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Bedform Association on a Ridge and Runnel Foreshore: Implications for the Hydrography of a Macrotidal Estuarine Beach

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ABSTRACT

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The association of bedforms occurring on a macrotidal 'ridge and runnel' foreshore (Silloth beach, NW England) is investigated. The ripple forms and their orientations point to distinctive stages of wave-current interaction as the topography is submerged and subaerially exposed in a tidal cycle. The estuarine tendency of the coast creates additional flows corresponding to the incursion and excursion of tides. The widespread presence of bedforms which are not related to the wave-generated flows points to an integral role of tidal currents in the hydro-sedimentary dynamics of strongly tidal beaches. Remarkable changes occur in the bedform configurations under extremely windy conditions, mainly expressed by the development of dunes in the zones which are normally rippled. Such changes, though occasional, bring sedimentologically significant alterations in the beach dynamics. The study shows that important inferences can be drawn from bedform association of barred foreshores about the intertidal hydrography and possible sediment movement trends.

ADDITIONAL INDEX WORDS: *Macrotidal beaches, ridges and runnels, sedimentary structures, foreshore processes, ripples/dunes, tidal currents, Solway Firth.*

INTRODUCTION

The usual response of a cohesionless sedimentary surface to a fluid drag is manifested by the generation of rhythmic undulations forming the various categories of ripples and dunes. The association of such bedforms in natural environments is quite capable of revealing the juxtaposed hydraulic inclinations as the structures normally get aligned to the spatial pattern of the flows. These bedforms generally are also a direct representation of the bedload transport and a good indicator of the hydrodynamic conditions. Intertidal barred foreshores, due to topography-induced complexity in the flow pattern, offer a site with an intricate assemblage of small and medium scale bedforms (VAN STRAATEN, 1953; EHLERS, 1988), often interpreted in terms of the depositional dynamics (REINECK, 1963; WUNDERLICH, 1972; PARKER, 1975; DABRIO and POLO, 1981; MOORE *et al.,* 1984). There is, however, a scarcity of bedform investigations in the typical sediment transport studies on such beaches, may be rather for the technological advancement which has led to a tendency of deploying improved instrumentation for this purpose (see for example VOULGARIS *et al.,* 1998, and the studies listed therein). The present paper aims at demonstrating the hydrographic complexity on a strongly tidal ridge and runnel foreshore as evaluated from the details of bedform association. And, though the sediment transport problem is not addressed directly, intention is to pass a message that bedform observations should be incorporated in such investigations for an improved understanding of the sedimentary system.

The study was carried out in the summer of 1993 on the Silloth beach which is located in the northwest of England on the southern shore of the Solway Firth (Figure 1). Solway Firth is a northeastwardly trending funnel-shaped estuary which experiences a dominant longshore wind from the southwest. NERC (1992) shows that the significant wave heights exceeded 1.0 m for 10% of the year in the vicinity of Silloth beach. The estuary is macrotidal, with a maximum tidal range of up to 10 m at Silloth. The beach section from Silloth to Dubmill Point exhibits a low-gradient ridge and runnel profile with a wide intertidal exposure at places spanning up to 2 km. A set of generally two to three subparallel ridges joined at one (southward) end to the coast, and the intervening runnels opening to the north, are subaerially exposed at low tide (Figure 2). The strong topographic and tidal control creates a marked spatial and temporal changeability of the depth and dynamics on the foreshore. The regular in/out flow of tidal water through the runnels along with the flood/ebb tide within the estuary creates a significant overlap on the general oscillatory flow dynamics. As a result, there is a complex pattern of wave-current processes on the foreshore, resulting in an assemblage of closely-related bedform fields. The ridge and runnel topography gives way to a broad sandflat in the seaward direction, the outer fringe of which,

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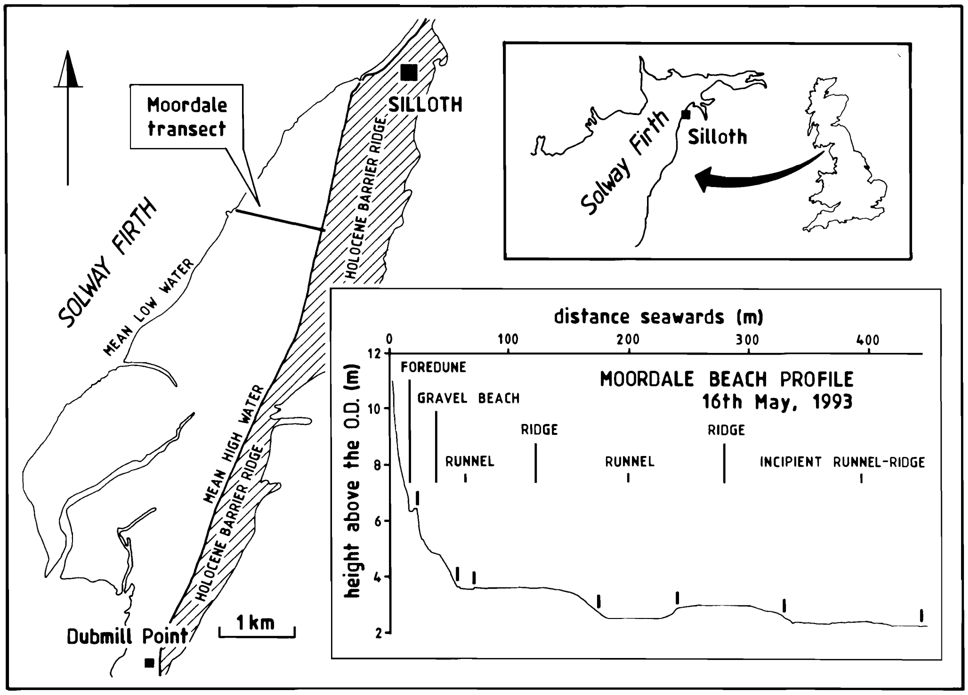

Figure 1. Study area.

near the low-tide levels, bears a zone of coast-transverse dunes which align with the dominant flow directions of the Solway Firth.

'RIDGE AND RUNNEL'

There is ample confusion regarding the use of the term 'ridge and runnel' as it has been variously employed for genetically dissimilar barred foreshores (see ORFORD and WRIGHT, 1978 for a review). Originally these were described as distinct intertidal features of low-gradient, fetch-limited strongly macrotidal foreshores, exemplified by the Blackpool and Normandy beaches (KING and WILLIAMS, 1949). The present paper follows the same context.

