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Morphometric characteristics and internal structures of intertidal bars on the northwest Cadiz littoral (southwestern Iberian Peninsula)

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ABSTRACT

The present paper deals with morphometric bar characteristics, to discriminate between bars that are associated with dissipative beaches and reflective ones. We shall focus on the former: their internal structures and migration rate. The beaches studied are located between the cities of Chipiona and Rota (southwest Iberian Peninsula). Dissipative beaches have a gentle slope (2 %) and are 120 m wide; moderately reflective beaches have a 5 % slope and are 90 m wide. We found that bars associated with reflective beaches are larger than those associated with dissipative beaches. On the reflective beaches, bars are convex upwards, with a seaward slope of 9° and a landward slope of 5°. On the dissipative beaches, bars have a wide, smooth crest, a seaward slope of 2°-3°, and a landward slope of 1°-2°. They are generally composed of thin sets of plane bedding laminae, parallel to the beach surface.

Key words: Intertidal bar, reflective beach, dissipative beach.

RESUMEN

Características morfométricas y estructuras internas de barras intermareales en el litoral noroccidental de Cádiz

Este trabajo pretende una descripción morfométrica de las barras intermareales para distinguir entre las asociadas a perfiles disipativos y las asociadas a perfiles reflectivos, profundizando más en las primeras en cuanto a estructuras internas y migración. El litoral estudiado se sitúa entre las ciudades de Chipiona y Rota (suroeste de la península Ibérica). Las playas disipativas presentan pendiente muy suave (2 %) y anchura de aproximadamente 120 m; las reflectivas tienen pendiente media del 5 % y anchura en torno a 90 m. Se ha encontrado que las barras asociadas a perfiles reflectivos son de mayores dimensiones que las asociadas a perfiles disipativos. Aquéllas son convexas y tienen una elevada pendiente en su lado hacia el mar (9°) y una pendiente menor en el lado hacia tierra. Las últimas presentan una amplia y aplanada cresta, el lado hacia el mar tiene una pendiente de 2°-3° y el lado hacia tierra de 1°-2°. Sus estructuras internas están constituidas por láminas paralelas a la superficie.

Palabras clave*: Barras intermareales, playa reflectiva, playa disipativa.*

INTRODUCTION

Sand bars are formed offshore with beach material eroded by storm waves; less energetic post- storm waves gradually move the sand bars onshore through the nearshore zone, and finally the bars pile up on the beach as a berm. Bar migration is favoured by swell waves (Komar, 1976) and tides passing from neap to spring. Bars of both micro- and mesotidal coasts have similar structures (Dabrio, 1982); in the former environment they have a greater migration speed (Davis, 1985). Onshore bar migration represents the most important way of beach material restoration after storm events.

The bars also function as submerged breakwaters against storms and act as filters for wave height, by protecting the beach (Carter, 1991; Takeda and Sunamura, 1992). There are many different kinds of bars (Wright and Short, 1984; Wright *et al.*, 1986): we shall describe intertidal bars, which have been called 'ridge and runnel systems' (King, 1972; Hayes, 1972), 'inner bars' (Orford and Wright, 1978), 'Type I bars: ridge and runnel', and 'Type II bars: swash bars' (Greenwood and Davidson-Arnott, 1979).

The present paper deals with morphometric bar characteristics, to discriminate between bars that are associated with dissipative beaches and moderately reflective ones; we shall focus our attention on the former: their structures, migration rate, and associated bedforms.

Our findings are derived from a monthly beach-profile monitoring carried out along the littoral between Chipiona and Rota (figure 1) for 18 months, and a 2-month study of bar structures and migration rate on the beaches of Tres Piedras, La Ballena and Aguadulce.

The study area is located in the north of Cadiz Bay and includes 14 km of southwest-facing littoral of quartz reach sand beaches backed by cliffs and dune ridges.

Intertidal beach width and slope both have a wide range: dissipative beaches have a gentle slope (2 %) and are 120 m wide; moderately reflective beaches have a 5 % slope and are 90 m wide. Other beaches face a rock shore-platform, usually have a steep slope (5-7 %), and are 50-80 m wide.

