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Holocene Filling of an Estuarine Lagoon Along the Mesotidal Coast of Huelva: The Piedras River Mouth, Southwestern Spain[1]

José Borrego, J.A. Morales and J. Gabriel Pendón

Universidad de Sevilla
Departamento de Geologia y Mineria
Facultad de Ciencias Experimentales
21819 La Rabida Palos Fra.
Huelva, Spain

ABSTRACT

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The mesotidal coast of Huelva (S.W. Spain) is a tide-dominated (mixed energy) coastline type. This littoral zone is subject to a warm-temperate climate. Tidal regime is both mesotidal and semidiurnal with a slight diurnal inequality. The Piedras River mouth operates like an estuarine lagoon, where sediment supply is of dominantly marine provenance. Depositional facies along the inner estuary includes: (1) channel, (2) active channel margin, (3) salt marsh and (4) sterile marsh facies. All these facies are very similar to those described in other locations. Inner facies are asociated along the estuary mouth with spit facies and related environments: beach and dunes.

Three stages in recent evolution of Piedras Estuary have been distinguished. The estuary-mouth morphology has evolved from a barrier-island system into an elongated spit accretion due to a decrease of the tidal prism. Two processes have changed the tidal prism: (1) estuary filling and (2) dam construction.

ADDITIONAL INDEX WORDS: *Littoral processes, tidal prism, estuarine facies, spit elongation, Gulf of Cadix.*

INTRODUCTION

A series of humid zones are located at the main river mouths developed along the coast of Huelva bordering the Gulf of Cadix, S.W. Spain (Figure 1). Tidal influence is pronounced and some estuaries were formed during the Flandrian (Holocene) transgression, aproximately 5,000 years ago (NICHOLS and BIGGS, 1985). Consequently, some vast bays were formed on a clastic Plio-Quaternary substrate, which also represents the source area for sediment.

Estuaries can work as a sediment trap, and during progressive infilling marsh deposits, intertidal flats and sub- and intertidal sandy bodies may accumulate through the combined action of tidal and fluvial processes related to local climatic conditions. Factors which control the development and evolution of the tidal environments vary from place to place and include: (1) climate, hydrography and soil formation; (2) sediment supply; (3) indigenous fauna and flora; (4) the interrelationships between substrate and organisms, and (5) eustatic sea-level changes and tectonics activity.

Distribution of depositional facies at the Huelva coast estuaries is mainly conditioned by: (1) propagation model of tidal waves, (2) fluvial sediment supply, and (3) nature of the substrate.

Studies of comparable basins have been made in different climatic zones, in situations with a different tectonic setting and tidal regime. This note deals with one estuary from the Huelva coast: the Piedras River mouth. Hydrodynamic processes and their modern products (sediments and depositional facies) are described and discussed. The evolution of Piedras estuary with respect to the changes which have occurred in the last century is also described. These two considerations, the main purpose of this paper, are compared with models established in other areas. An evolution model of estuary-mouth morphology is proposed, which differs from other models in different locations but within a similar hydrodynamic setting.

GEOGRAPHICAL, MORPHOLOGICAL, GEOLOGICAL AND CLIMATIC BACKGROUND

Since the middle of the last century, the morphology of the area has undergone significant changes (GOZALVEZ, 1982; MADOZ, 1985) (Figure

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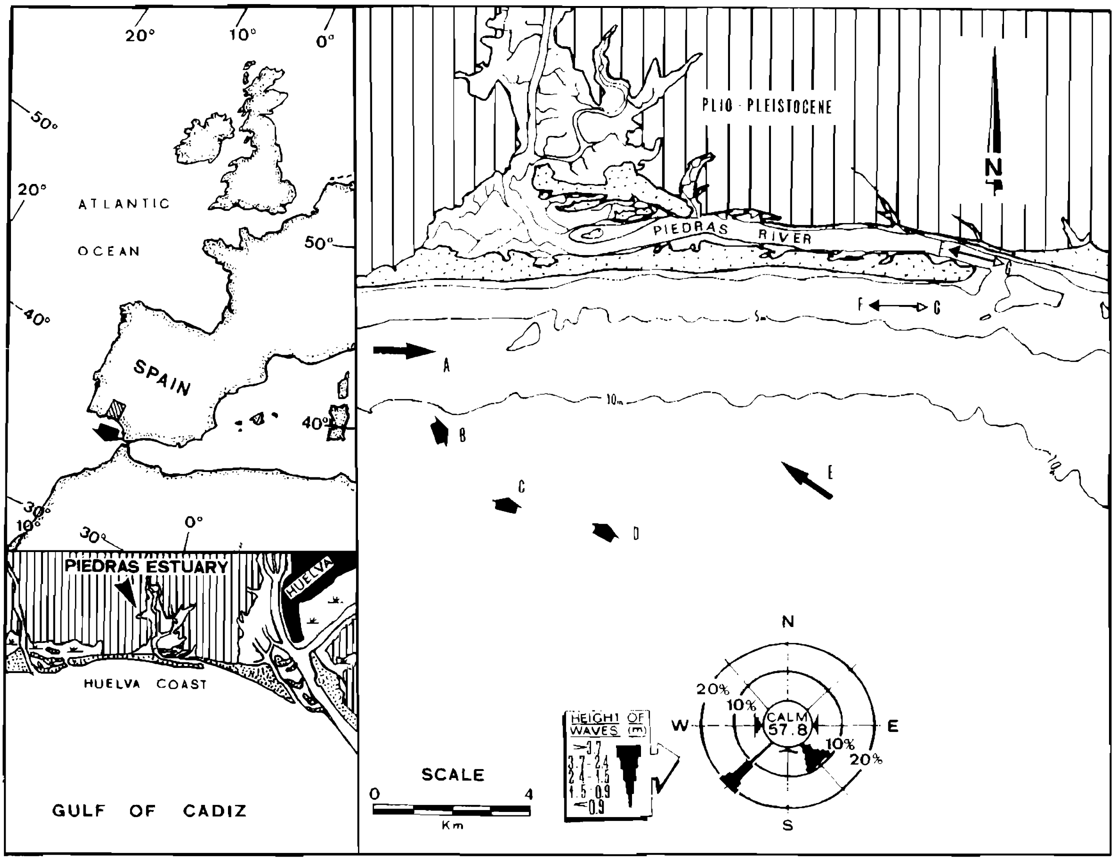

Figure 1. Location of the study area and hydrodynamic setting of the Huelva coast. (A) Littoral drift current. (B) Bottom currents. (C) Dominant waves-approach direction. (D) Wave approach direction during Atlantic storms. (E) Direction of waves during storms from the Gibraltar Strait. (F, G) Tidal currents (F: flood, G: ebb).

