

FLOW REGIME AND BEDFORMS IN A RIDGE AND RUNNEL SYSTEM, S.E. SPAIN

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ABSTRACT

During landward migration, ridge and runnel systems are subjected to asymmetric oscillatory and/or unidirectional flow regimes, depending on the stage of development reached by these systems. In the early stages of evolution, when the ridge is situated in the upper shoreface, the whole system is subjected to asymmetric oscillatory flow. The runnel is under lower flow regime conditions and the ridge may be under upper or lower flow regime according to water depth and wave energy. Later, when the ridge has migrated to a position on the foreshore, the runnel is largely under a unidirectional lower flow regime while the ridge itself is under oscillatory upper flow regime. When the ridge welds to berm, it is largely emergent and exposed to high-tide swash action under upper flow regime conditions. The runnel is eventually filled with sand and transformed into a low-lying area. All these types grade laterally into each other. One or more ridge and runnel systems can occur at the same time. Wave energy, tide level and position of the ridge control the variations in the characteristics of the ridge and also the position of the zones of bedforms found at the upper shoreface.

INTRODUCTION

A ridge and runnel system is a combination of a swash bar and a trough. The ridge is a tabular body of sand which develops on the low-tide terrace during periods when the beach is in a constructional phase (Hayes and Boothroyd, 1969). The ridge has a steep landward-oriented slip face and, on its landward side, is fronted by a trough. Hayes and Boothroyd (1969), Hayes (1972), Owens and Frobel (1977) and Hine (1979) have studied in detail the morphological changes associated with the origin and development of these systems. They found out that the ridges are built after storms and they migrate toward the land until they weld onto the backshore to form a berm.

Ridge and runnel systems have been found in many places covering a wide

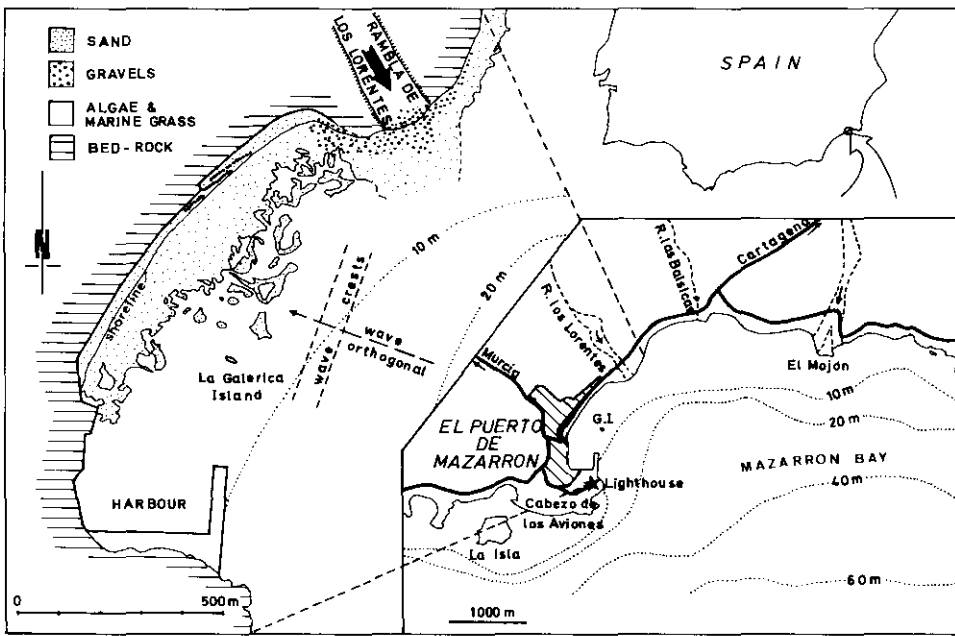


Fig. 1. Location map of the study area. Ramblas are valleys of ephemeral streams which feed sediment to the beach.

spectrum of tidal ranges, for instance, Lake Michigan which has a tidal range of 8 cm (Davis and Fox, 1972) and the coast of Massachusetts which has a tidal range of 1.3–3.3 m. The main differences between tidal and non-tidal coasts are the scale and the rate of migration of the ridges: the ridges of tidal coasts are higher and slower migrating than the ones of non-tidal coasts (Davis et al., 1972).

The present authors have studied an area of the southeastern coast of Spain that is a low-energy, non-barred shoreline with a very small tidal range. This coast differs in many aspects from the coast studied by Clifton et al. (1971), which is a high-energy shore, and the coast studied by Davidson-Arnott and Greenwood (1977), which is a barred shoreline. In this paper, the concept of flow regime, both in unidirectional and asymmetrical oscillatory flow, is used to explain the bedforms occurring at the various parts of the coast with ridge and runnel systems.