KING and WILLIAMS (1949) discussed the mechanism and condition for the formation of ridge and runnel features. Their study suggested that a ridge is formed by the swash action of waves on those coastlines having a limited fetch and a flat profile. The exact process involves generation of a steeper gradient on an otherwise flat surface, in equilibrium to the length of waves. A short fetch produces shorter waves, which in turn require a steeper equilibrium gradient, and hence build up a steeper swash slope in the form of a ridge on a rather flat foreshore. Subsequent to the development of a ridge there is an obstruction to the drainage on the beach, and a runnel develops on the landward side of the ridge to drain off water at the ebb. Areas with large tidal range provide an extensive intertidal foreshore where a sequence of ridges can develop successively from low tide to high tide level.

The ridge and runnel foreshore of Silloth beach seems to be a permanent feature. The contact between the gravelly beachface and the fronting runnel is always sharp, represented by the abrupt passage of plane bedded beachface into the small-scale wave-rippled runnel. The foreshore sand is moderately sorted and subangular, ranging in size from mainly fine (in the runnel) to medium and even coarse (on the ridge beachface). Quartz forms the dominant lithological component, but a variety of rock fragments, shell debris and coal particles are also present. The ridge beachface, especially of the first ridge, often has small pebbles along with shell fragments. Mud is generally evident in the runnels, especially in the second runnel and beyond on the sandflats, where it occurs as drapings over the ripple troughs and other larger bedforms.

Organic life on the sandy foreshore comprises different trail-making gastropods, and burrowing bivalves and annelids. *Arenicola marina* is widespread on the extensive sandflat and on the runnel floor, along with *Macoma balthica, Tellina tenuis* and *Cerastoderma edule.* In muddier parts, *Corophium volutator* is also seen. The landward edge of the beachface and the high-tide litter has an abundance of sandhoppers (*Talitrus saltator*) which appear as the tide retreats. Birds feeding on tellins leave their foot prints on the sand surface and a scatter of open shells. In general, the sub-surface bioturbation is strong in the runnels and on the sandflat. Over the ridge, bioturbation is sparse due to high swash energy, but, the burrower *Nereis diversicolor* shows its presence even on the beachface. *Arenicola marina* often encroaches the seaward slope of the seaward ridge along with *Macoma balthica, Tellina tenuis* and *Cerastoderma edule.*

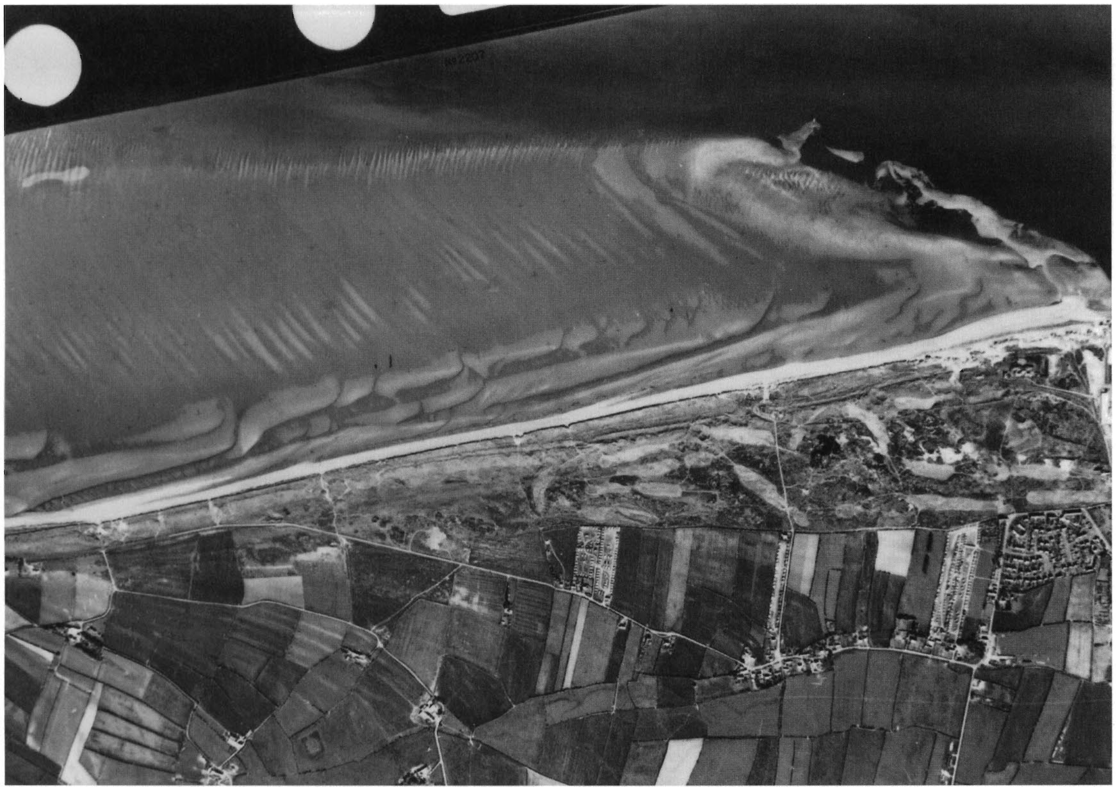

Figure 2. Aerial photo showing the ridge and runnel foreshore. The stretch of shoreline covered is about 3.6 km. Silloth township on the extreme right. (NMR OS/70199-092; Reproduced from Ordnance Survey aerial photographs with the permission of The Controller of Her Majesty's Stationery Office © Crown copyright.)

The gently sloping ridge and runnel foreshore provides a large intertidal exposure within each tidal cycle, resulting in onshore sand transport from the first (and at times even from the second) ridge under the influence of strong wind. An increase in wind strength, however, can also change the spectrum of physical structures present, which usually get aligned in the direction of wind by stretching and breaking. Often there is development of a field of subaqueous dunes around the second ridge and runnel under such high energy phases (Figure 3). This is the zone of small ripples under normal conditions. PARKER (1975) noticed dune development on the ridge crests when the angle between the breakers and the ridge was large. Their inference as forms related only to the wave action, in the present case, however can not be without doubt, because strong wind in conjunction with tidal flows can also generate appreciable currents in the form of water sheet flows. Strong offshore wind has a reverse effect with respect to the transport of wind blown sand, when large amount of sand can be transported back to the foreshore from the foredunes (Figure 4).

BEACH STRUCTURES

There is a distinct assemblage of small ripples within each morphologic unit of the ridge and runnel foreshore under normal wind conditions. Figure 5 synthesises this information from different transects to form an idealised sequence of surface structures occurring within successive ridges and runnels in a seaward direction. The beach profile of Moordale transect (Figure 1) has been chosen as the basis to identify different subdivisions because this section of the coast exhibits the foreshore morphology in its entirety. All observations were made with the ebbing tide and hence few if any of the structures due to the flood were seen.

