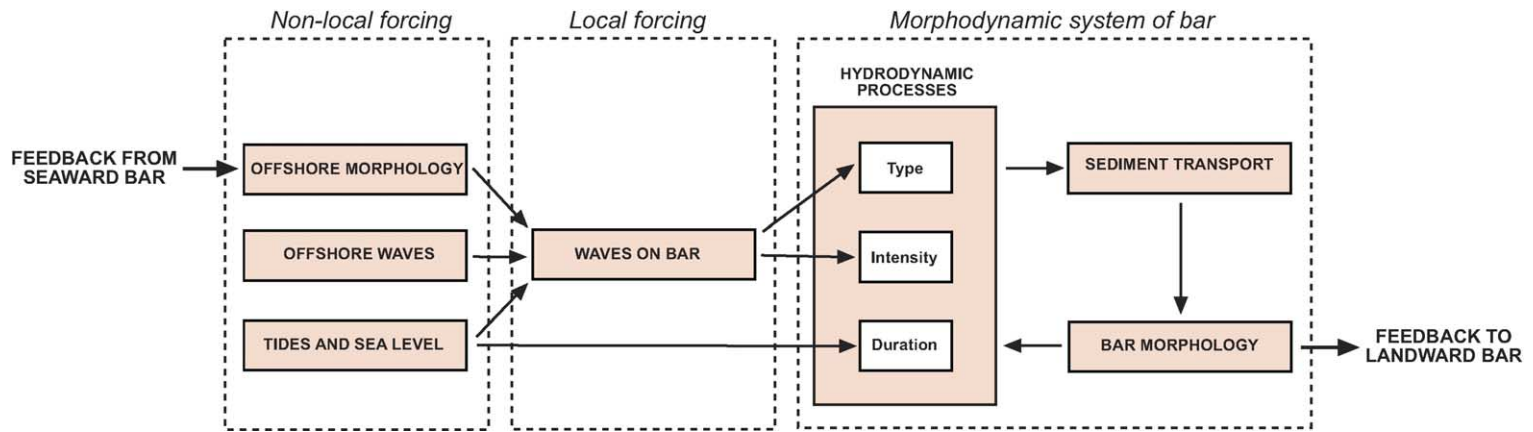
Fig. 9. Conceptual diagram summarising the intertidal bar morphodynamic system and its local and non-local forcing.

6. Conclusions

Intertidal bar systems are ubiquitous features on wave-dominated beaches in coastal settings with a significant (>1 m) tidal range and can assume a variety of forms: slip-face bars, low-amplitude ridges and sand waves. The morphological response of intertidal bars to changing wave conditions is largely forced: bars build up and migrate onshore under calm waves, and are flattened and may migrate offshore during storms. The morphological response is, however, significantly affected by relaxation time effects and morphological feedback, particularly on beaches with intertidal multiple bars. The response of intertidal bar morphology over longer time scales is determined by the type, intensity and duration of the wave processes operating on the cross-shore profile. The main difference between intertidal and subtidal bar morphodynamics is the importance of tidal water level variations, rather than wave height variability.

Acknowldgements

References

Aagaard, T., Masselink, G., 1999. Chapter 4: the surf zone. In: Short, A.D. (Ed.), Handbook of Beach and Shoreface Morphodynamics. Wiley, Chichester, pp. 72–118.

Aagaard, T., Nielsen, J., Greenwood, B., 1998a. Suspended sediment transport and nearshore bar formation on a shallow intermediate-state beach. Marine Geology 148, 203–225.

Aagaard, T., Nielsen, J., Davidson-Arnott, R., Greenwood, B., Nielsen, N., 1998b. Coastal morphodynamics at Skallingen, SW Denmark: high energy conditions. Geografisk Tidsskrift, Danish Journal of Geography 98, 20–30.

Aagaard, T., Davidson-Arnott, R.G.D., Greenwood, B., Nielsen, J., 2004. Sediment supply from shoreface to dunes: linking sediment transport measurements and long-term morphological evolution. Geomorphology 60, 205–224.