The tide is semidiurnal and its average range is more than 2 m. Winds blow from east and west; the latter is more import, and is related to the coastal orientation. Reyes (unpublished) has analysed wave data obtained from the Cádiz offshore buoy, which

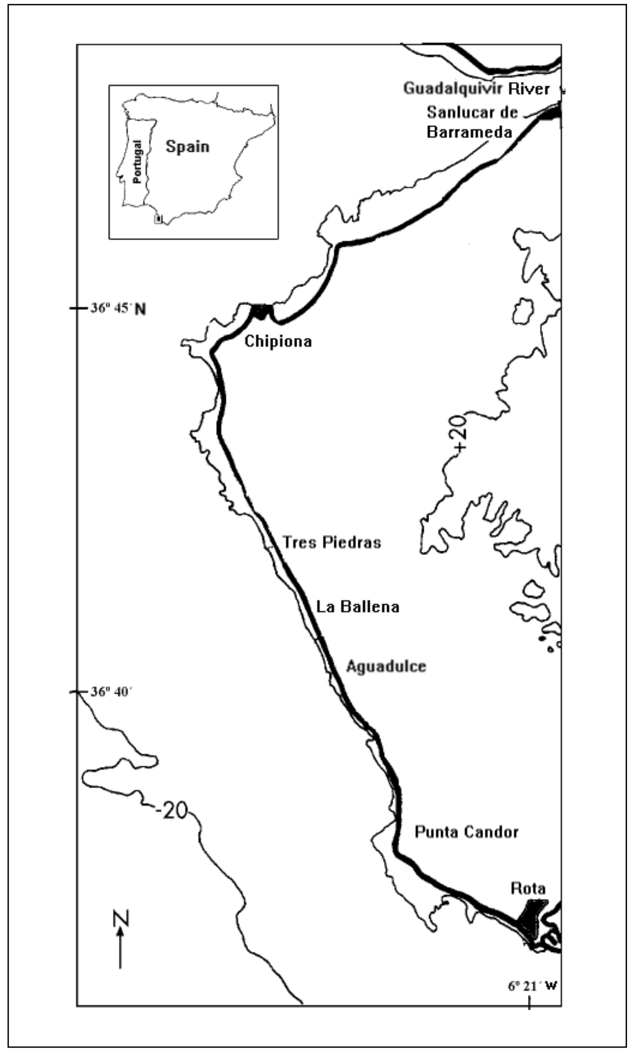

Figure 1. Location map

belongs to the Spanish oceanographic recording system: the average wave height of both sea and swell waves is 1 m, and the significant wave height is 2 m, with a 7 s associated period. Fair weather and storm waves approach generally from the west.

MATERIALS AND METHODS

Different techniques have been applied in the present study; first, we shall describe the methods used in field surveys, and then the theoretical formulation employed in order to interpret the results of our field observations.

The morphology of the beaches between the cities of Chipiona and Rota (Cadiz province) was recorded from March 1996 to May 1997, throughout 12 topographic profiles, surveyed monthly with an electronic theodolite Zeiss Eth 4.

This methodology, which was also employed to monitor bar migration speed (form April to May 1997), enabled us to describe bar morphometry.

In order to monitor changes in bar topography and to evaluate bar migration speed during a single tidal cycle, a field assessment was carried out at La Ballena beach. During morning low tide, 10 rods and associated plugs of black beach sand (Ciavola *et al.,* 1995) were inserted along each of the two intertidal beach profiles studied. Rods gave a measure of erosion and deposition at different times, while plugs recorded the maximum remobilisation depth. Wave period, height and longshore current were monitored, as well. During two consecutive low tides, beach morphology was also surveyed with the theodolite. During the field assessment and the period from April to May 1997, cuts in the seaward and landward sides of bars and in the crests, as well as in the troughs, were made to study internal structures. Measurements of sets and laminae thickness and slopes were carried out; schemes, pills and photos were also realised.

In the present paper, only the most representative profiles have been used to determine bar characteristics and beach slope. Thus, bars were defined through intersections of the measured profile with an equilibrium profile (Larson and Kraus, 1994) similar to the Dean (1977) profile that best fits the natural profile (figure 2).

Beach slope was assessed along the intertidal area of the equilibrium beach profile. Bar height (h) and length (l) were calculated and a bar index, l/h, similar that of Carobene and Brambati (1975), was obtained. Moreover, temporal bar distribution was related to the wave data obtained from the offshore buoy.

A ripple index, L/H (Reineck and Singh, 1980), was also calculated in order to define both megaripple and ripple morphology.