2). Especially noteworthy is spit progradation which restricted entry to the estuary. At present, the Piedras River mouth forms a bar-built estuary (FAIRBRIDGE, 1980). The Piedras River drains a catchment area of approximately 250 km^2 on Paleozoic bedrock, with Neogene sediments near the mouth. Since 1968 the river has been regulated by means of a dam located 12 km upstream from the mouth.

The Piedras Estuary consists of one active channel at the head of the estuary, and two active channels after the tributary that enters to the south of Cartaya (Figure 2). Two different shapes of the channel bottom are distinguished: (1) flattened trough-shaped and smooth hills, which represent the effects of fluvial deposition (El Rompido-El Terron at the inner side of the spit) and (2) a V-shaped channel, which may indicate erosional activity. Additional tidal subenvironments include (1) fluvial channels, (2) outer beach, (3) attached beach, (4) sand dunes, and (5) curved spits.

The stratigraphy of the region is represented by the Neogene-Quaternary from the Guadalquivir foreland basin and some Paleozoic bedrock outcrops. PENDÓN and BORREGO (1987) outlined the following Plio-Pleistocene units: Niebla Calcarenite Formation (Tortonian)—up to 30 m; Gibraleón Shales Formation (Tortonian-Lower Pliocene)—60 m; Huelva Sands Formation (Pliocene)—15 m of sandy silts; Bonares Sands Formation (Pliocene ?)—13 m; and the conglomerates of Upper Aluvial Level (Pleistocene)—12 m.

The mean annual rainfall in the region is 516

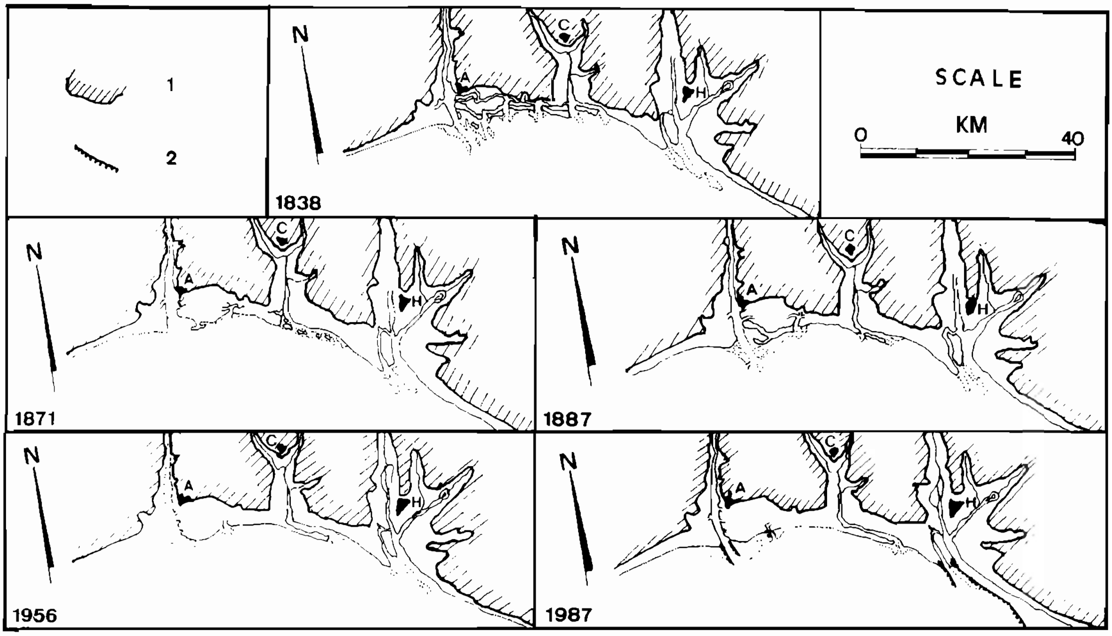

Figure 2. Map of the Huelva coast showing changes from 1838 (After GOZÁLVEZ, 1982; MADOZ, 1985; and aerial photographs). (A) Ayamonte (Guadiana Estuary). (C) Cartaya (Piedras Estuary). (H) Huelva (Odiel Estuary). (1) Substrate. (2) Bank and sumerged levees.

mm and is irregularly distributed throughout the year, with December and January being the wettest months. The relative humidity is above 60% throughout the year except during July and August when it averages about 50%. The average annual temperature is 18 °C (maximum during August 33.9 °C and minimum in January 11.3 °C). The overall climate is characterized as temperate and dry.

PREVIOUS WORKS

Literature about the Huelva coast has treated various subjects: (1) coastal morphology (VANNEY and MENANTEAU, 1979; FIGUEROA and RUBIO, 1982; RODRIGUEZ, 1987a,b; FLOR, 1990); (2) dynamic processes (OJEDA, 1989); (3) depositional products from beach sectors (DABRIO *et al.*, 1980a,b; DABRIO, 1982) and (4) effects of artificial construction works (BORREGO and PENDÓN, 1988, 1989a). No other works have featured the sedimentology of the Piedras estuary.

METHODS

The conclusions in this paper were reached by developing several sedimentological techniques. Field work was conducted beteeen 1989 and 1991. In the study sector, various intermittent transects were stablished across the main tidal channel in an effort to construct fathometer profiles. Hand operated cores were taken at some points. Thickness of recent sediments was determined by electric logs. Core samples were studied in laboratory by: (1) core X-ray radiographies to enable study of depositional structure sequence, (2) sediment textural analysis by sieving (fractions larger than 63 microns) and coulter counts with a 100 microns tube (fractions smaller than 63 microns), (3) carbonate content by ionometer with carbon dioxide electrode, and (4) total organic matter content was determined by loss-on-ignition at 485 °C for 4 hr.