STUDY AREA

The study was carried out at Puerto de Mazarrón Beach (Fig. 1). The average slope off the beach is $2^{\circ} 30'$ down to a depth of 20 m. The shoreline is non-barred and the bottom is covered by algae and marine grass below an average depth of 1.5–2 m. Landward of the vegetated bottom is a sandy

region dominated by bedforms striking parallel to the shore.

Along this section of coastline the sediment is medium sand (mean grain size: 0.360 mm). At some places there are also pebbles up to 30 mm in diameter which typically accumulate to form active gravelly bars on the foreshore. Most of the sediment is provided by ephemeral rivers (ramblas) debouching into the Mazarrón Bay.

The studied coastline experiences low wave energy. During observation periods (four weeks in August 1977, one week in March 1978 and six weeks in August–September 1978), which were essentially restricted to fair weather, wave heights were typically 10–20 cm, wave periods 3–3.5 sec and wave velocity 2–2.5 cm/sec. The waves approached the coast in a direction slightly oblique to the shoreline (Fig. 1). This fact is responsible for a longshore transport of sediment to the southwest which causes silting up of the fishing harbour placed to the south.

The mean tidal range is 10 cm but meteorological tides can reach up to 18–20 cm.

METHODS

Observation of water movements, sediment transport and bedforms were made onshore and underwater (using snorkels). Water depth and wave heights were obtained with a stadia rod. The wave periods were measured during five-minute intervals. Wave velocities were calculated from the time required for waves to pass between two fixed rods 15 m apart in the nearshore perpendicular to the wave approach. The tidal range was determined from direct measurement in the harbour during a six-week interval (August–September 1978). Longshore current velocities were calculated from dye techniques.

BEDFORMS ON RIDGE AND RUNNEL SYSTEM

During the landward migration of the ridge and runnel system, the position of the ridge to some extent controls the flow regime which in turn controls the type of bedform. Three types of beach morphology can be distinguished at the study area on the basis of: (1) lateral position of the ridge relative to the shoreline; (2) flow regime and energy level; and (3) bedform sequences, their associations and their evolution at the various zones of the ridge and runnel system. They represent three successive stages of evolution but many transitions occur between them due to varying rates of ridge and runnel migration.

Type 1 ridge and runnel

The ridge and runnel system develops on the upper shoreface or lower foreshore during the early stages of accretion. The morphology and distribu-

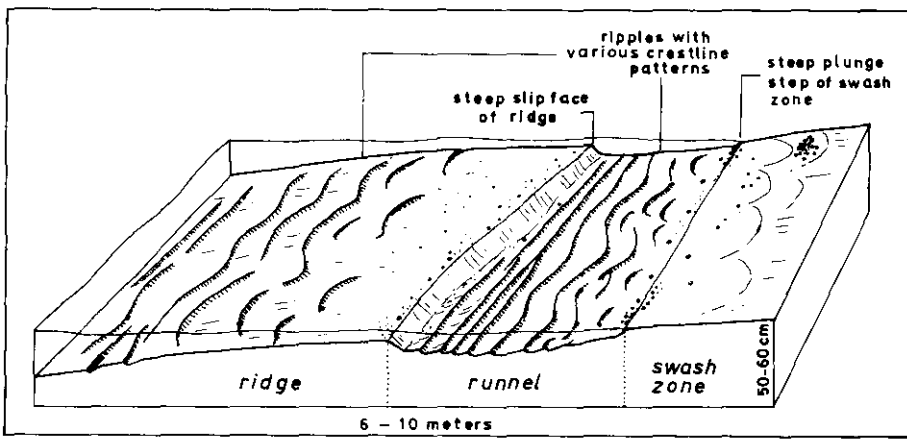


Fig. 2. Bedform distribution in a typical ridge and runnel system which is influenced by asymmetrical oscillatory flow. Asymmetrical ripples with various crestline patterns occur both on top of the ridge and in the runnel.