RESULTS

Morphometric bar characteristics

We observed that bars associated with reflective profiles were 20-30 m wide and 50-70 cm high. Bars associated with dissipative profiles were 30-40 m wide and 15-30 cm high. The seaward bar slope associated with reflective beaches had an average value of 9°, and a 2°-3° value on dissipative beaches. The landward bar slope ranged from 5° (on reflective beaches) to 1°-2° (on dissipative beaches).

The morphologic study of the 35 observed beach bars was conducted by taking into account the bar index and intertidal beach slope on which the bars appeared (figure 3).

From this study, three different groups can be discerned. The first shows a bar index value of 50 and a slope ranging from 2.5-7 %. This group includes both larger bars associated with reflective profiles (2-5 % in slope), and smaller bars associated with steeply sloping beaches facing rock platforms. An intermediate group shows a 100-150 bar index and a 2.5-5 % slope: it includes bars associated with beaches facing rock platforms, as well as large bars associated with dissipative profiles. These bars are located in the upper part of the beach and appear after storm events. A third group has a 250-300 bar index and small beach-slope values: it includes only bars associated with dissipative beaches.

A stepwise discriminant analysis (BMDP, 7M) was carried out: the program finds the combination of variables that best predicts the group to which a case belongs. In this case, the four classification functions are: 1) a subjective morphological classification of the beach on which the bar appears (reflective, dissipative and rock-platform beaches, i.e. three groups); 2) bar height; 3) bar length; and 4) beach slope of each case. The classification matrix was 100 % correct for the number of cases classified as reflective and dissipative categories, and 94 % correct for the number of cases classified as bars associated with rock-platform beaches. The 6 % error is due to a single bar (subjectively classified into the dissipative beach group) that the program associated with the rock-platform group, due to the bar's morphometric characteristics.

In figure 4, the variation of time vs significant wave height (weekly average value) and bar index are shown.

We can assert that bars associated with reflective beaches appear only after storm events, whereas bars associated with both rock platform-beaches and dissipative beaches have a wider distribution throughout the period studied.

Internal structures and migration speed

At Tres Piedras, a dissipative beach composed of fine sand, we observed small bars, parallel to the