HYDRODYNAMIC REGIME

The fundamental hydrodynamic processes in the Gulf of Cadix and the Huelva littoral zone are tidal regime, wave action, littoral drift current and the fluvial discharge (Figure 1). BORREGO and PENDÓN (1989b) describe the tidal regime in this sector as mesotidal (mean range 2.15 m) and semidiurnal with a low diurnal inequality. The maximum difference in tidal range between spring and neap tides is 2 m. The mean tidal prism approaches 15.6 × 10^6 m^3 during spring tides. For mean tides, this parameter decreases to 10.4 × 10^6 m^3 and is 5.9 × 10^6 m^3 for mean neap tides (BORREGO *et al.*, 1992). Several cycles of diverse lengths (half-yearly, biweekley and semidiurnal periods) in tidal fluctuation are recorded as Critical Tide Levels (CTLs *sensu stricto*; DOTY, 1946). An assymetrical tidal cycle and an hyposincronic model (LE FLOCH, 1961) of tidal wave propagation are both developed. Tidal wave propagation along the Gulf of Cadix moves from east to west (OJEDA, 1988).

Prevailing winds are from the southwest and north. Dominant waves, which are associated with an Atlantic circulation regime, come from the southwest (20% of the time), whereas waves from southeast blow 10% of the time (Figure 1). Characteristic parameters of the significant wave ($H_{1/3}$) at the 22 m water depth are given in Table 1. The average significant wave height along the Huelva coast is 0.76 m. For comparison, the average significant wave height at East Frisian Islands is 1.6 m and at Savannah, Georgia, $H_{1/3}$ = 0.9 m (water depth = 15.8 m) (FITZGERALD *et al.*, 1984). A littoral drift current flows from west to east along the Huelva littoral zone.

The fluvial sediment supply is restricted by a dam upstream (constructed in 1968), although for the period 1946–1976 the annual yield of water has been of 71 × 10^6 m^3 and distributed across wetter months (January to March). This estuary is located along a tide-dominated (mixed energy) coastline according to HAYES (1979) and DAVIS and HAYES (1984).

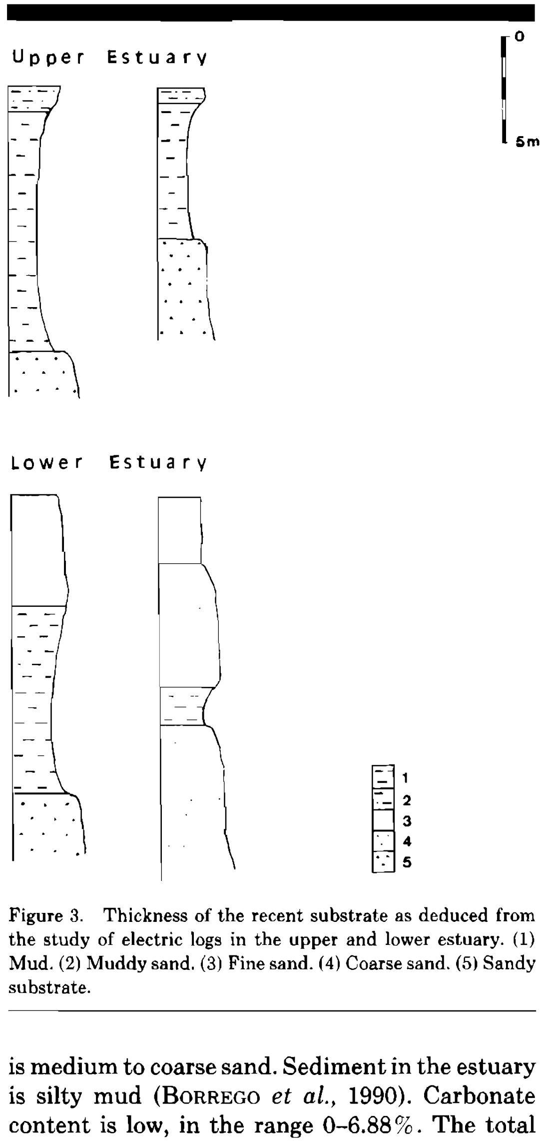

Figure 3. Thickness of the recent substrate as deduced from the study of electric logs in the upper and lower estuary. (1) Mud. (2) Muddy sand. (3) Fine sand. (4) Coarse sand. (5) Sandy substrate.

PRESENT-DAY SEDIMENTS AND FACIES

Recent sediments from the Piedras Estuary mainly consist of fine detritus, as determined from cores and outcrops. Thickness of recent sediments ranges between 7.7 and 14.3 m at the sector close to the head, as deduced from a study of electric logs (Figure 3), but between 13 and 15 m at the mouth (I.G.M.E., 1974). Sediment along the beach is medium to coarse sand. Sediment in the estuary is silty mud (BORREGO *et al.*, 1990). Carbonate content is low, in the range 0–6.88%. The total organic content oscillates between 7 and 15%.

Biogenic content of the sediments includes foraminifera and ostracods (GONZALEZ-REGALADO *et al.*, 1990). Biological diversity is low in the upper estuary where the discharge rate increases. Nevertheless, the rate of deposition is high close

Table 1. *Parameters of the significant wave along the Huelva coast at the 22 m water depth.*

Significant Wave (1/3)	Max.	Aver.	Median	Mode	Min.
Height (m)	3.80	0.76	0.65	0.50	0.10
Period (sec)	15.60	5.28	5.00	4.60	2.80
Wavelength (m)	379.6	43.5	39.0	33.0	12.2
Accumulated time frequency (%)	0.09	45	50	74	100