Aagaard, T., Kroon, A., Andersen, S., Møller Sørensen, R., Quartel, S., Vinther, N., 2005. Intertidal beach change during storm conditions; Egmond, the Netherlands. Marine Geology 218, 65–80.

Anthony, E.J., Levoy, F., Monfort, O., 2004. Morphodynamics of intertidal bars on a megatidal beach, Merlimont, northern France. Marine Geology 208, 73–100.

Anthony, E.J., Levoy, F., Monfort, O., DeGryse-Kulkarni, C., 2005. Short-term intertidal bar mobility on a ridge and runnel beach, Merlimont, northern France. Earth Surface Processes and Landforms 30, 81–93.

Battjes, J.A., 1974. Surf similarity. Proceedings 14th International Conference on Coastal Engineering. ASCE, pp. 466–480.

Boczar-Karakiewicz, B., Davidson-Arnott, R.G.D., 1987. Nearshore bar formation by non-linear wave processes — A comparison of model results and field data. Marine Geology 77, 287–304.

Borrelli, M., Wells, J.T., 2003. Swash bars and spit growth: Evolution of a rapidly prograding spit along a sediment starved coast. Proceedings Coastal Sediments '03. ASCE (paper on CD-ROM).

Bowen, A.J., 1980. Simple models of nearshore sedimentation, beach profiles and longshore bars. In: McCann, S.B. (Ed.), The Coastline of Canada, Geological Survey of Canada Paper, vol. 80-10, pp. 1–11.

Carter, R.W.G., 1988. Coastal Environments. Academic Press, London.

Chauhan, P.P.S., 2000. Bedform association on a ridge and runnel foreshore: implications for the hydrography of a macrotidal estuarine beach. Journal of Coastal Research 16, 1011–1021.

Cowell, P.J., Thom, B.G., 1994. Morphodynamics of coastal evolution. In: Carter, R.W.G., Woodroffe, C.D. (Eds.), Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, pp. 33–86.

Dabrio, C.J., Polo, M.D., 1981. Flow regime and bedforms in a ridge and runnel system, S.E. Spain. Sedimentary Geology 28, 97–110.

Dally, W.R., Dean, R.G., 1984. Suspended sediment transport and beach profile evolution. Journal Waterway, Port, Coastal and Ocean Engineering 110, 15–33.

Davidson-Arnott, R.G.D., 1981. Computer simulation of nearshore bar formation. Earth Surface Processes and Landforms 6, 23–34.

Davidson-Arnott, R.G.D., McDonald, R.A., 1989. Nearshore water motion and mean flows in a multiple parallel bar system. Marine Geology 86, 321–338.

Davidson-Arnott, R.G.D., Pember, G.F., 1980. Morphology and sedimentology of multiple parallel bar systems, Southern Georgian Bay, Ontario. In: McCann, S.B. (Ed.), The Coastline of Canada, Geological Survey of Canada Paper, vol. 80-10, pp. 417–428.

Davis, R.A., Fox, W.T., 1972. Coastal processes and nearshore sandbars. Journal of Sedimentary Petrology 42, 401–412.

Davis, R.A., Fox, W.T., Hayes, M.O., Boothroyd, J.C., 1972. Comparison of ridge and runnel systems in tidal and non-tidal environments. Journal of Sedimentary Petrology 2, 413–421.

Dawson, J.C., Davidson-Arnott, R.G.D., Ollerhead, J., 2002. Low-energy morphodynamics of a ridge and runnel system. Journal of Coastal Research SI 36, 198–215.

De Boer, D.H., 1992. Hierarchies and spatial scale in process geomorphology: a review. Geomorphology 4, 303–318.

Dolan, T., Dean, R., 1985. Multiple longshore sand bars in the Upper Chesapeake Bay. Estuarine, Coastal and Shelf Science 21, 727–743.