The landward edge of the sequence is marked by a sharp contact of the sandy rippled runnel with the plane bedded gravelly beachface. This first runnel comprises four distinct subdivisions with coast-parallel wave-generated ripples forming the general background. From the landward to the seaward edge of the runnel, there is a change in the asymmetry of the ripples from landward asymmetric to symmetric and finally seaward asymmetric. These ripples vary in height (H) from 0.8 to 1.3 cm and a crest to crest length (C.C) of 6.0 to 9.0 cm. The trough to crest length (T.C) ranges up to 7.0 cm. (Note: The term crest and trough are used here for respectively the highest and lowest point of a ripple leeside; height is the vertical difference between the two.) In the second subdivision, some ebb-oriented (directed towards the open end of the runnel) linguoid ripples appear in scattered clusters, with their crests transverse to the shoreline. In the adjoining seaward unit, these ripples become more widespread and tend

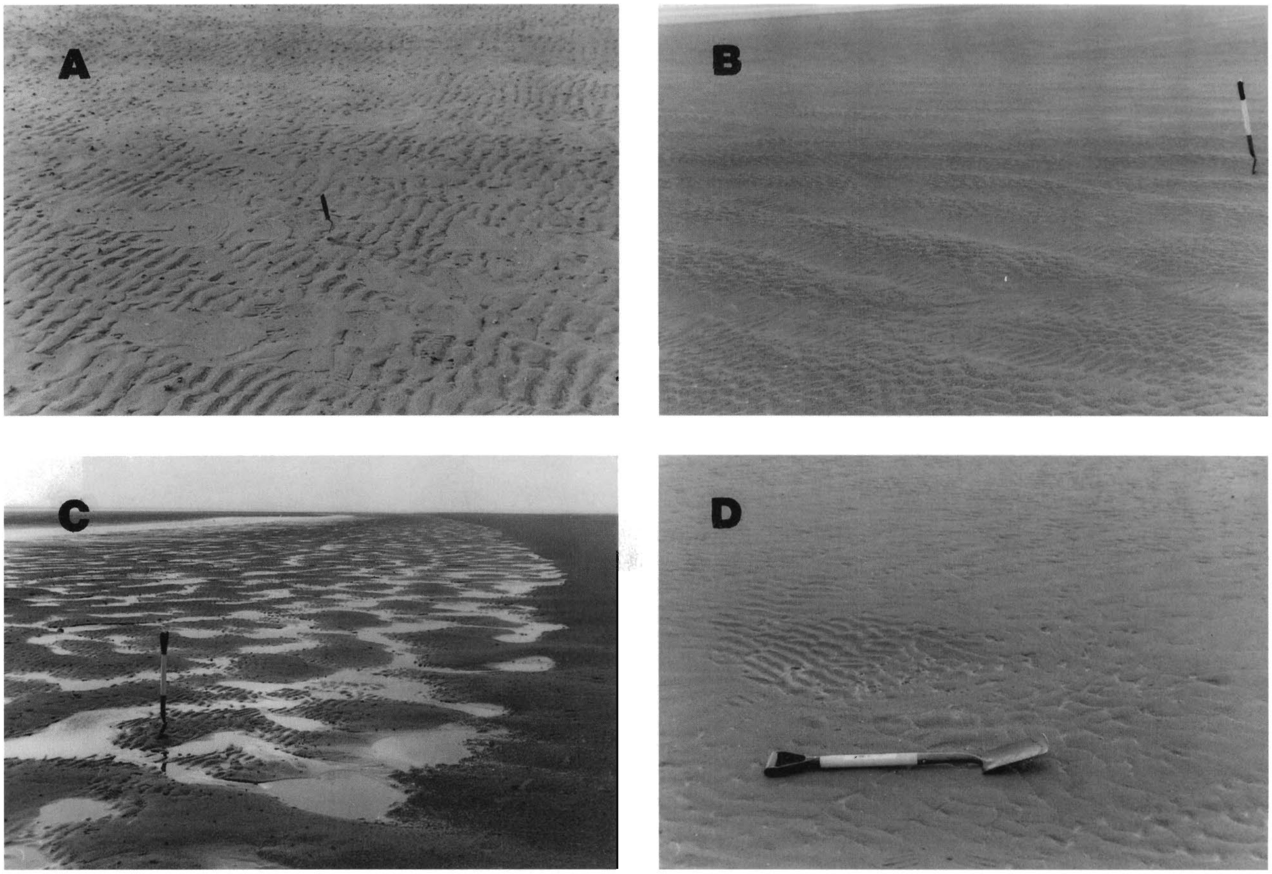

Figure 3. Foreshore features generated under strong wind on the second set of ridge and runnel. (A) Flow of sand in patches by the breaking of coast parallel wave ripples on the ridge. (B) Development of a dune field on the ridge. (C) Formation of dunes with negative relief within the runnel. (D) A dune of negative relief on the ridge. Sea on the left in all photos.

to develop a ladder pattern over the coast-parallel wave ripples (Figure 6A). The last subdivision, restricted to the seaward edge of the runnel, has sparsely scattered current-generated linguoid ripples directed towards the sea, representing the final ebbing of tidal water by overtopping the ridge. These ripples seem to be a product of the fast flowing shallow stretch of water in the zone of runnel breach over the ridge, which results in breaking of the linear crests and flow of sand in the form of linguoid ripples. In the runnel, mud is generally present as drapes in the ripple troughs.

As the ridge crest is approached, the coast-parallel linear wave ripples experience a flattening of crests (Figure 6B) and tend to acquire a symmetrical shape (measurements for a rather asymmetric ripple are: H = 3.0 cm; C.C = 7.5 cm; T.C = 5.0 cm). In the more seaward parts, crest flattening is enhanced and a plane bedded beachface is finally achieved at the seaward edge of the ridge. In the first subdivision, linguoid and rhomboid ripples are present within the zone of breaching, where flow is directed towards the second runnel. At the end, there are rill channels flowing into the runnel.