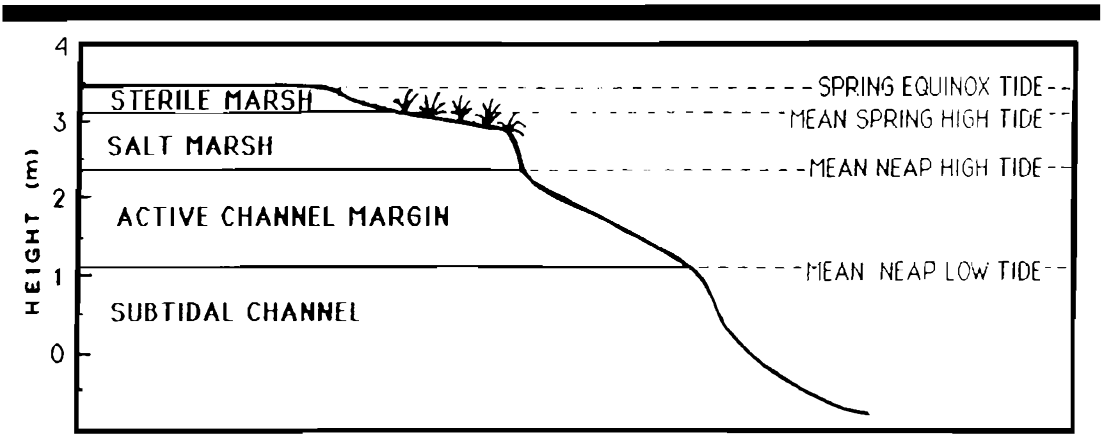

Figure 4. Critical Tide Levels (CTL's) and related tidal subenvironments along the Huelva coast.

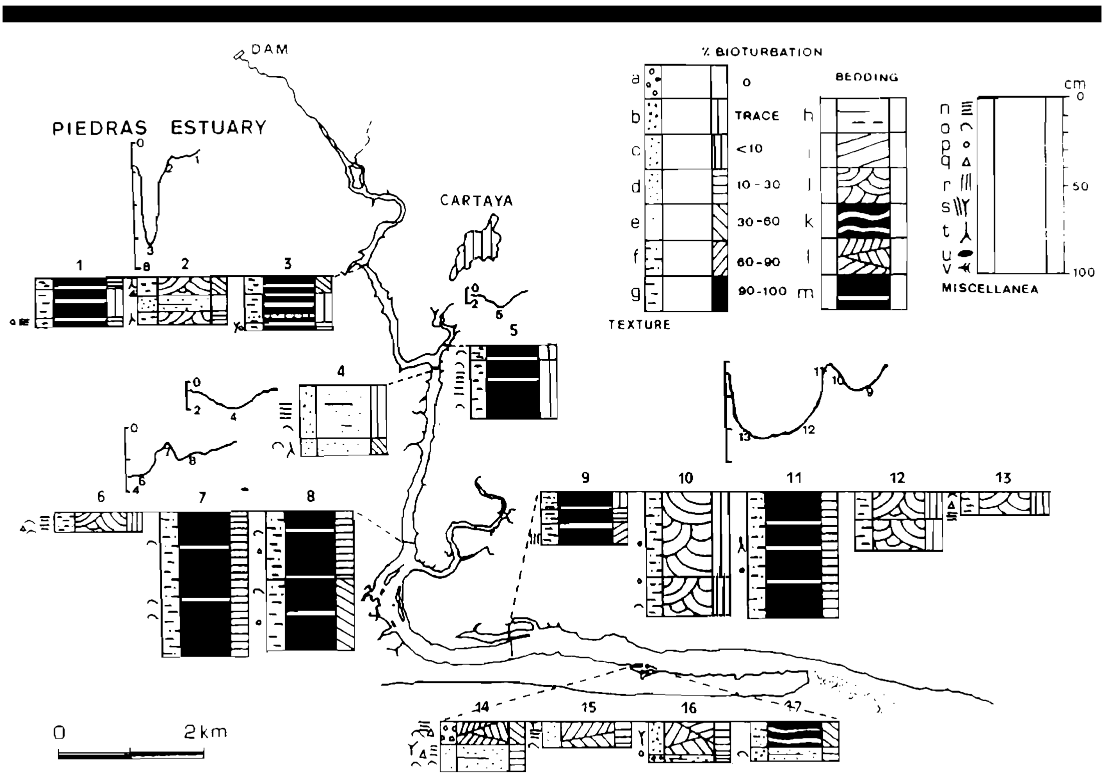

Figure 5. Transverse profiles of the Piedras River main channel from fathometer profiles. Some selected core logs are also given. (a) Very coarse sand. (b) Coarse sand. (c) Medium sand. (d) Fine sand. (e) Very fine sand. (f) Silt. (g) Shale. (h) Horizontal lamination. (i) Cross-lamination. (j) Ripple lamination. (k) Wavy lamination. (l) Ripples-megaripples. (m) Laminated muds. (n) Shell accumulations. (o) Scattered shells. (p) Sand grains. (q) Scattered pebbles. (r) Intense bioturbation. (s) Bioturbation galleries. (t) Roots. (u) Shale clasts. (v) Plant debris. Subtidal channel facies: 3, 4, 5, 6, 8, 9, 12, 13. Active channel margin facies: 1, 2, 7, 10. Salt marsh facies: 11. Spit facies: 14, 15, 16. Spit-channel transition facies: 17.