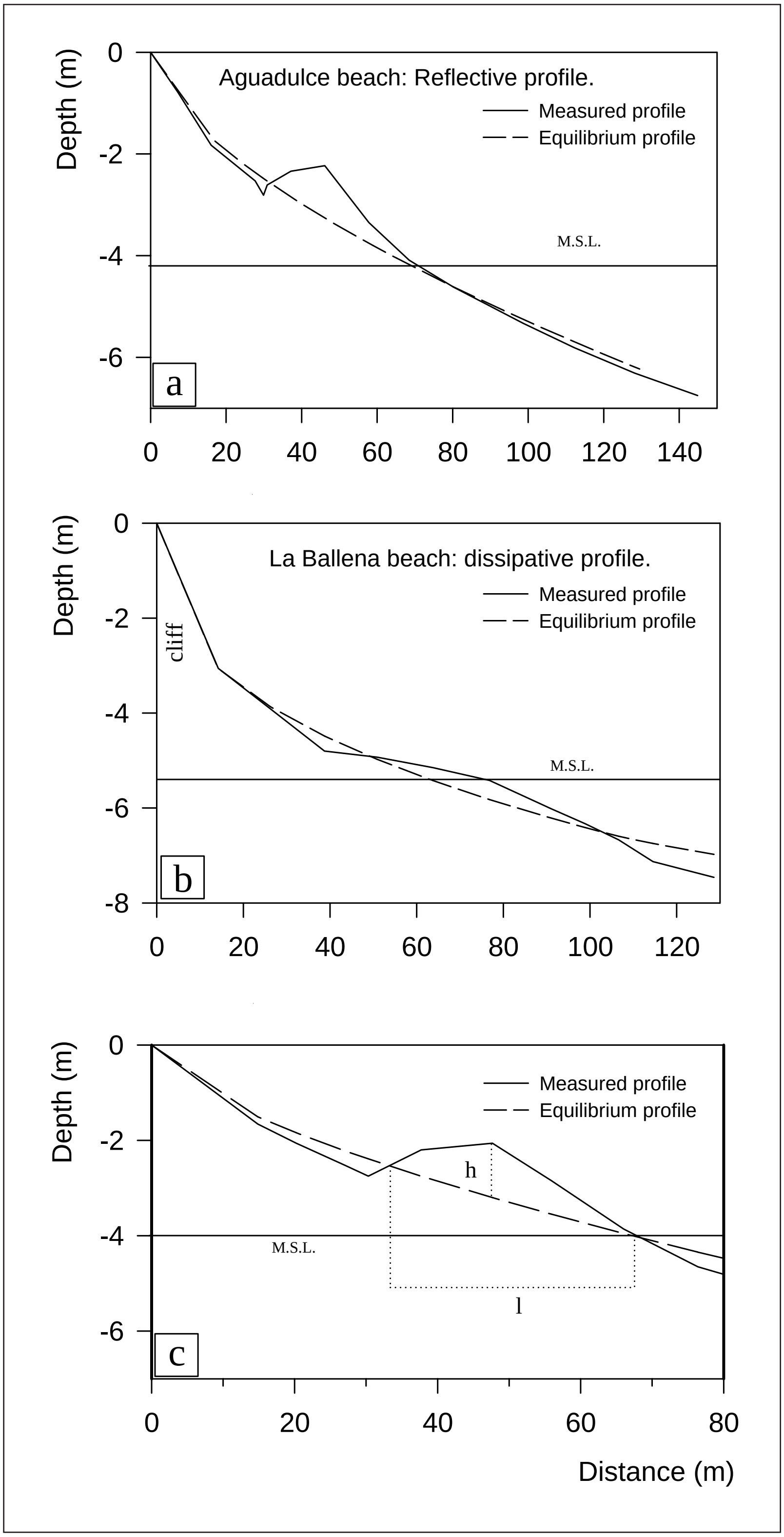

Figure 2. Reflective and dissipative beach profiles with associated Dean profiles. Definition sketch of calculated bar properties. Depths refer to a concrete monument on the backshore. (M.S.L.): Mean Sea Level

shore and located between mean and low sea levels. The beach usually showed only one bar, 40-50 m wide and 15-22 cm high. The average seaward slope was about 1.5°-2° and 1° landward, the crest being quite wide and horizontal. Seaward-dipping plane bedding (parallel to beach surface) and interbedded 1-2 cm thick laminae of coarse sand are characteristic of the seaward slope of the bar. The ridge

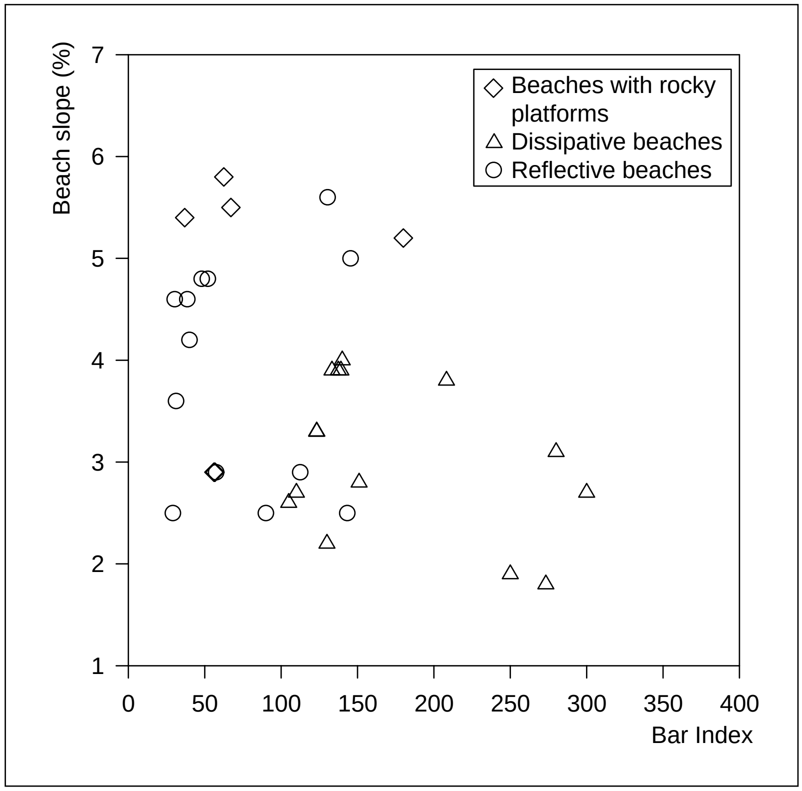

Figure 3. Bar index vs beach slope. Bars belonging to the same beach are represented by the same symbol