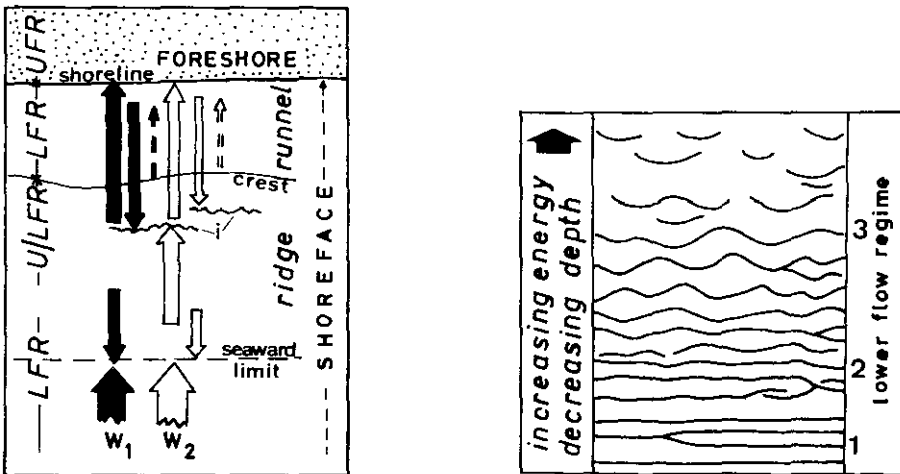


Fig. 3. Water motion over a typical Type 1 ridge and runnel system. W_1 and W_2 are consecutive waves. Wave energy is indicated by arrow width. Note that the waves lose much or their energy when passing over the ridge. UFR = upper flow regime; LFR = lower flow regime; i = interferences between incoming and reflected waves.

Fig. 4. Type 1 runnel bedform sequence under oscillatory flow (plan view; ripple facing to the top of the picture). 1 = Straight-crested asymmetrical wave ripples; 2 = asymmetrical wave ripples with undulatory crests; 3 = asymmetrical wave ripples with strongly undulatory or discontinuous crests. Land is placed toward the top of the picture (decreasing depth).

tion of bedforms in type 1 ridge and runnel systems (Fig. 2) depend on the existence of a landward asymmetric oscillatory flow created by the passage of waves.

Water motion in the system (Fig. 3) is induced by consecutive waves as they move across the ridge and runnel and are reflected at the shoreline. This water motion produces not only avalanching all along the slip face of the ridge, and landward asymmetrical wave ripples in the runnel (Figs. 4, 5 and 6), but also seaward asymmetrical wave ripples after reflection. Interferences of reflected and incoming waves cause a reduction of wave velocities, resulting in the deposition of the coarser material on top of the ridge. In the runnel, there is a slow longshore movement which is thought to produce small linear to sinuous crested ripples transverse to the shoreline (indicated by arrow in Fig. 6).

Under these conditions the ridge and runnel system shows several bedforms depending on the flow regime (Figs. 2, 5 and 6). With decreasing water depth (increasing flow regime), the following sequence of bedforms occurs in the runnel: (1) straight-crested asymmetrical wave ripples, (2) asymmetrical wave ripples with undulatory crests, and (3) asymmetrical wave ripples with strongly undulatory or discontinuous crests (Figs. 4 and 6). Ripple facing is directed landward.

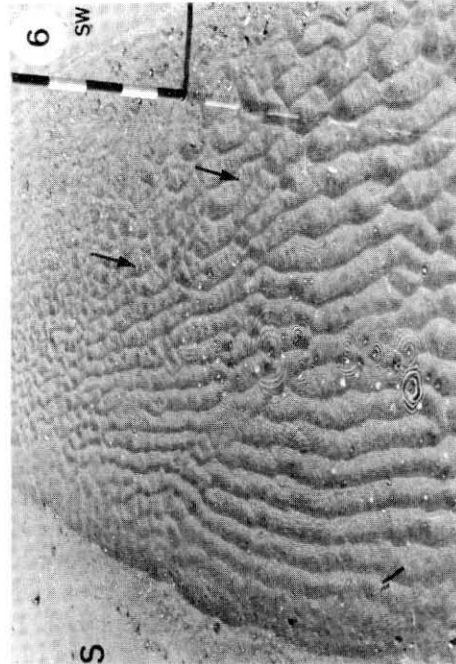
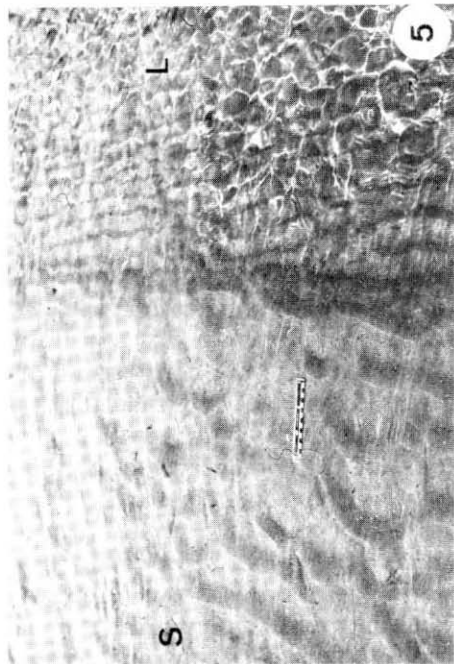
As the ridge migrates landward, the water depth over the ridge decreases, increasing the wave orbital velocities at the bottom which results in a shift from lower to upper flow regime. These conditions cause the ripples to flatten and eventually to form plane beds (compare the tops of the ridges in Figs. 5 and 6).