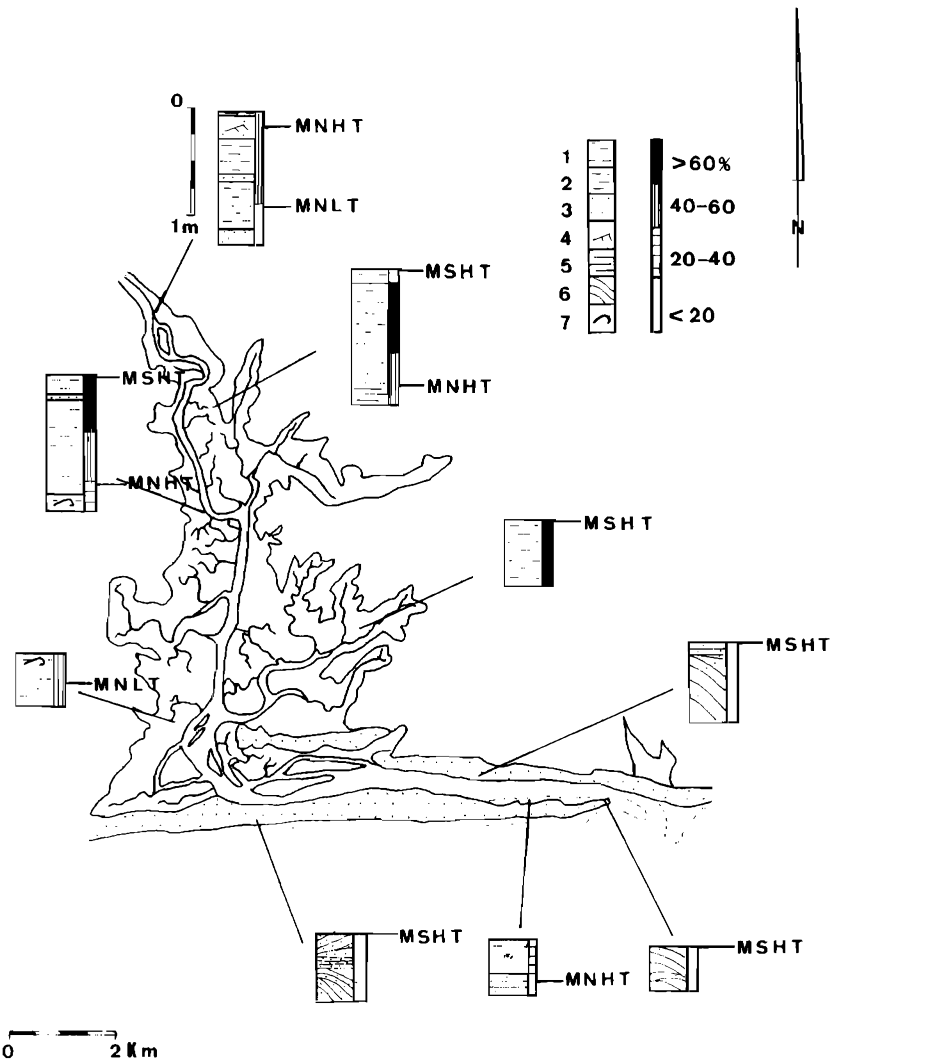

Figure 6. Sedimentary sequences distinguished at the Piedras River mouth. (1) Mud. (2) Muddy sand. (3) Fine sand. (4) Ripple. (5) Parallel lamination. (6) Cross-bedding. (7) Lag deposits. Percentages refer to bioturbation content. MNHT: Mean neap high tide; MNLT: Mean neap low tide; MSHT: Mean spring high tide.

to the mouth and around the curve of the main channel, where a dynamic shadow zone is formed receiving the marine sedimentary supply (BORREGO *et al.*, 1990). The ichnofacies exhibited consists of burrowing and bioerosion caused by plants, annelids and crustacea.

The description and interpretation of sedimentological characteristics of an estuary can be presented in different ways. We have carried out this study by characterising the main subenvironments and sequences. Four tidal subenvironments are delimited which coincide with the main geomorphic units. Subenvironments are defined in relation to tidal critical levels, as shown in Figure 4.

Characteritics of the sequence of subenvironments distinguished along the Piedras River mouth is as follows (Figures 5 and 6):

(a) Channel-Margin Subenvironment

Channel margins are unvegetated because rapidly alternating submergence and emergence in-

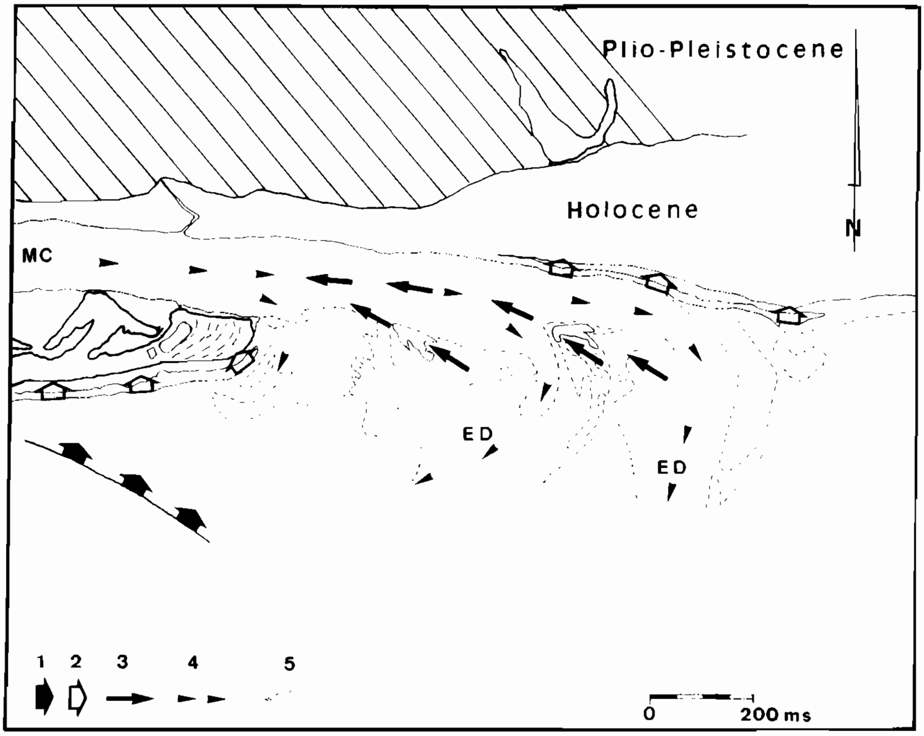

Figure 7. Hydrodynamic setting along the spit. (1) Sense of dominant waves approach. (2) Sense of runnels accretion. (3) Flood tidal currents. (4) Ebb tidal currents. (5) Berme. (MC) Main channel. (ED) Ebb tidal deltas.

hibits colonization by plants. The margins are actived by flood and ebb-tidal currents. The sediment is sandy lutite deposited in flat-lying beds with burrowing by crustacea and annelids.

(b) Salt Marsh Subenvironment

The alternating conditions of exposure and submersion allow colonization by halophytes, with *Spartina* sp and *Salicornia* sp dominant. The sediment consists of silty muds in flat-lying beds that are deformed by the action of plant roots. There is also scattered crustacean burrowing. This facies is more oxidized than the channel margin. The salt marsh sectors are more extensive.

(c) Sterile Marsh Subenvironment (Similar to Salt Pans of Warmer, 1971)

This subenvironment comprises sectors that are exposed over long periods of time with a poor drainage. Consequently, salt acumulates due to evaporation. During extreme tides, additional marine water is introduced. Because processes and products are similar to those of a salt marsh, the sediments are also quite similar. They consists of silty muds, interlaminated with sandy silts that are supplied by the wind and trapped by the sheltering effect of the vegetation. When the wind blows on a thin layer of water some sediment can be reworked into undulating laminae. Some mud cracks are also found with this condition. This subenvironment is scarce in the overall environment. The term *sterile* is applied to this subenvironment because of the low biomass production.