crest is composed of plane thin laminae parallel to the beach surface (according to Hunter, Clifton and Pillips, 1979); interbedded lens of coarse sand and sets of centimetric ripple cross-lamination have also been observed. Landward-dipping plane bedding, parallel to the beach surface, is characteristic of the slip side. In certain places, plane bedding was very thin, and a 2°-4° landward-dipping bedding was present. Such structures represent the foreset laminae of the bar' lee side, and record bar migration. Furthermore, in the upper part of the intertidal area, sigmoidal laminae, showing the filling up of the runnel, were observed: they represent the late stages of accretion. Many researchers have studied the landward migration of inner bars; Sunamura and Takeda (1984) related the migration rate to nearshore wave parameters; however, few studies have dealt with ridge-and-runnel migration speed. The bar migration discussed in the present paper was from April-May 1997. On 25 April the beach presented a bar located at mean sea level: it was 30 m wide, with a seaward slope of 1° and a landward slope of 2°; after four days the beach showed a ridge-and-runnel system with a lower bar at low sea level, and a second one at mean sea level: the entire structure had moved landward at an average speed of 10 m/day. By 7 May the system had migrated 30 m landward. On 10 May the observed morphologies were 10 cm higher. Finally, on 22 May the bar was smoothed by a small storm.

At La Ballena beach, a dissipative one, we observed bars 30-40 m wide and 20-30 cm high, similar, in orientation and position with respect to sea level, to the ones mentioned above. Bars usually had a seaward slope of 3° and were characterised by interbedded units of plane bedding, sets of ripple cross-lamination and lens of coarse sand. The wide and horizontal bar crest was characterised by plane bedding and filling structures of scour pools (8 cm thick) associated with megaripples. In certain places, the horizontal plane bedding (only 2 cm thick) cut a landward 8°-12° dipping lamination, which represents the internal structures of the former landward bar side. Wide variations in grain size were also observed: the crest, composed of fine sand (Md = 0.16 mm), was 18 cm thick, with a storm level of coarse sand (Md = 0.74 mm) on the bottom. The landward side had a 1.5° slope and was characterised by interbedded horizontal plane bedding and festooned ripple cross-lamination linked to a reversible flux direction. On 25 April we observed a bar in the lower part of the intertidal area; the ridge

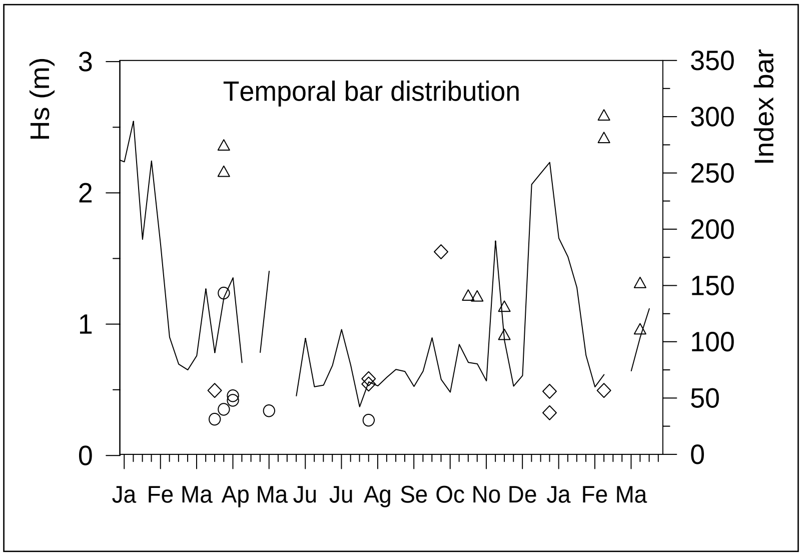

Figure 4. Temporal bar distribution vs bar index and signif-icant wave height

was 40 m wide, 40 cm high and had a 4°-5° seaward slope and 1° landward slope. On 29 April, the entire system moved 30 m landward. On 7 May, the beach profile was smoothed by a storm. On 10 May, the beach presented an incipient bar in the lower intertidal area. On 22 May, the structure had not varied its position and its height had grown.

Finally, at Aguadulce beach, a reflective beach composed of medium sand, on 10 May we observed a bar 50 m wide and 50 cm high located on the upper part of the foreshore. A beach berm was also present, with a storm cut 1 m high. On 22 May, the bar had not changed its location and had been eroded by rill marks. A great accumulation of water in the berm produced an effluent zone that impeded landward migration of the bar (Duncan, 1964). A sketch of the observed internal structures is presented in figure 5.