Changes in flow regime are also induced by the rising of the sea level which is caused by tides (astronomic or meteorologic), specially if coincident wind action pushes water onshore. Increases in water depth reduce wave action on the bottom because of decrease in the orbital velocity. This causes the bedforms to adapt to lower flow regime conditions.

Type 2 ridge and runnel

As the ridge and runnel system migrates landward, it reaches a higher elevation with respect to the sea level. This causes higher wave energy and flow regime conditions and results in different morphology and distribution of bedforms (Fig. 9). At this stage the ridges are dissected by runnel outlet channels which drain the ponded waters behind the ridge systems.

The flow pattern is rather complex because of the co-existence of oscillatory and unidirectional flow: the former acts over the entire ridge and runnel system (see type 1) while the latter dominates only the runnels. The transformation from oscillatory to unidirectional flow takes place when the reflected waves are unable to pass over the ridge and the water is forced to flow through the runnel (Fig. 10A). The incoming waves entering the runnel outlet channels, and also the ones deflected in adjacent ridges, cause inter-



ferences or, even, reversal of the drainage flow in some parts of the runnel (Fig. 10B).

In response to this flow pattern, two sequences of bedforms occur: the previously discussed sequence due to asymmetrical oscillatory flow, with ripple crests parallel to the coast and another due to unidirectional flow, with ripple crests in various directions (Fig. 9). The bedform sequence for increasing unidirectional flow velocity shows five steps (Fig. 11), as described by Allen (1968). Ripple height increases with increasing flow velocity, but megaripples do not occur in the study area because of the very shallow water depth.

Where runnels turn to meet an outlet channel, a triangular zone can occur in which a sequence of seaward-asymmetric oscillatory ripples is formed. This sequence shows increasing energy toward the sea and it is due to the dragging effect of the two lateral drainage currents in the runnels, and the action of backwash.

In the neck of the runnel outlet channel the current velocity is strong enough to plane off the bottom, resulting in the accumulation of a pebble lag deposit.

Double-crested asymmetrical wave ripples (Fig. 7) were locally observed to form in runnels dominated by asymmetric oscillatory flow. They are created under the action of small waves reaching the runnel. These waves induce small vortices at the landward lee side of the asymmetrical wave ripples. The vortices have an action radius of about $1/3$ to $1/2$ of the length of the lee side of the ripple and they erode a narrow trough in the lee side, which is parallel to the crest line of the ripple. Deposition takes place on a secondary crest beyond the small trough and double-crested ripples are formed, partly as superimposed bedforms on top of asymmetrical wave ripples. However, under stronger waves, vortices covering the whole landward lee side appear, leading to full-size avalanching which prevents the formation of secondary troughs and crests.

Figs. 5—8: Photographs of bedforms on typical ridge and runnel systems under various wave conditions.

Fig. 5. A Type 1 ridge covered by undulatory or discontinuous asymmetrical wave ripples (left) and a runnel with smaller straight-crested asymmetrical wave ripples (right).

Fig. 6. A more mature stage of development of the system (almost transition from type 1 to Type 2). The ridge, under upper flow regime, shows flat beds and sharp slip face. The runnel (center) shows the whole sequence of asymmetric bedforms with increasing energy towards the shore (right). Note the small transverse ripples (arrow) indicating a weak longshore component of the flow.

Fig. 7. Double-crested asymmetrical wave ripples (Types 1 and 2). Flow asymmetry towards the left.

Fig. 8. Berm (welded ridge) with sharp edge associated with a seaward-sloping face indicated by arrow (Type 3). Residual runnel and drainage channels are still visible. Observer looking North. In the four photographs, *S* = seaward, *L* = landward, *SW* = swash zone. Ruler in centimeters (Figs. 5 and 8) and decimeters (Fig. 6).