(d) Fluvial Channel Subenvironment

Some fluvial bedforms record the recent conditions near the upper estuary: sandy megaripples and ripples covered by a thin film of mud as the result of tides.

(e) Spit Subenvironment

Since the end of the last century, spit progradation has restricted entry to the estuary. It results from the transformation of an earlier barrier island system (see below). At present, tidal deltas form close to the tidal inlets located among the former islands and they are often reworked forming curved spits (Figure 7).

(f) **Outer Beach Subenvironment**

On the seaward side of the spit a sandy beach has developed by wave action. Migrating ridge and runnell systems characterise the beach (DABRIO, 1982).

(g) **Attached Beach Subenvironment**

At the inner side of the spit a silty sand beach is formed subjacent to the Neogene-Quaternary slope. BORREGO and PENDÓN (1989b) point out that tidal waves are responsible for its development and modification. Some tide-critical levels are recorded. Algal mats and burrowing are found in the lower part of the intertidal zone. The sedimentary body is composed of silty sand horizons gently dipping towards the main channel. For this reason, the attached beach differs from the outer beach in terms of sediment texture as well as structural arrangement. There is no berme because the dynamics of ridge and runnel systems do not exist.

(h) **Sand Dunes Subenvironment**

A single dune belt is formed on the spit as a result of eolian reworking. FLOR (1990), who recently classified the littoral dunes from the Huelva coast, found these dunes to be incipient forms with a low sedimentation rate.

EVOLUTION OF DEPOSITIONAL ENVIRONMENT

The Piedras estuary can be subdivided into four sectors. Each one is characterized by its own process/product relationships.

(a) **Upper Estuary**

Fluvial products are abundant in this section. These fluvial sands and bedforms are overlain by a thin layer of red tidal mud. These fluvial bedforms result from seasonal events of the recent past. They are supplemented by minor effluents which flow over Neogene-Quaternary sandy sediments.

(b) **Lower Estuary**

This is the only sector dominated by tidal processes and products. The subenvironment sequences include active tidal channel margins, salt marsh, and sterile marsh.

(c) **Beach Subenvironment**

This zone is located on the outer face of the spit where the interaction of waves and tidal currents influence depositional processes. There is a sandy beach on the outer face of the spit and a silty sand beach attached to the Plio-Quaternary slope of the inner side of the spit.

(d) **Spit**

The combined actions of wind, littoral drift currents, waves, and tidal currents produce the appropriate conditions for accretion of the spit which restricts entry to the estuary. Subenvironments include: beach, tidal channels, tidal deltas, and curved spits; all of these features occur on the outer face of the spit. Curved spits are interfingered with mud tidal facies on the landward side of the spit. A single belt of sand dunes results from sand reworking on the spit.

The idealized sequences from the different subenvironments at the Piedras River mouth has been described. Recent history in this area indicates that these systems were not always as active as they are now. Recognition of this situation is important in developing a facies model. Until the early decades of the present century, the Piedras River mouth was an estuary protected by a series of barrier islands (Figure 2). At present, it is an estuarine lagoon (*sensu* DAVIES, 1980), closed by a long spit. The Piedras River mouth operates today as an estuarine lagoon because: (1) fluvial supply is both extremely low and seasonal; (2) the spit partially restricts entry/exit of currents to/from the estuary; (3) there is no significant mixing of fresh and salt water (this process is restricted to a small sector in the upper estuary); (4) the environment is cleary salty as evidenced by the presence of fauna-flora; and (5) sediment supply is almost exclusively from a marine provenance (BORREGO *et al.*, 1990).

The natural tendency of this system is toward infilling as suggeted by historical data such as loss of navigation conditions and areal growth of salt marsh facies. The infilling sequence of this estuarine lagoon can be subdivided in three stages (Figure 8):

Stage 1 (4000–3500 years BP). When the Flandrian transgression reached its maximum, the main river mouths along the Huelva coast were flooded. Consequently, littoral sediments which were supplied by littoral drift currents, from Plio-Pleistocene cliffs and the fluvial stream, regulated the littoral profiles. Drowning of older sandy shoals