Elgar, S., Gallagher, E.L., Guza, R.T., 2001. Nearshore sandbar migration. Journal of Geophysical Research 106, 11623–11627.

Exon, N.F., 1975. An extensive offshore sand bar field in the western Baltic Sea. Marine Geology 18, 197–212.

Favas, F., Cooper, J.A.G., Malvarez, G.C., Jackson, D.W.T., 2000. Theoretical approach to the investigation of ridge and runnel topography of a macrotidal beach: Dundrum Bay, Northern Island. Journal of Coastal Research SI 34, 172–182.

Fisher, P.R., O'Hare, T.J., 1996. Modelling sand transport and profile evolution on macrotidal beaches. Proceedings 25th International Conference on Coastal Engineering. ASCE, pp. 2994–3005.

Fisher, P.R., O'Hare, T.J., Huntley, D.A., 1997. Morphological effect of spring-neap tidal variations on macrotidal beaches. Proceedings Coastal Dynamics '97. ASCE, pp. 476–485.

Foote, Y., Huntley, D.A., O'Hare, T.J., 1994. Sand transport on macrotidal beaches. Proceedings Euromech 310. World Scientific, Singapore, pp. 360–374.

Gallagher, E.L., Elgar, S., Guza, R.T., 1998. Observations of sand bar evolution on a natural beach. Journal of Geophysical Research 103, 3203–3215.

Garcez Faria, A.F., Thornton, E.B., Lippmann, T.C., Stanton, T.P., 2000. Undertow over a barred beach. Journal of Geophysical Research 105, 16999–17010.

Greenwood, B., Davidson-Arnott, R.G.D., 1979. Sedimentation and equilibrium in wave-formed bars: a review and case study. Canadian Journal of Earth Sciences 16, 312–332.

Hale, P.B., McCann, S.B., 1982. Rhythmic topography in a mesotidal, low-wave-energy environment. Journal of Sedimentary Petrology 52, 415–429.

Hardisty, J., 1986. A morphodynamic model for beach gradients. Earth Surface Processes and Landforms 11, 327–333.

Hardisty, J., Laver, A.J., 1989. Breaking waves on a macrotidal barred beach: a test of McGowan's criteria. Journal of Coastal Research 5, 79–82.

Hayes, M.O., Boothroyd, J.C., 1969. Storms as modifying agents in the coastal environment. In: Hayes, M.O. (Ed.), Coastal Environments: NE Massachusetts. Department of Geology, University of Massachusetts, Amherst, pp. 290–315.

Henderson, S.M., Allen, J.S., Newberger, P.A., 2004. Nearshore sandbar migration predicted by an eddy-diffusive boundary layer model. Journal of Geophysical Research 109, C06024.

Hoefel, F., Elgar, S., 2003. Wave-induced sediment transport and sand bar migration. Science 299, 1885–1887.

Houser, C., Greenwood, B., 2003. Response of a swash bar to a sequence of storms. Proceedings Coastal Sediments '03. ASCE (paper on CD-ROM).

Jackson, R.G., 1975. Hierarchical attributes and a unifying model of bed forms composed of cohesionless material and produced by shearing flow. Geological Society of America Bulletin 86, 1523–1533.

King, C.A.M., 1972. Beaches and Coasts, 2nd edition. Edward Arnold, London.

King, C.A.M., Barnes, F.A., 1964. Changes in the configuration of the inter-tidal beach zone of part of the Lincolnshire coast since 1951. Zeitschrift für Geomorphologie 8, 105–126.

King, C.A.M., Williams, W.W., 1949. The formation and movement of sand bars by wave action. Geographical Journal 113, 70–85.

Komar, P.D., 1998. Beach Processes and Sedimentation, 2nd edition. Prentice Hall, New Jersey.

Kroon, A., 1994. Sediment Transport and Morphodynamics of the Beach and Nearshore Zone near Egmond, The Netherlands. PhD thesis, Utrecht University.