There is a sharp contact between the plane bedded beachface of the first ridge and the rippled surface of the second runnel (Figure 6C). The background here is of coast-parallel symmetrical ripples, with slight landward asymmetry in the initial subdivision (H = 0.8 cm; C.C = 7.5 cm; T.C = 5.0 cm). These wave ripples disappear as the landward slope of the second ridge and the water-filled main channel of the runnel fronting it is approached. There is, however, a transition from the landward to the seaward edge of the runnel, in the nature and alignment of the superimposed current ripples which represent the influence of tidal and longshore currents. At the beginning of the runnel, there is appearance of some asymmetric current ripples trending 190°, which is the flow direction of the early ebb in the runnel. Current ripples within the next subdivision are oriented in the same direction as before, but with an ebb capping in the opposite direction (Figure 6D) of the late ebb flow in the runnel (H = 1.5 cm; C.C = 19.0 cm; T.C = 15.0 cm; ebb cap 1 cm width). There is a laddering of coast-parallel wave ripples in this and the units further seaward. In the next subdivision, the current ripples acquire a symmetrical (coast transverse) form due to the gradual increase of the late ebb currents in the runnel towards its seaward edge. In the central subdivision, the ripple field is represented by late ebb and longshore current directioned (both same, *i.e.,* 3°) asymmetric current ripples, with a laddering of coast-parallel symmetrical wave ripples. In the

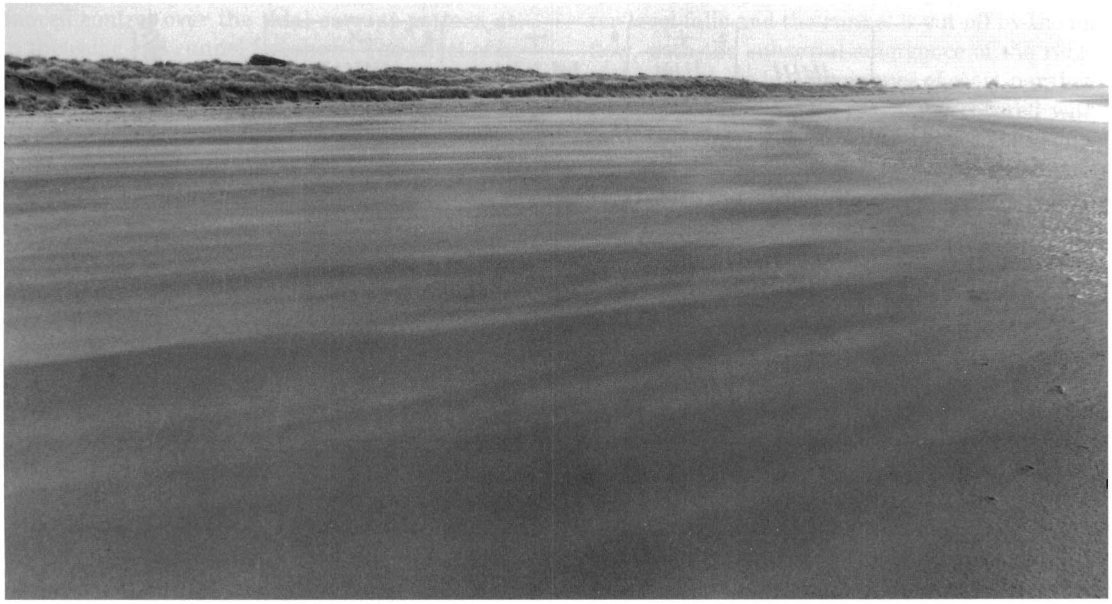

Figure 4. Sand blowing from the foredunes back to the foreshore. Sea on the right.

still more seawardly lying units only ebb and longshore oriented current ripples are present, which have a linguoid form (H = 0.8 cm; C.C = 15.0 cm; T.C = 12.0 cm) in the main water filled drain channel, grading to straight-crested and subsequent catenary shape (H = 2.0 cm; C.C = 17.0 cm; T.C = 8.5 cm) on the steep slope separating the runnel from the second ridge (Figure 6E). Further upslope the ripples experience some flattening and planing-off, and there are rills directed toward the runnel bottom (Figure 6F). In the second runnel, presence of subaqueous dunes is common, their crests trending across the length of the runnel (Figure 6G and 6H). One such occurrence is found near Dubmill Point where dunes are facing towards 200° (SSW). Their wavelength is 6 to 11 m, height about 15 to 20 cm, and the crest to trough separation about 1 m. Often structures of the runnel are partly superimposed on these low-relief features.

At the beginning of the second ridge, which has a gentle landward slope in this part, there are seaward-directed medium-sized linguoid ripples (H = 2.0 cm; C.C = 15.0 cm; T.C = 11.5 cm) (Figure 6I) which become more continuous crested at the ridge crest. The commencement of the seaward slope of the ridge is marked by landward asymmetric wave ripples (H = 1.0 cm; C.C = 7.5 cm; T.C = 5.5 cm). On the particular day when this section was measured, there has been an obliqueness (NE-SW) in the orientation of the ripple crests caused by the strong wind blowing towards the sea in 250° direction. In the next broad subdivision, within the field of landward asymmetric wave ripples which are mainly flat-topped in this zone, there is a presence of some incipient symmetrical medium size crests aligned transverse to the wind direction. These seem to originate in response to the influence of the nearshore ebb currents. The last subdivision shows a mixing of wave- and current-ripples. The landward asymmetric wave ripples are replaced here by seaward directed linguoid (H = 0.6 cm; C.C = 7.5 cm; T.C = 6.0 cm) and rhomboid ripples, possibly a response to the backwash and the ebb water sheet flows over the ridge. The ripples gradually show flattening and planing-off before merging into the incipient ridge-runnel zone (Figure 6J).

The incipient ridge and runnel shows a similar ripple sequence, but due to the rather flat nature of the ridge, the ebb (and flood) flows are not restricted to the runnel, adopting a wide range of directions. There is an overall presence of landward asymmetric small (H = 0.8 to 1.0 cm; C.C = 4.5 to 6.5 cm; T.C = 3.0 to 5.0 cm) wave ripples superimposing some weak crests. The latter seem to have developed from the interaction of the wind blowing towards 250° and the nearshore-influenced ebbing tide (Figure 6K). Gradually, in the seaward direction, these incipient crests (over the incipient ridge) acquire an asymmetry along the ebb flow of Solway Firth, to finally dominate and make the background ripple field by replacing the landward asymmetric wave ripples, through stages of forming laddered ripples and then total replacement. The strong wind affects the normal configuration of a ripple field by generating various forms of flattening, breaking and flow of ripple crests in the wind direction.

HYDROGRAPHIC CYCLE

The distribution and alignment of small-scale physical sedimentary structures present on the post-ebb ridge and runnel foreshore of the Silloth beach (Figure 5) has a direct implication in establishing the late-stage (of ebb tide) water and sediment transport pathways. The information on the pattern of the flooding tide from visual observations can be linked with this to obtain a more complete possible picture of the hydrography. The beach stretch is itself part of a bigger system—the Solway Firth, which forms its nearshore zone.