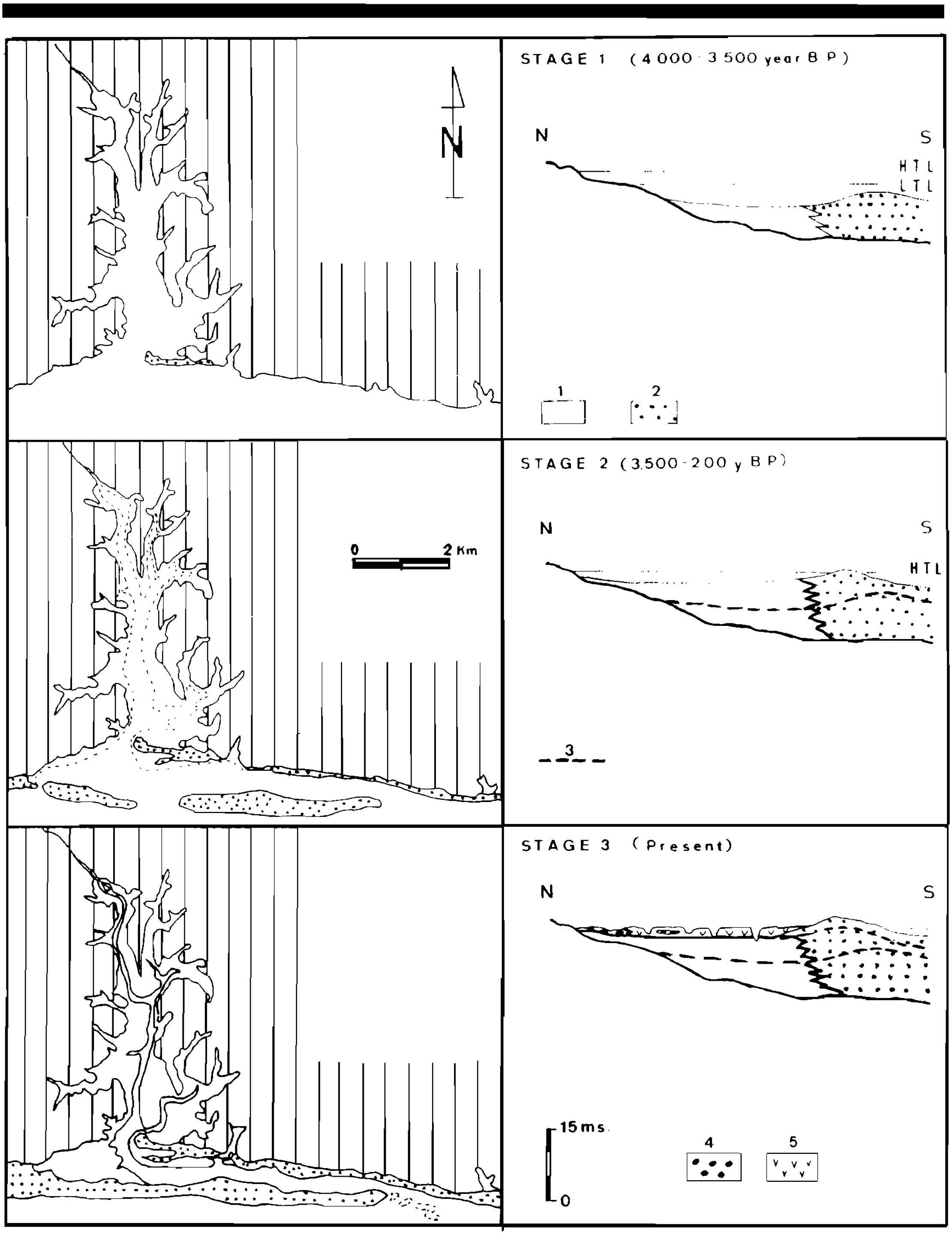

Figure 8. Infilling evolution of the Piedras River mouth. (1) Tidal muds. (2) Littoral sands. (3) Isochronic lines. (4) Fluvial sediments. (5) Salt marsh. (HTL) High tide level. (LTL) Lower tide level. See text for explanation.

at the more protected sectors began 3,500 years ago. Estuarine muds were deposited in the inner fluvial valley. Tides quickly redistributed the fluvial sediment supply without characteristic accumulation. The bottom of this valley is situated under the low tide level.

Stage 2 (3500–200 years BP). Littoral accretion continued and one barrier island chain was formed at the mouth, as well as some beachs attached to Plio-Pleistocene bluffs. An extensive mud flat, partially exposed during mean low tide, was formed in the inner estuary. A decrease in the redistribution power of fluvial sediment supply then took place as a consequence of excavation of the fluvial channel, though this effect is still powerful and does not allow the preservation of these sediments as well differentiated deposits.

Stage 3 (200 years BP–Present). Filling of inner estuarine zones produced a decreasing tidal prism as wave action increased with respect to ebb-tidal current activity. For this reason, the spit developed and grew. Dam construction since 1968 accelerated the natural tendency to infill the estuary. In this way, the spit accretion rate increased from 30 m yr^{-1} to 60 m yr^{-1} (Figure 9 and Table 2). Extensive salt marshes were developed at the inner estuary and deposited over the former estuarine muds. Both fluvial and tidal channels remained excavated. There was a significant decrease in redistribution power of fluvial sediment supply caused by tides. Finally, these fluvial sediments accumulated as well-differentiated deposits which are situated at the upper estuary, in both channel-fill and channel-margin sequences.

DISCUSSION AND CONCLUSIONS

When compared to other locations, three main aspects must be taken into account: (1) dynamic processes, (2) coastal morphology, and (3) peculiar features of depositional environments. The Huelva littoral zone works as a tide-dominated (mixed energy) coastline, where tidal currents come from east to west (flood) and from west to east (ebb). Accretion of Piedras Spit is eastward because the interaction of inner-estuary tidal currents with tidal currents flowing parallel to the coastline (outer currents) produces a dynamic shadow zone where sediment deposition takes place. This interaction between both inner and outer tidal currents is very important along the Huelva coastline.

The mesotidal regime of the Huelva coast is similar to that in the East Frisian Islands

Table 2. *Longitudinal growth of the Piedras Spit.*

Period	Long. Growth (m/year)	Artificial Constructions
1873–1956	30	Piedras Dam (1968)
1956–1973	32	Isla Cristina bank (1974)
1973–1980	60	Santo Antonio bank (1977)
1980–1984	40	Huelva bank (1979)
1984–1987	63	Fish ponds (1982/1985)

(FITZGERALD *et al.*, 1984) and along the Georgia coast (OERTEL, 1975, 1977). Nevertheless, waves are less energetic along Huelva coast than in these examples. In spite of these similarities, the morphology of the Piedras River mouth consists of an elongated spit with high accretion rate while along the Georgia coast and in the East Frisian Islands barrier islands systems are present. We have interpreted these similarities in hydrodynamic processes and different coastal settings because the Piedras River mouth has progressed from a barrier-island system to an elongated spit accretion, caused by a decrease of the tidal prism. Two main mechanisms have changed tidal prism: (1) infilling of the estuary and (2) dam construction.

The example of the Piedras River mouth differs from HAYES (1979) coastal morphology type for a mesotidal coast (short barriers with numerous inlets). For this reason we consider it necessary to analyse other variables besides wave energy and tidal range, as DAVIS and HAYES (1984) point out. The fundamental effect of a decreasing tidal prism is so pronounced, as described in our example, that a barrier island system passed into spit accretion. This mechanism causing barrier spits to elongate may be considered as a mixed model among those described by AUBREY and GAINES (1982). Littoral drift current and/or longshore currents produce a sediment supply which is reworked by tidal currents at the end of Piedras Spit to form tidal deltas. Refracted waves again rework linear bars from the ebb channel margin producing swash bars migrating toward the spit front (westward). In turn, spit growth generates tidal inlet migration eastward (Figure 7).