Kroon, A., De Boer, A.G., 2001. Horizontal flow circulation on a mixed energy beach. Proceedings Coastal Dynamics '01. ASCE, pp. 548–557.

Kroon, A., Masselink, G., 2002. Morphodynamics of intertidal bar morphology on a macrotidal beach under low-energy wave conditions, North Lincolnshire, England. Marine Geology 190, 591–608.

Levoy, F., Anthony, E.F., Barusseau, J.-P., Howa, H., Tessier, B., 1998. Morphodynamics of a macrotidal ridge and runnel beach. C. R. Academie des Sciences 327, 811–818.

Masselink, G., 1993. Simulating the effects of tides on beach morphodynamics. Journal of Coastal Research SI 15, 180–197.

Masselink, G., 2004. Formation and evolution of multiple intertidal bars on macrotidal beaches: application of a morphodynamic model. Coastal Engineering 51, 713–730.

Masselink, G., Anthony, E.J., 2001. Location and height of intertidal bars on macrotidal ridge and runnel beaches. Earth Surface Processes and Landforms 26, 759–774.

Masselink, G., Russell, P., submitted for publication. Flow velocities, sediment transport and morphological change in the swash zone of a dissipative and reflective beach. Marine Geology.

Masselink, G., Short, A.D., 1993. The effect of the tide range on beach morphodynamics: a conceptual model. Journal of Coastal Research 9, 785–800.

Masselink, G., Turner, I.L., 1999. The effect of tides on beach morphodynamics. In: Short, A.D. (Ed.), Handbook of Beach and Shoreface Morphodynamics. Wiley, Chichester, pp. 204–229.

Mulrennan, M.E., 1992. Ridge and runnel beach morphodynamics: an example from the Central East Coast of Ireland. Journal of Coastal Research 8, 906–918.

Navas, F., Cooper, J.A.G., Malvarez, G.C., Jackson, D.W.T., 2001. Theoretical approach to the investigation of ridge and runnel topography of a macrotidal beach: Dundrum Bay, Northern Ireland. Journal of Coastal Research SI 34, 183–193.

Nilsson, H.D., 1973. Sand bars along low energy beaches: Part 1. Multiple parallel sand bars of southeastern Cape Cod Bay. In: Coates, D.R. (Ed.), Coastal Geomorphology. Allen & Unwin, London, pp. 99–102.

Orford, J.D., Wright, P., 1978. What's in a name? Descriptive or genetic implications of 'ridge and runnel' topography. Marine Geology 28, M1–M8.

Orme, A.R., Orme, A.J., 1988. Ridge and runnel enigma. Geographical Review 78, 169–184.

Osborne, P.D., Greenwood, B., 1992a. Frequency dependent cross-shore suspended sediment transport: 1. A non-barred shoreface. Marine Geology 106, 1–24.

Osborne, P.D., Greenwood, B., 1992b. Frequency dependent cross-shore suspended sediment transport: 2. A barred shoreface. Marine Geology 106, 25–51.

Owens, E.H., Frobel, D.H., 1977. Ridge and runnel systems in the Magdalen Islands, Quebec. Journal of Sedimentary Petrology 47, 191–198.

Parker, W.R., 1975. Sediment mobility and erosion on a multibarred foreshore (southwest Lancashire, UK). In: Hails, J., Carr, A. (Eds.), Nearshore Sediment Dynamics and Sedimentation. Wiley and Sons, London, pp. 151–179.

Plant, N.G., Holman, R.A., Freilich, M.H., Birkemeier, W.A., 1999. A simple model for interannual sandbar behavior. Journal of Geophysical Research 104, 15755–15776.

Plant, N.G., Freilich, M.H., Holman, R.A., 2001. Role of morphologic feedback in surf zone sandbar response. Journal of Geophysical Research 106, 973–989.

Puleo, J.A., Beach, R.A., Holman, R.A., Allen, J.S., 2000. Swash zone sediment suspension and transport and the importance of bore-generated turbulence. Journal of Geophysical Research 105, 17021–17044.