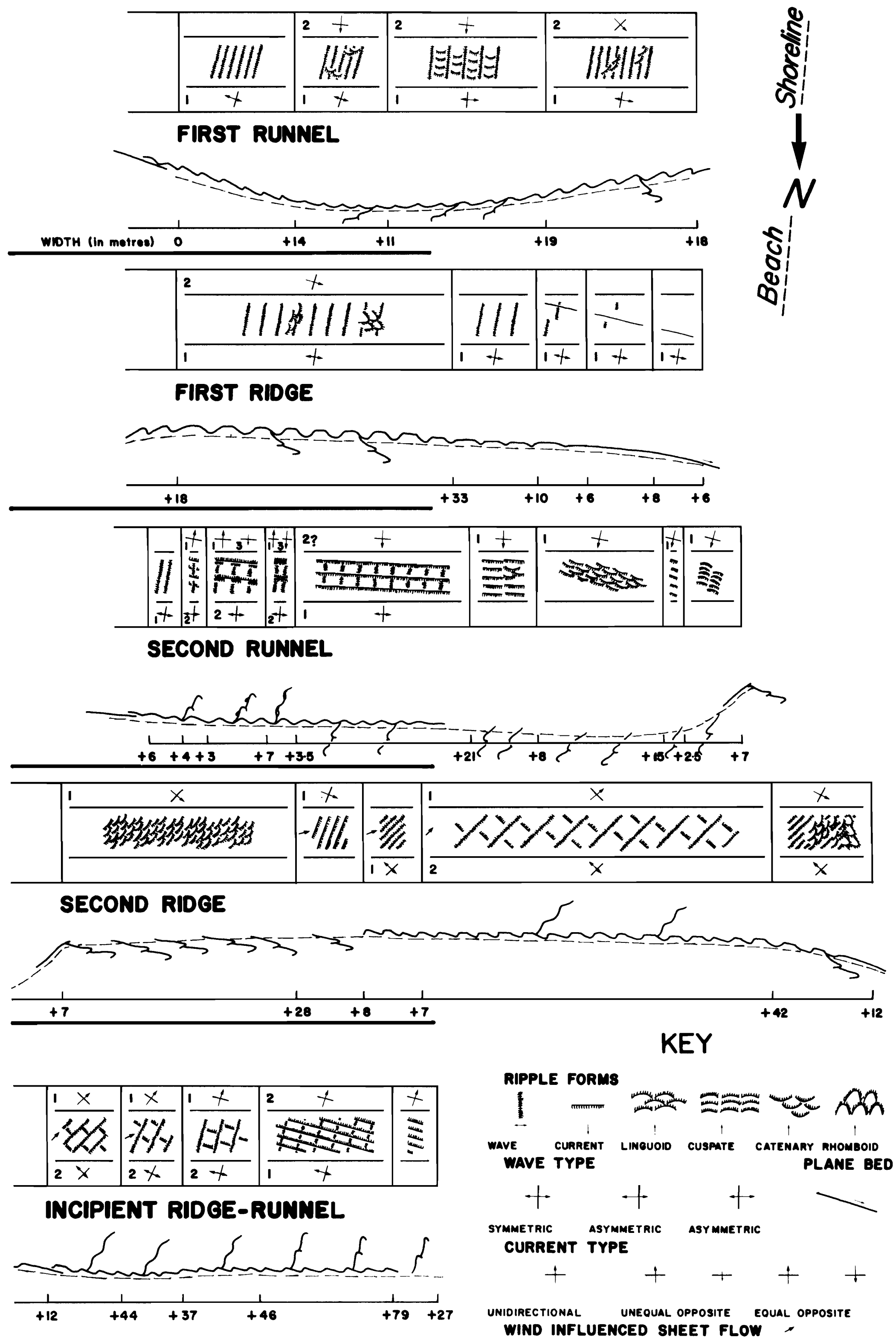

Figure 5. Distribution and alignment of small-scale physical sedimentary structures on the ridge and runnel foreshore. Numbers in the blocks showing bedform and wave/current type refer to the inferred superimposition of different flows.

The regular rise and fall of tide in the Solway Firth, hence, has a pronounced control over the tidal current pattern associated with the ridge and runnel foreshore. The effect of in- and out-flow of tide in the Solway is readily expressed in the nature of bedform assemblages on the sandy foreshore. In Figure 7 an attempt has been made to reconstruct the water and sediment movement paths associated with the ridge and runnel morphology in a tidal cycle. The following sequence of stages is recognised.

STAGE I. Rise in tide from its lowest. In the nearshore channel of Solway, incursion of flood tide is to the north towards the estuary head. On the ridge and runnel foreshore, the tide floods into the runnel from the open end and a tidal bore moves southwards towards the runnel head.

STAGE II. Swash action over the seaward slope of the ridge, with some transference of water and sediment into the runnel by wave swash spilling over the ridge crest. Tidal flows in the runnel and the sandflat in opposite directions, as in the previous stage.

STAGE III. Ridge submerged, and formation of a breaker zone over its crest. Just landward of the breaker, northerly longshore currents are generated in the runnel. Owing to the submergence of the runnel and the ridge, formation of a single stretch of water, but of variable depth. The headward flood tide flow in the runnel diminishes, while an overall flood dominated flow towards the estuary head is maintained. Swash action occurs on the next landward ridge; sand movement from the ridge crest into the runnel at the breaker zone.

STAGE IV. High tide slack, weak currents, breaker forming at the crest of the landward ridge.

STAGE V. Reversal of tide. Overall ebb flow southwards, swash action over the seaward slope of the landward ridge, breaker zone over the ridge crest, and generation of northwardly directed longshore currents in the runnel nearer to its seaward edge. At this stage, ebb flow over the runnel due to sufficient water depth and flow energy attained, can produce southward directed dunes.

STAGE VI. A further drop in water level re-exposes the ridge crest. This leads to the separation of water in the runnel from the main flow, and hence a reversal in the ebb flow, which now is directed northward *i.e.,* opposite to that in the nearshore zone. Swash action occurs over the seaward slope of the ridge. Ebbing water from the runnel, at this stage, can breach parts of the ridge in an attempt to drain out, or prior to this when the ridge was still under water, ebbing could occur transverse to the ridge as water sheet flow.

STAGE VII. Late stage of ebbing low tide. Flow in the estuary southwards; remaining water in the runnel drains by northward transport through the open end.