Field Assessment

At La Ballena beach, during a tidal cycle, a field experiment on remobilisation depth, internal structures and bar migration speed, was carried out according to the methods described. Rods were inserted into the beach-face along two transepts normal for a bar 40 m wide, 35 cm high and characterised by a large plane crest 15 m wide. Tidal range was 2.7 m and sea waves approached the beach from the west, quite normal to the shoreline, with a 30 cm significant wave height (4.5 s period) and an associated 45 cm/s longshore current. Maximum remobilisation depth was observed on the bar, with higher values (5 cm) on the seaward side (which had the steepest slope), while lower values (3 cm) were observed on the landward side. Average remobilisation depth at the crest was approximately 2 cm. Finally, the bar showed a small erosion at the crest, no changes on the seaward side, and a certain growth on the landward side. Topographic surveys indicated a 5 m landward migration of the ridge-and-runnel system.

Ripples and megaripples

These morphologies were monitored, as well, using terminology according to Reineck and Singh (1980). Straight-crested ripples represent the most common bedform: they are symmetric ripples, 4 mm high, 5 cm long and with a 1.25 ripple index, having coarse grains at the toe of the lee side. These ripples are formed in very shallow water (a few centimetres) laminae by swash-backwash action. Their small size is related both to the low energy and to the fine beach sand. Centimetric linguoid-shaped and small rhomboid ripples (8 cm long and 2-3 cm high, 1.5-2 ripple index) were also observed in the runnels during the last stages of tidal fall.

The megaripple terminology includes a wide range of different morphologies, sizes and internal structures. Reineck and Singh (1980) classify such bedforms as megaripples from 30-60 m in length. Their size depends on the speed of the current and

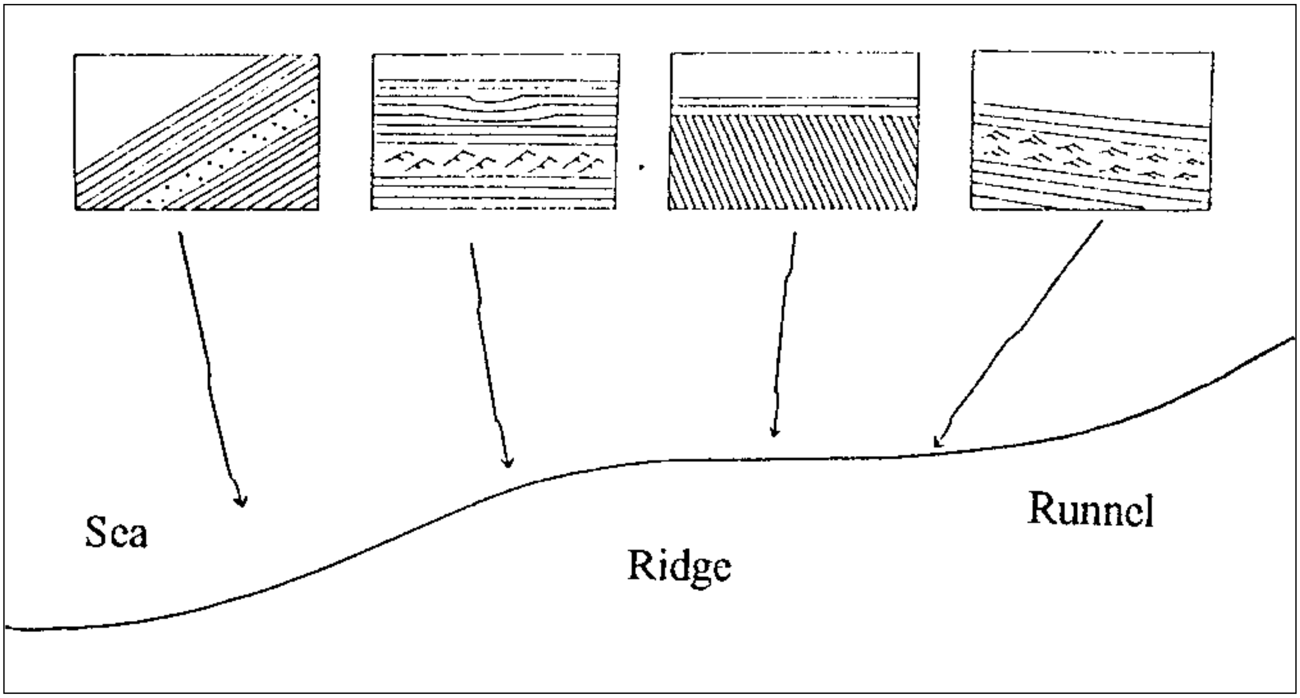

Figure 5. Bar topography showing characteristic sedimentary structures

grain size. A description of the different forms observed is as follows.