Reineck, H.-E., Singh, I.B., 1980. Depositional Sedimentary Environments. Springer-Verlag, Berlin.

Roelvink, J.A., Stive, M.J.F., 1989. Bar-generating cross-shore flow mechanisms on a beach. Journal of Geophysical Research 94, 4785–4800.

Ruessink, B.G., Kroon, A., 1994. The behaviour of a multiple bar system in the nearshore zone of Terschelling, the Netherlands: 1965–1993. Marine Geology 121, 187–197.

Russell, P.E., Huntley, D.A., 1999. A cross-shore transport 'shape function' for high energy beaches. Journal of Coastal Research 15, 198–205.

Short, A.D., 1991. Macro-meso tidal beach morphodynamics — an overview. Journal of Coastal Research 7, 417–436.

Short, A.D., Aagaard, T., 1993. Single and multi-bar beach model. Journal of Coastal Research SI 15, 141–157.

Simmonds, D.J., O'Hare, T.J., Huntley, D.A., 1996. The influence of long waves on macrotidal beach morphology. Proceedings 25th International Conference on Coastal Engineering. ASCE, pp. 3090–3103.

Sipka, V., Anthony, E.J., 1999. Morphology and hydrodynamics of a macrotidal ridge and runnel beach under low wave conditions. Journal Recherche Oceanographique 24, 24–31.

Stepanian, A., Levoy, F., 2003. Morphodynamical evolution sequences of intertidal bars on a macrotidal beach: case study of Omaha Beach (Normandy France). Oceanologica Acta 26, 167–177.

Stewart, C.J., Davidson-Arnott, R.G.D., 1988. Morphology, formation and migration of longshore sandwaves; Long Point, Lake Erie, Canada. Marine Geology 81, 63–77.

Sunamura, T., Takeda, I., 1984. Landward migration of inner bars. Marine Geology 60, 63–78.

Thornton, E.B., Humiston, R.T., Birkemeier, W., 1996. Bar/trough generation on a natural beach. Journal of Geophysical Research 101, 12097–12110.

Van den Berg, J.H., 1977. Morphodynamic development and preservation of physical sedimentary structures in two prograding recent ridge and runnel beaches along the Dutch coast. Geologie en Mijnbouw 56, 185–202.

Van Houwelingen, S.T., 2004. Spatial and Temporal Variability in Ridge and Runnel Morphology along the north Lincolnshire Coast, England. PhD thesis (unpublished), Loughborough University.

Van Houwelingen, S.T., Masselink, G., Bullard, J.E., in press. Characteristics and dynamics of multiple intertidal bars, North Lincolnshire, England. Earth Surface Processes and Landforms.

Voulgaris, G., Mason, T., Collins, M.B., 1996. An energetics approach for suspended sand transport on macrotidal ridge and runnel beaches. Proceedings 25th International Conference on Coastal Engineering. ASCE, pp. 3948–3961.

Voulgaris, G., Simmonds, D., Michel, D., Howa, H., Collins, M.B., Huntley, D.A., 1998. Measuring and modeling sediment transport on a macrotidal ridge and runnel beach: an intercomparison. Journal of Coastal Research 14, 315–330.

Wijnberg, K.M., Kroon, A., 2002. Barred beaches. Geomorphology 48, 103–120.

Wijnberg, K.M., Terwindt, J.H.J., 1995. Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. Marine Geology 126, 301–330.

Wright, P., 1976. The Morphology, Sedimentary Structures and Processes of the Foreshore at Ainsdale, Merseyside, England. PhD thesis (unpublished), University of Reading.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Marine Geology 56, 93–118.

Wright, L.D., Nielsen, P., Short, A.D., Green, M.O., 1982. Morphodynamics of a macrotidal beach. Marine Geology 50, 97–128.

Zenkovich, V.P., 1967. Processes of Coastal Development. Oliver and Boyd, Edinburgh.