The sequence of structures observed on the ridge and runnel foreshore (Figure 5) can be explained from this conceptual model. The southward directed current ripples which form a laddered pattern with the coast-parallel wave ripples, at the landward edge of the second runnel, display the southward directed ebb flow in Stage V. The seaward part of the runnel, on the other hand, is dominated by structures indicative of the northerly longshore current and the late-ebb flow of Stage VI. In between these two extremes, there is a transformation from southward-directed to northward-directed ripples (Figure 6D); an expression of the ebb current reversal as the water-level falls and the runnel is cut-off by the main nearshore flow, with the subaerial emergence of the ridge. On the second ridge, there is a dominance of coast-parallel wave ripples, but the landward part is usually covered with seaward directed ripples, often of linguoid type. These appear to be generated when the ebb takes a direct course over the ridge crest just before the emergence (Stage VI), probably in the form of fast water sheet flow. Often these ripples are decorated with falling tide marks (Figure 6I).

The development of dunes in foreshore runnels/troughs is generally associated with the generation of strong longshore currents (see PARKER, 1975; DABRIO, 1982; MOORE, *et al.,* 1984); contrary to this, these features show an alignment opposite to the direction of the longshore currents in the present area. Here, in a tidal cycle, the runnel twice experiences a unidirectional current which conforms to this alignment. The flood flow of Stage II is directed southwards, which is same as the direction of movement of the dunes, if this was responsible for the observed orientation of the features, then one should expect imprints of the later stage flows to superimpose these structures. In the following stage (Stage III), with the submergence of the ridge, water in the runnel gets connected to the main nearshore flow, which results in a reversal of tidal flow within the runnel. At this stage, the overall flow in the runnel is northerly, added to the flooding tide is the longshore current too. Any dunes formed in the previous stage would be significantly overprinted with this unidirectional flow pattern, which in fact, is not evident. At Stage V, however, there is another occasion when flow in the runnel is southwardly directed. This time it is the ebb flow which can be accounted for the dune development. A successive lowering of tide would subaerially expose the morphology being observed.

According to the model, sediment retained on the upper foreshore is primarily that fraction which escapes the currents towards the open end of the runnels. A small component of this is represented by the landward asymmetric wave ripples in the interior (landward) parts of the runnels. The northerly flows generally lead to sediment being moved through the runnels back into the channel of Solway with the ebbing tide, hence hindering any significant sediment transport north of Silloth. The ebb, possibly can help in retaining some sediment in the form of asymmetric dunes in the runnel, if this asymmetry represents a resultant migration direction of the dunes too. The headward migration of these dunes in the runnel, and a later reworking and piling of the sediment contained over the landward ridge by waves, may then aid in sediment addition to the upper foreshore.

CONCLUDING DISCUSSION

The oscillatory flow dynamics of a ridge and runnel system, in general terms, can be analogued with that of a barred nearshore, where a number of investigations have reported sequence of structures and the processes to account them, though with a common objective to develop models of internal stratification for the identification and hydraulic interpretation of these environments in the rock record (for example