Lunate megaripples, due to a unidirectional flow, were observed in a runnel with a 10 cm water depth. Megaripple crests were normal to the coast line, ripple index was 6 (L = 36 cm and H = 6 cm), and migration speed was 0.04 cm/s. Afterwards, the observed structures migrated downdrift: the water depth was then about 15 cm and the runnel was wider. Megaripples were larger (L = 50 cm and H = 7 cm) and migration speed was only 0.08 cm/s. Internal structures showed foreset laminae and coarser grains at the lee-side toe.

Straight-crested megaripples were also observed, with ripple indices ranging from 20 to 150. These structures were formed by currents; usually the crests were straight or curved, and did not emerge with respect to the beach surface; associated scour pools were well developed. We observed parallel trains at different positions on the beach face by recording successive steps of sea-level fall. They had a characteristic path: parallel to the shoreline, but displaced seawards. The main axis, parallel to the shoreline, was 1.5-2 m long, while the minor one was 1-1.5 m long. It is noteworthy that straight-crested forms, as well as D-shaped scour pools, prevailed downcurrent. At certain places, these megaripples were covered with water-level marks and small ripples, both related to tidal fall. A trench along the main axis showed 8 cm thick plane bedding laminae that filled the scour pools with an onlap geometry. A trench along the minor axis showed sigmoidal laminae quite similar to the dunes described by Davis (1985). These morphologies have been cited by several authors: Dalrymple, Knight and Lambiase (1978) classified the studied structures as Type I megaripples; Chakrabarti (1977) described similar structures in a tidal flat: they are generated during storms and are formed by foreset laminae. Leeder (1992) describes 'straight sinuous dunes', composed by sigmoidal structures with well developed scour pools (in a tidal flat). Carter (1991) describes 'rough inner facies' on a dissipative beach; they are related to wave action, and usually appear at mean sea level due to the rapid tidal fall.

DISCUSSION

We have described how bars associated with reflective beaches are larger than those ones associated with dissipative beaches; they are also similar to the bars described by Dabrio and Polo (1981) on the Huelva littoral. Reflective beaches are generally affected by storm events, and bars usually appear

1-2 months after erosive processes. Moreover, dissipative beaches do not suffer great erosion, and bars have a wide distribution throughout the year. On the reflective beaches, the bars studied are convex upwards with a steep seaward slope (9°) and a smooth landward slope (5°). On the dissipative profiles, bars usually have a seaward slope of 2°-3° and a landward slope of 1°-2°.

They are generally composed of sets (2-50 cm thick) of plane bedding laminae parallel to the beach surface, in disagreement with Reineck and Singh's (1980) observed values. Concentrations of heavy minerals often define the described lamination. Low angle ripple and megaripple cross-bedding laminations were observed in trenches along crest bars: these structures record the runnel position. At certain places, seaward-dipping laminae record slip-side internal structures, i.e. bar migration. The high values of dipping laminae were observed only on the landward side of inner bars, but they are not common on the slip sides of intertidal bars. Probably, these structures develop during the first stages of bar migration, and are replaced by a plane bedding lamination linked to bar migration. In fact, according to Hine (1979), waves built up in the runnel can smooth the ridge, giving rise to a low-angle discontinous surface. This process may also be related to erosive processes associated with falling tide. We can therefore assert that the observed crest bars are quite small, and composed by sets of thin laminae, which indicates a limited growth of the crest. Finally, we have pointed out how the maximum remobilisation depth occurs on the seaward side of the bars, when the waves climbing over this slope uniformly affect the entire crest ridge. This process gives rise to the described horizontal plane bedding which moves the ridge-runnel system landward without any vertical growth of the crest.

Bars associated with dissipative beaches are quite symmetric during the early migration stages, due to large periods of immersion. When the bar climbs up the intertidal area, it achieves an asymmetric profile and grows in height, due to the larger influence of the waves on its seaward side.