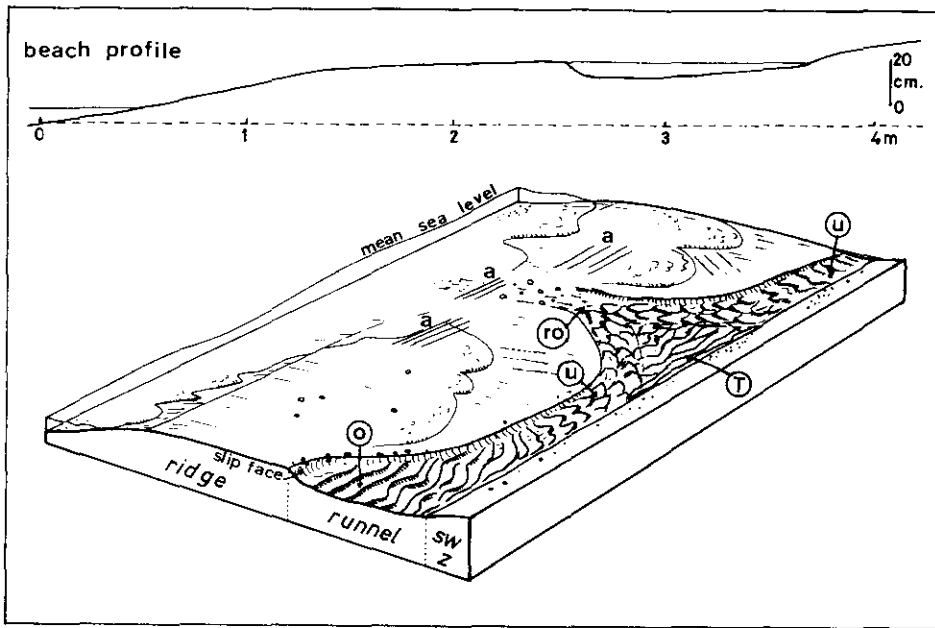


Fig. 9. Type 2 ridge and runnel configuration. Transition from oscillatory (*o*) to unidirectional (*u*) flow occurs in the runnel and is demonstrated by the type of bedforms and crest orientations. Landward of the runnel outlet channel (*r.o.*) there is a triangular-shaped area (*T*) in which seaward-oriented asymmetrical wave ripples occur. At high tide, small asymmetrical wave ripples (*a*) can be found on top of the ridges.

Type 3: welded ridges (berms)

As the landward-migrating ridge finally welds onto the backshore to form a berm, the runnel is obliterated (Figs. 8 and 12). After this stage is completed, water will cover the welded ridge only during extreme high tides.

Swash action erodes the seaward face of the berm, producing a small cliff (Fig. 8). Drainage channels connecting the residual low-lying areas beyond the berms with the sea, cut sharp vertical edges. In the drainage channels, current velocities are low and only rill marks develop at the bottom but, sometimes, at the neck of the drainage channel the outflow currents can be strong enough to form small antidunes.

BEDFORMS AT THE UPPER SHOREFACE

The bedforms encountered at the upper shoreface (Fig. 12) depend on the energy transmitted by the waves to the bottom. As the waves approach the shore, the bottom orbital velocity [u_m : defined by Clifton, (1976) as the maximum velocity reached by the particles at the sea bottom during the passage of wave crest] and the velocity asymmetry [Δu_m : difference in maxi-