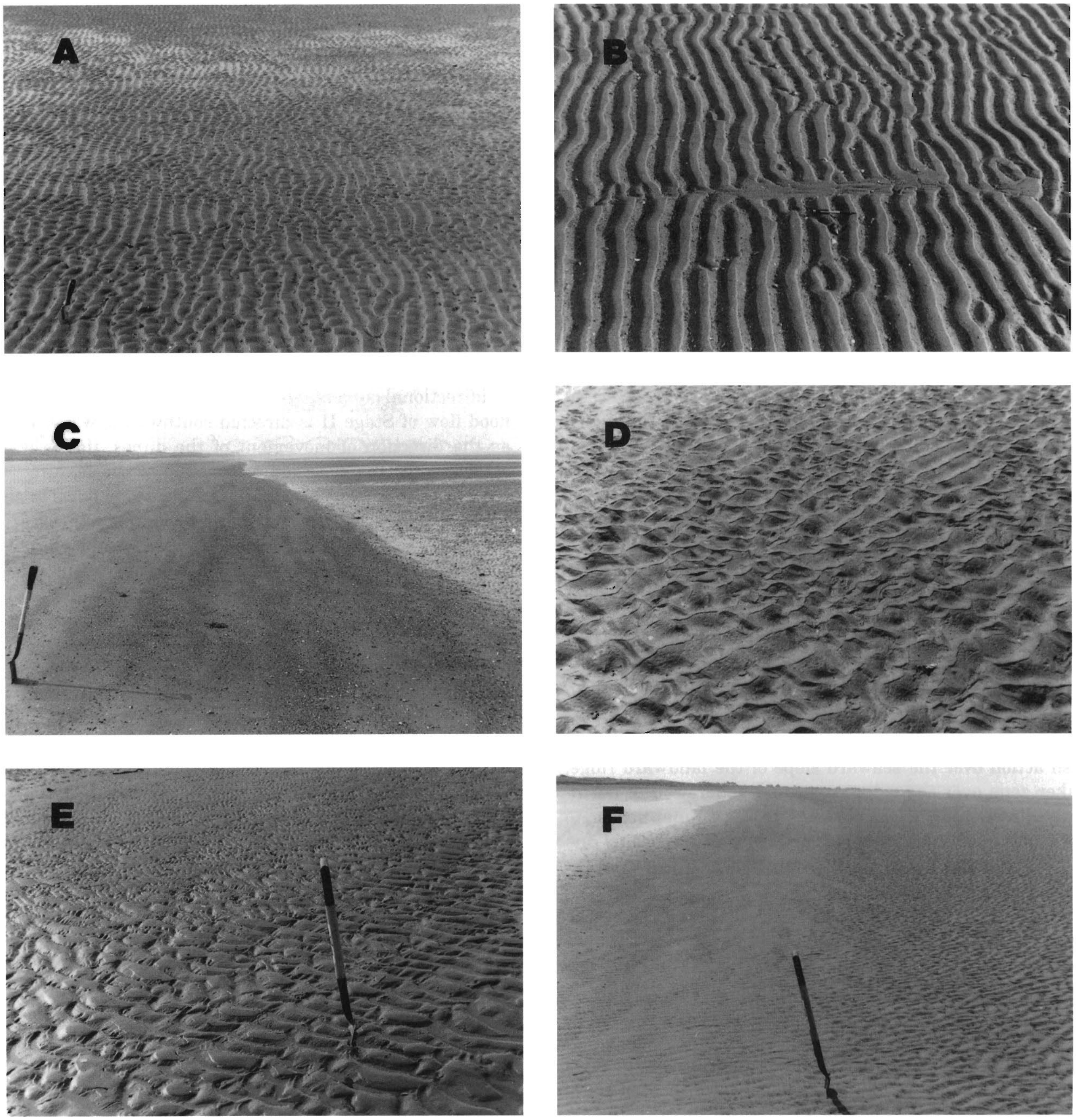

Figure 6. Sequence of bedforms on the ridge and runnel foreshore. Full description in the text. (A) Ladder-backed ripples in the first runnel. Sea on the left. (B) Flat-topped ripples at the crest of the first ridge. Sea on the right. (C) Sharp contact of the first ridge and the second runnel. Sea on the right. (D) Ebb capping on the ripple crests in the second runnel. Sea on the right. (E) Catenary ripples at the seaward edge of the second runnel. Sea on the left. (F) Planar landward edge of the second ridge. Sea on the right. (G) Dune bedforms in the second runnel. Looking towards the sea. (H) Closer view of the dune. Looking towards the land. Arrow indicates the flow direction in both photographs. (I) Linguoid ripples on the second ridge. Sea on the left. (J) Extensively rilled seaward edge of the second ridge. Sea on the right. (K) Incipient medium-scale ripples in the zone of incipient ridge and runnel. View facing the sea.

DAVIDSON-ARNOTT and GREENWOOD, 1976; HUNTER *et al.*, 1979; SHIPP, 1984; SHORT, 1986). The identification of flow regimes for the bedform zonation found on a barred nearshore, is generally based on a concept originally developed by CLIFTON *et al.* (1971) for a high-energy non-barred nearshore; who ascribed the offshore to shoreward occurrence of asymmetric small ripples, small lunate dunes and, plane bed, of respectively, offshore swell, nearshore wave build-up and,

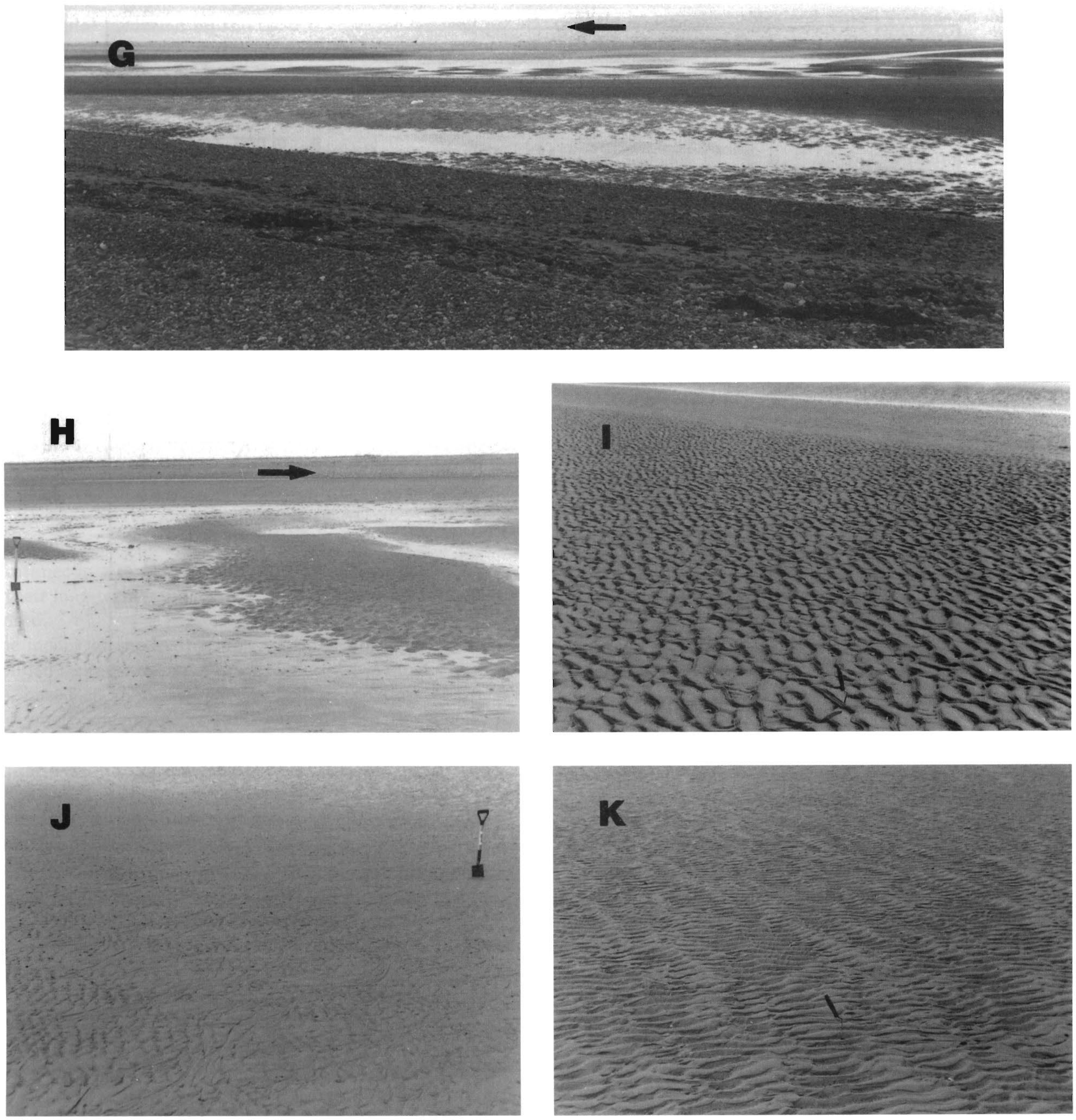

Figure 6. Continued.

outer surf zone to a gradual shoreward increase in flow regime from the lower part of the lower flow regime to the lower part of the upper flow regime. In the innermost part of the nearshore, a further presence of plane bed and, lying seaward to it a rough zone comprising coast-parallel large ripples/ridges-and-troughs, of respectively, swash and inner surf zone was related to a transformation from upper to the upper part of the lower flow regime. The barred nearshores show a similarity in the structural transitions on the seaward slope and the crest of the bar. However, additional zones of structures are created on the landward slope of the bar and along the longshore trough which extends into a rip channel, both respectively dominated by wave breaking and unidirectional currents (DAVIDSON-ARNOTT and GREENWOOD, 1976).