ACKNOWLEDGMENTS

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REFERENCES

Carobene, L. and A. Brambati. 1975. Metodo per l'analisi morfologica quantitativa delle spiagge. *Boll. Società Geologica Italia* 94: 479-493.

Carter, R. W. G. 1991. *Coastal environments*. Academic Press. London: 617 pp.

Chakrabarti, A. 1977. Mass-spring-damper system as the mathematical model for the pattern of sand movement for an eroding beach around Digha, West Bengal, India. *J. Sediment. Petrol.* 47: 311-330.

Ciavola, P., O. Ferreira, R. Taborda and J. Alveirinho Días. 1995. Field assessment of longshore transport at Culatra Island (Portugal) using sand tracers. Universidade do Porto. Fac. de Ciencias. *Museu e Laboratorio Mineralógico e Geologico*. Mem. 4: 905-909.

Dabrio, C. J. 1982. Sedimentary structures generated on the foreshore by migrating ridge and runnel systems on microtidal and mesotidal coasts of S. Spain. *Sediment. Geol.*32: 141-151.

Dabrio, C. J. and M. D. Polo. 1981. Flow regime and bedforms in a ridge and runnel system, S.E. Spain. *Sediment. Geol.* 28: 97-110.

Dalrymple, R. W., R. J. Knight and J. J. Lambiase. 1978. Bedforms and their hydraulic stability relationships in a tidal environment, Bay of Fundy, Canada. *Nature* 275: 100-104.

Davis, R. A. Jr. 1985. Beach and nearshore zone. In: *Coastal Sedimentary Environments*. R. A. Davis Jr. (ed.): 379-445. Springer-Verlag. Berlin.

Dean, R. D. 1977. Equilibrium beach profiles: U.S. Atlantic and the Gulf Coasts. *Ocean Eng. Rep.* 12: 1-45. Dep. Civ. Eng. Univ. Delaware. Newark (Delaware).

Duncan, J. R. 1964. The effects of water table and tide cycle on swash-backwash sediment distribution and beach profile development. *Mar. Geol.* 2: 186-197.

Greenwood, B. and R. G. D. Davidson-Arnott. 1979. Sedimentation and equilibrium in wave-formed bars: a review and case study. *Can. J. Earth Sci.* 16: 312-332.

Hayes, M. O. 1972. Forms of sediment accumulation in the beach zone. In: *Waves on Beaches*. R. E. Mayer (ed.): 297-356. Academic Press. New York.

Hine, A. C. 1979. Mechanisms of berm development and resulting beach growth along a barrier spit complex. *Sedimentology* 26: 333-351.

Hunter, R. E., H. E. Clifton and R. L. Phillips. 1979. Depositional processes, sedimentary structures, and predicted vertical sequences in barred nearshore systems, Southern Oregon coast. *J. Sediment. Petrol.* 49 (3): 711-726.

King, A. 1972. *Beaches and Coasts*. Edward Arnold. London: 570 pp.

Komar, P. D. 1976. *Beach processes and Sedimentation*. Prentice-Hall. Englewood Cliffs, New Jersey: 429 pp.

Larson, M. and N. Kraus. 1994. Temporal and spatial scales of beach profile change, Duck, North Carolina. *Mar. Geol.* 117: 75-94.

Leeder, M. R. 1992. *Sedimentology*. Pergamon. U.K.: 344 pp.

Orford, J. D. and P. Wright. 1978. What's in a name?: genetic or morphological origins for ridge and runnel topography. *Mar. Geol.* 28: M1-M8.

Reineck, H. E. and I. B. Singh. 1980. *Depositional Sedimentary Environments*. Springer-Verlag. Berlin: 551 pp.

Sunamura, T. and Y. Takeda. 1984. Landward migration of inner bars. *Mar. Geol.* 60: 63-78.

Takeda, I. and T. Sunamura. 1992. Conditions for beach erosion on a barred beach. *Zeitschrift fuer Geomorphologie* 36 (4): 453-464.

Wright, L. D., P. Nielsen, N. C. Shi and J. H. List. 1986. Morphodynamics of a bar-trough surf zone. *Mar. Geol.* 70: 251-285.

Wright, L. D. and A. D. Short. 1984. Morphodynamic variability of surf zones and beaches: a synthesis. *Mar. Geol.* 56: 93-118.