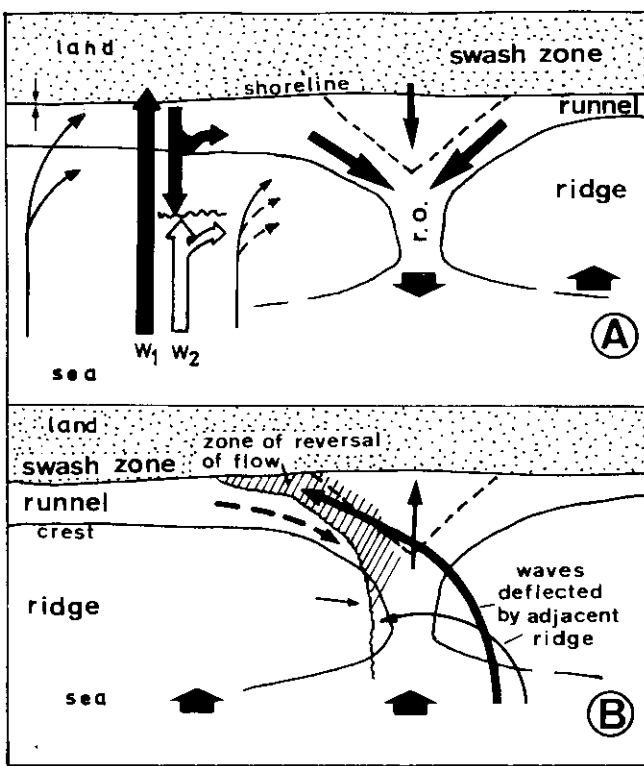


Fig. 10. Flow pattern in the areas neighbouring runnel outlet channels and feeder channels in Type 2. A: transformation from oscillatory to unidirectional flow in runnel. W_1 and W_2 are successive waves which may interfere with each other (interferences marked by a wavy line between black and white arrows). B: interference and flow reversal caused by waves moving up the runnel outlet channel (r.o.) or being deflected by the adjacent ridges.

imum velocity, defined as the sum of maximum velocity under the wave crest in the direction of wave propagation, taken as a positive vector, plus the maximum velocity under the trough of the wave, which for reversing flow is a negative vector, according to Clifton (1976)] increase. The sequence of bedforms due to the landward asymmetric oscillatory flow comprises more terms than the one occurring in runnels (compare Figs. 4 and 13): (1) no sediment movement, (2) straight-crested asymmetrical wave ripples, (3) undulatory asymmetrical wave ripples, (4) strongly undulatory to discontinuous (irregular) asymmetrical wave ripples and (5) flat (plane) bed (Fig. 13).

The boundaries between the different types of bedforms are gradational, and threshold velocities of bottom orbital velocity (u_m) in the nearshore of Puerto de Mazarrón Beach have been calculated from $u_m = \pi H/T \sin kh$, where H : wave height, T : wave period, h : water depth, $k = 2\pi/L$ and L : wave

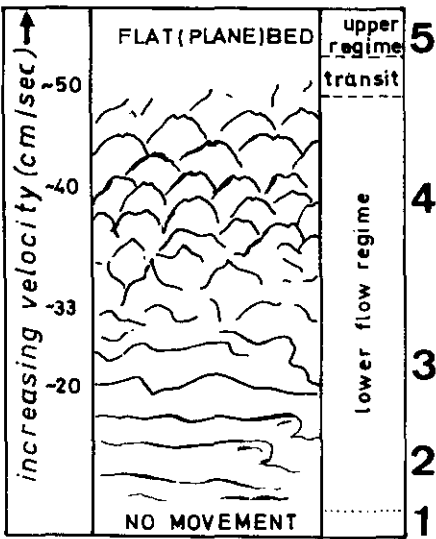


Fig. 11. Sequence of bedforms (plan view of crest pattern) in unidirectional flow in runnels (Type 2). 1 = No sediment movement (plane bed); 2 = straight-crested current ripples (ripple height increasing with current velocity); 3 = undulatory current ripples; 4 = linguoid ripples (ripple height and size increasing with current velocity and, later, decreasing again); 5 = flat bed. The flow regime increases as the drainage current flows toward the runnel outlet channel.