Depositional facies produced in the Piedras estuarine lagoon is the third aspect to compare. Eight depositional facies or subenvironments have been distinguished: inner facies (subtidal channel, active channel margin, salt marsh, sterile marsh and attached beach) and outer facies (spit, outer beach

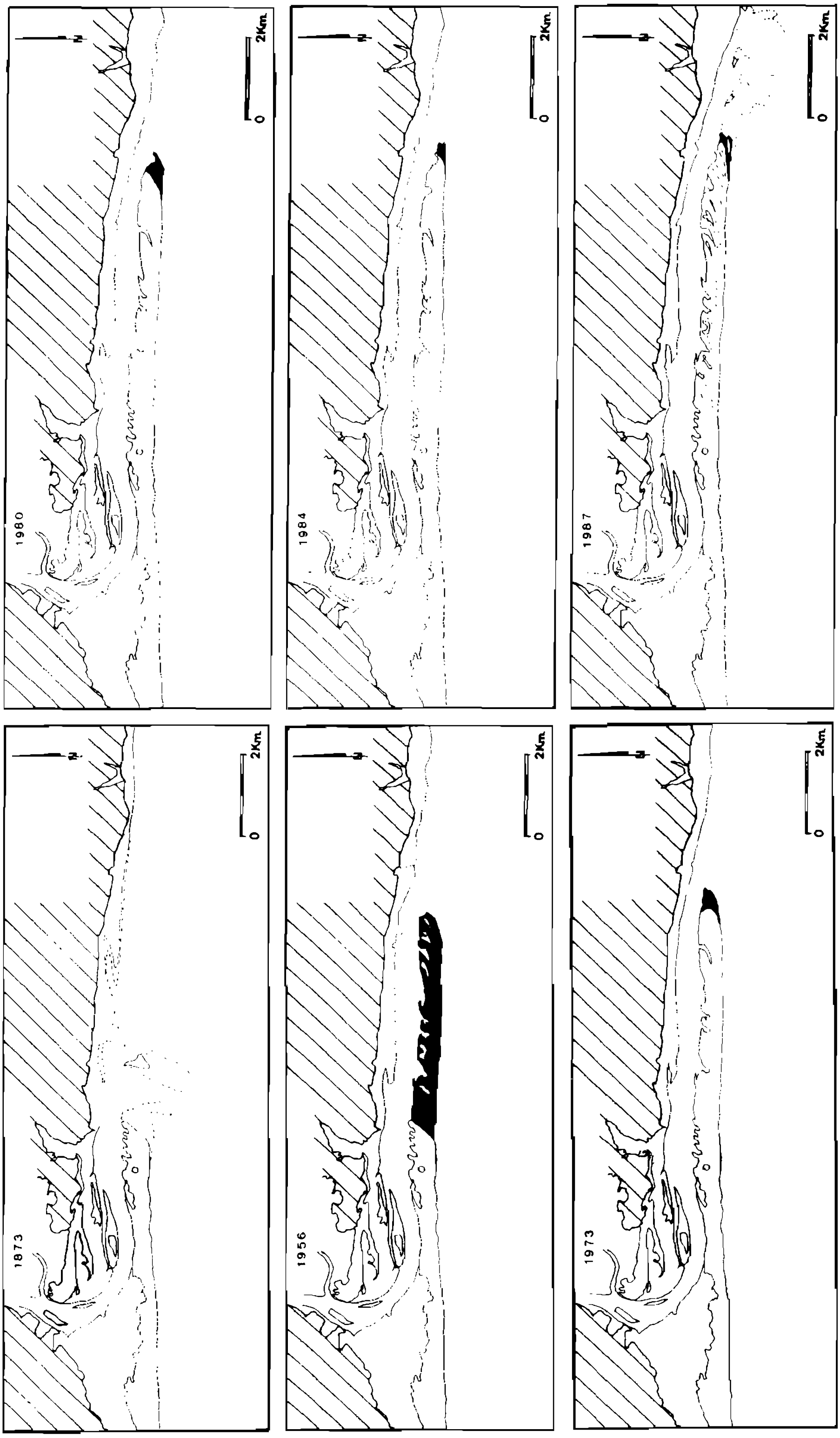

Figure 9. Piedras Spit elongation during the period 1873–1987. Accretion sectors from one stage to another are darkened.

and dunes). These facies show very similar depositional feautures to those described in other areas: *e.g.* along the Georgia coast (HOWARD and FREY, 1985; FREY and HOWARD, 1986), or New Jersey (ZEFF, 1988). These similarities result because depositional feautures are controlled by several factors, including indigenous fauna-flora, hydrodynamic setting, local sediment source and climatic conditions. Depositional products are similar in all of these examples due to the almost identical nature of controlling factors.

CONCLUSIONS

(1) The Huelva littoral zone (northern Gulf of Cadix) operates as a tide-dominated (mixed energy) coast with mesotidal range.
(2) Depositional facies or subenvironments of Piedras estuary are similar to those from other locations.
(3) Holocene filling of the Piedras estuarine lagoon consisted of a bay culmination by means of subtidal channel, active channel margin, salt marsh and sterile marsh facies. Three stages have been distinguished in Holocene evolution.
(4) The estuary mouth morphology evolved from barrier islands into an elongated spit due to a decrease in tidal prism. This example differs from other models proposed for locations with a similar hydrodynamic setting.

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□ RESUMEN □

La costa mesomareal de Huelva (S.W. España) es un ejemplo de costa dominada por las mareas de energia mixta. Este sector litoral está sometido a un clima templado-cálido. El régimen mareal es mesomareal, semidiurno y con una oscilación diaria leve. En la desembocadura del rio Piedras se conforma un *lagoon* estuarino, donde el aporte es dominantemente marino, siendo el fluvial de naturaleza estacional y muy escaso. Las facies estuarinas internas, de naturaleza fluvial y/o mareal (facies de canal, borde de canal, marisma salobre y marisma estéril), son muy similares a las descritas en otras localidades. Estas facies se asocian en la desembocadura a facies de flecha litoral y submedios asociados: playa y dunas.

Se distinguen tres estadios en la evolución reciente del *lagoon* estuarino del Piedras. Destaca la morfologia en la desembocadura del estuario, que evoluciona desde un sistema de islas barrera hacia la acreción de una flecha litoral alargada. Este cambio morfológico es consecuencia de la disminución del prisma mareal, que viene motivada por: 1) el relleno del estuario y 2) la construcción de una presa en el curso fluvial.