On macrotidal coasts, sweeping shoreline is the norm for beach morphodynamics whereby there is a regular variability in the zones of shoaling waves, breaker, surf and swash in a tidal cycle (WRIGHT *et al.,* 1982; JAGO and HARDISTY, 1984;

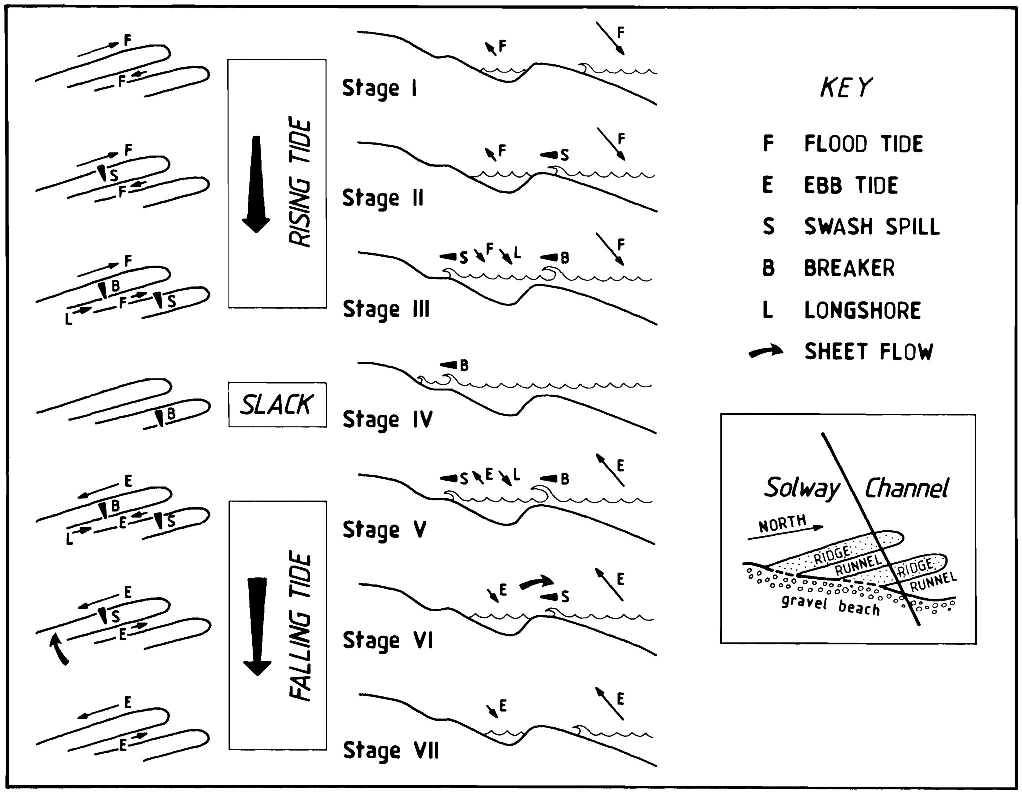

Figure 7. Model for the hydrography of the ridge and runnel foreshore of Silloth beach in a tidal cycle. Inset shows the orientation of ridge and runnel sets in relation to the channel of Solway. Full description in the text.

MASSELINK, 1993). The significance of tidal currents which characterise such foreshores and their role in sediment dispersal, has been recognised (WRIGHT *et al.,* 1982), but gained only little mention probably because considered unimportant in the beach morphodynamics itself or seemed more suitable to be grouped together with the longshore currents (which are commonly understood to be derived from wave processes). The observed and implied absence of tide-generated bedforms on the non-barred macrotidal foreshore investigated by HAWLEY (1982) led to a conclusion that the function of tidal range is to limit the width of structural zones which basically developed from wave action. Hawley's observations, however, were restricted to a tidally exposed foreshore and a situation can not be precluded when tide-generated bedforms did formed under tidal immersion. JAGO and HARDISTY (1984), on similar beaches, found surface structures of oscillatory flows mainly represented by plane bed/antidunes and small ripples, however, they reported an array of internal stratifications corresponding to the bedforms generated during high tides, some presumably of longshore/tidal current origin.

The impression of tidal currents is much evident on ridge and runnel foreshores where the undulatory topography of the beach restricts the flow pattern to certain zones, and many of the structures generated by these remain even after the foreshore exposure. The predominance of structural transitions resulting from tidal currents has overprinted any idealistic oscillatory-related bedform sequence at the present coast, of which, the coast-parallel ripples of varied asymmetry and the plane bed are the representatives. The general absence of wave-related dune forms is indicative of the prevalent lower-energy conditions. The interaction of wave- and tide-generated currents has created a complex pattern of flow on the Silloth beach, where the dominant lower flow regime bedforms show varied superimposition and transitions; the bedforms described, however, are just a snapshot in the continuum of changing configuration with the rise and fall of tide. The signatures of hydrographic complexity are particularly evident in the small ripples of the second runnel where, morphological transitions clearly illustrate the changeability in flow direction caused by tidal stage variations. The linguoid ripples on the second ridge overprint any wave structures by recording the water sheet flows of the ebbing tide. The presence of small dunes in the second runnel, however, is of much significance as it indicates the bedload response to tidal current in a direction opposite to the prevalent longshore current direction.

It is clear that a continued interplay of wave- and tide-generated currents characterises a ridge and runnel foreshore, which is more pronounced on the seaward set/s of these features. The tidal flows follow varied orientations depending on the topographic expression of the foreshore, direction of tidal incursion on the coastal segment, as well as the tidal stage itself. The effect of such flows is easily discerned by the presence of bedforms which are not syndirectional to the currents generated by oscillatory motion. It should become increasingly difficult to extract the influence of tidal currents when they rather complement the wave-generated flows. As for instance, with the asymmetry of coast-parallel ripples; which can be acquired solely by oscillatory-related processes (see ALLEN, 1979), but a contribution of tides can not be always denied too (HARMS, 1969; ARNOTT and SOUTHARD, 1990). In a recent study, VOULGARIS *et al.* (1998) measure a cross-shore near-bed tidal flow on a macrotidal beach which is driven by the changes in the sea surface elevation. It may be surmised then, that tidal currents must also form an important component on non-barred beaches in strongly tidal areas, though the bedform association after an ebbed tide may just hide the imprints. It was also observed during this investigation that the normal bedform configurations can be drastically changed by any marked variability of wind strength and direction. Rough weather changes in bedform types were also reported by HAWLEY (1982) and more recently by THORNTON *et al.* (1998). Such events cause instantaneous alteration in the routine sediment dynamics, and their long-term impact on beach stability must be further explored.

The model for the hydrography of Silloth beach provides a simplified representation of the foreshore flows during a tidal cycle, based on the occurrence of bedforms, many of which are strongly suggestive of tidal currents. On the whole, it becomes right to emphasise that in any study of hydro-sedimentary dynamics of macrotidal beaches, particularly those of ridge and runnel type, consideration should be taken of the complex interaction of flows. It goes without saying that the association of bedforms can be of significant assistance in this matter.

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