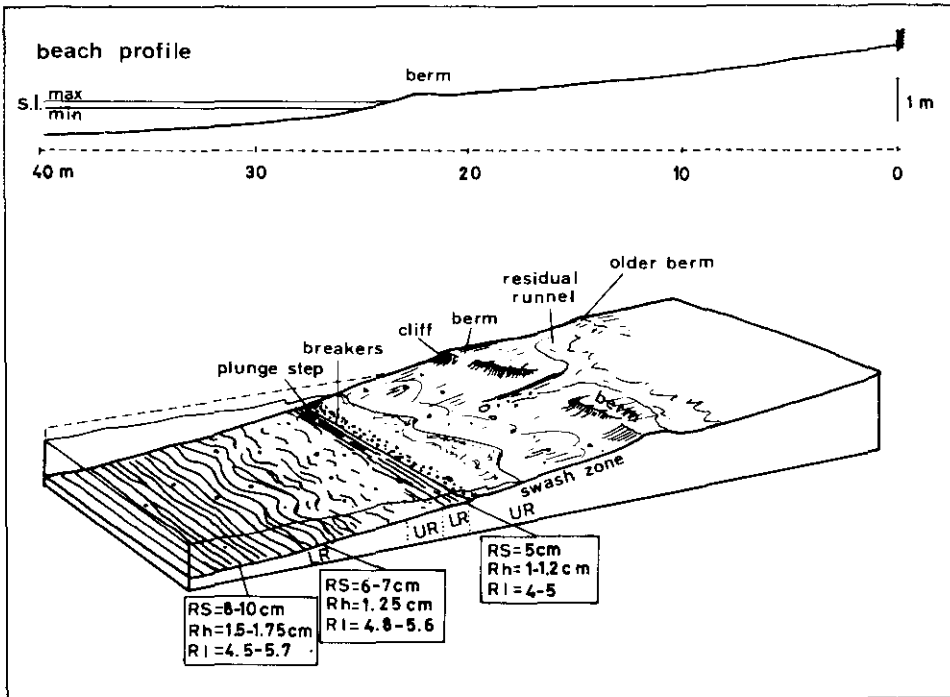


Fig.12. Beach morphology at the late accretion stage (Type 3). The ridge welds onto berm and the runnel is eventually filled with sand. Remains of a former berm are still visible. UR = upper flow regime conditions; LR = lower flow regime; RS = ripple spacing; Rh = ripple height; RI = ripple index.

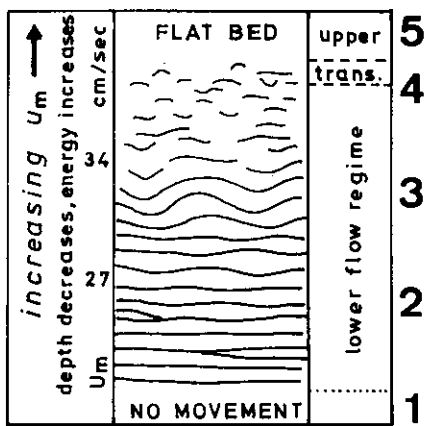


Fig. 13. Sequence of bedforms (plan view of crests, ripple asymmetry pointing to the top of the picture) under oscillatory flow in the upper shoreface. 1 = No sediment movement; 2 = straight-crested asymmetrical wave ripples; 3 = undulatory asymmetrical wave ripples; 4 = strongly undulatory to discontinuous (irregular) asymmetrical wave ripples; 5 = flat (plane) bed. Threshold values of the bottom orbital velocity (u_m) for transition from one to another type of bedforms are also indicated. Land is toward the top.

length. The transition from straight-crested to undulatory asymmetrical wave ripples occurs at about $u_m = 27$ cm/sec. The transition from undulatory to strongly undulatory (irregular) asymmetrical wave ripples takes place at $u_m = 34$ cm/sec. The upper limit of the lower flow regime is thought to be within the zone of very irregular ripples with decreasing ripple height, but the threshold velocity could not be calculated due to the small depth of water and the strong interference between the incoming and reflected waves. Flat bed occurs primarily in the swash zone. These different bedform fields are arranged in zones which run more or less parallel to the coast. The position and width of the bedform fields shift landward or seaward as a result of changes in sea level. These features are comparable to the ones described by Clifton et al. (1971), but the coast of Mazarrón is of a lower energy type and the scale of processes and features is smaller.

The breaker zone is marked by coarser grain-size, pebble accumulation and a small step. This plunge step occurs at the base of the swash zone and is caused by the sudden deceleration of backwash and subsequent deposition of some of the coarse-grained material. The seaward flow does not completely disappear at the breaker zone but, instead, it extends some distance along the bottom beyond the breakers and interferes with the incoming waves. This interference is responsible for a ribbon of small straight-crested ripples (Fig. 12). Most of these ripples are asymmetric towards land due to the predominance of incoming waves over backwash.

This bedform zone is formed under lower flow regime and it is placed between two zones of upper flow regime (Fig. 12). It is over 50 cm wide, at

a water depth of 7–14 cm, and occurs at about 50 cm seaward of the plunge step. These ripples are comparable to the 'inner rough facies' from Clifton et al. (1971).

CHANGES IN WAVE ENERGY AND EVOLUTION OF THE COAST

The previously described bedforms and bottom morphologies are stable under the wave conditions listed above, which are, in fact, acting most of the time. If larger waves approach the shore, several changes take place: (1) the sea bottom and ridges are flattened and eroded because of the transition from lower to upper flow regime, (2) berms and ridges are partly or completely eroded and the beach profile is smoothed, (3) gravelly bars are destroyed and removed to be rebuilt in other places and (4) coarse material is incorporated in the breaker zone. These changes occur at the study area with the following wave parameters: wave height 30–40 cm, wave length 12–14 m, wave period 6–7 sec and wave velocity 2 m/sec.

CONCLUSIONS

Observations of wave propagation over ridge and runnel systems along the low-energy non-barred coast of Puerto de Mazarrón, lead to the differentiation of asymmetric oscillatory and unidirectional flow regimes each characterized by a distinct sequence of bedforms. The existence of one or other flow condition depends on the position of the ridge and runnel system (Fig. 14).

In the early stages of evolution (Type 1), when the ridge is placed in the upper shoreface, the whole system is subject to asymmetric oscillatory flow. The runnel is under lower flow regime conditions and the ridge may be under upper or lower flow regime according to the water depth and wave energy.

Later, when the ridge has migrated to a position on the foreshore (Type 2), the runnel is connected to outlet channels and largely under conditions of unidirectional lower flow regime, while the ridge itself is under oscillatory upper flow regime.

When the ridge welds to berm (Type 3), it is largely emergent and exposed to high-tide swash action under upper flow regime conditions. The runnel is eventually filled with sand and transformed in a low-lying area, active only for a weak drainage.

All these types grade laterally into each other. One or more ridge and runnel systems can occur at the same time. Wave energy, tide level and position of the ridge control the variations in the characteristics of the ridge and the position of the bedform zones differentiated at the upper shoreface.

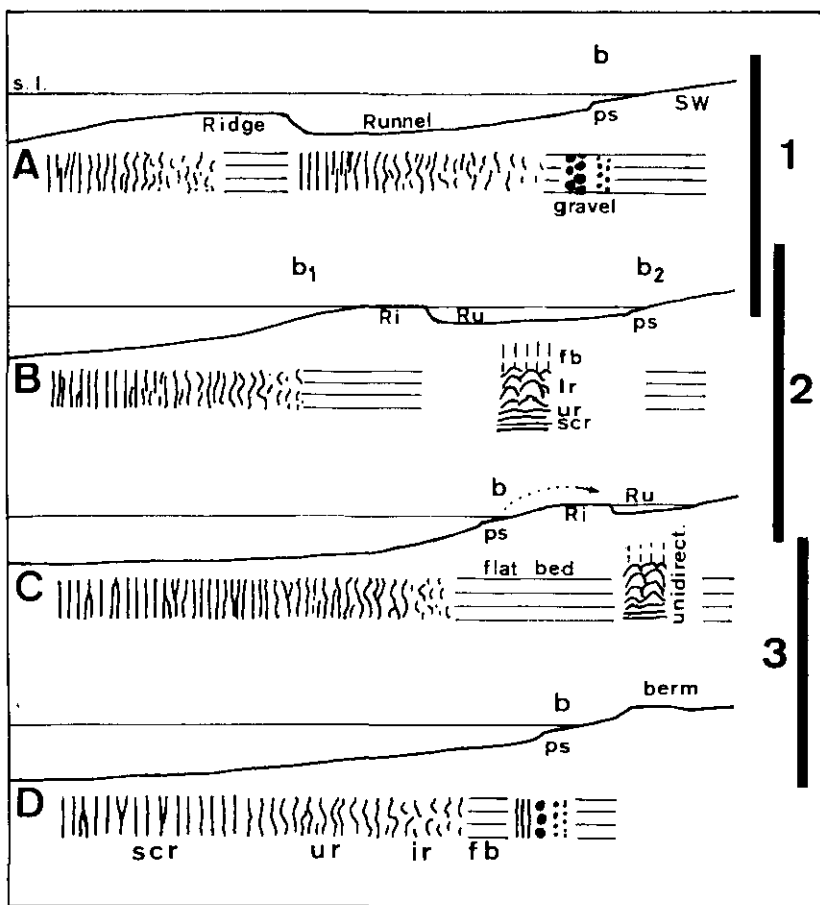


Fig. 14. Beach profiles A–D marking successive stages of evolution from early accretion (1) to mature welded-on stage (3). Distribution of the various bedforms (sequences) and their position relative to the ridge (Ri) and runnel (Ru) system shown by signatures. S.r.c. = straight-crested wave and current ripples; u.r. = undulatory wave and current ripples; l.r. = linguoid ripples; f.b. = flat (plane) bed; s.l. = mean sea level; b. = breaker zone; p.s. = plunge step at the base of the swash zone (SW). Flow conditions vary from A to D: A = asymmetric oscillatory flow; B = oscillatory flow (in the runnel, both oscillatory and unidirectional flow occur); C = the runnel is dominated by unidirectional flow; D = only drainage flow in the residual runnel. Note that at the stage B, both asymmetrical oscillatory and unidirectional flow can occur in the runnel, but only the sequence of bedforms for unidirectional flow has been indicated.

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