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Recent evolution of the river mouth intertidal zone at the Río San Pedro tidal channel (Cádiz Bay, SW Spain): controlling factors of geomorphologic and depositional changes

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ABSTRACT

Sedimentary and photogrammetric analysis of a sector of Cádiz Bay (SW Spain), including the intertidal zone on the left bank of the Río San Pedro tidal channel, were performed to understand its environmental evolution and the main factors that controled it. The study of this especially vulnerable environment has allowed to establish its depositional and morphological responses to the dynamic processes caused by recent environmental or climate changes. In the bank of the Río San Pedro tidal channel, there is a well-developed saltmarsh, which alternates with sandy beaches the data indicate erosional processes. The saltmarsh retreat rate was estimated in 0.65m/yr from 1977 to 2008. In this time-period, the tidal channel experienced a lateral displacement toward the SE of 1.24m/yr, and the beach width decreased from 50 to 21m. Three evolutionary stages were established: a youth stage, represented by a relatively high water energy beach environments; a maturity stage: represented by saltmarsh with deposition of mud and halophyte vegetation; a reactivation stage: represented by erosive features in the saltmarsh, such as tidal pools, tidal channel, etc. The geological location of Cádiz, close to the Eurasian–African plate boundary, account for its relatively high seismic and tsunami activity, that caused significant depositional changes in the area. Others important factors controlling the sedimentation are: first the tides, followed by the waves and the proximity to a sand source, such as the sandy mantle of La Algaida.

KEYWORDS **Cádiz Bay. Coastal environments. Saltmarsh. Recent evolution. Morphological changes.**

INTRODUCTION

Sedimentary and morphological variations in coastal environments are caused by depositional regime changes. In current saltmarsh and estuarine areas, these modifications are significant because of the vulnerability of these environments to climate and sea-level changes, as well as to anthropic actions, which result in significant environmental and morphological variations. These changes have prompted governments and local administrations to adopt corrective measures to counteract environmental deterioration and sustain economic activity (Long, 2000; Kolker *et al.*, 2010; Van Soelen *et al.*, 2010). To properly implement corrective actions and prevent problems from worsening, these interventions should be based on a solid understanding of the sedimentary processes that occur within the zone, as well as the possible depositional and morphological responses.

Through sedimentary and photogrammetric analysis of the intertidal zone of the Río San Pedro tidal channel, a sensitive and vulnerable sector of Cádiz Bay (SW Spain, Fig. 1), the environmental evolution during a period of 57 years has been studied, including the controlling factors and the morphological responses to the dynamic processes linked with the recent climate changes.

Cádiz Bay has been studied by several authors who have produced models of sedimentary and hydrodynamic interaction (Zazo *et al*., 1994; Dabrio *et al*., 1998, 2000; Lario *et al*., 2002a; Gutiérrez-Mas *et al*., 2009a and b). However, some aspects have not received sufficient consideration, such as the nature and layout of the deposits from the sedimentary environments, and their temporal evolution. Other interesting goal is to establish the factors controlling the dominant processes in each environment (hydrodynamic agents, depositional mechanisms, anthropic action, etc.) as well as the different observed changes and the general evolutionary trend.

On the bank of the Río San Pedro tidal channel, there is a well-developed saltmarsh, that alternates with protected sandy beaches (Fig. 2). The two environments exhibit different depositional features, consequence of the dominant hydrodynamic agents, essentially the tidal current, and small waves. While in the south sector, erosive processes are dominant, with sand deposit coming from the erosion of the substrate of La Algaida, in the north sector depositional processes dominate with clay sedimentation established by halophytic plants.

GEOLOGICAL SETTING AND HYDRODYNAMIC REGIME

The study area is located in the Cádiz Bay, in the Andalusian Atlantic Coast (SW Spain) (Fig. 1). From a geological perspective, Cádiz Bay is a tectonically controlled barrier-island system and features two main littoral sandy spits: one located at the northern end of the bay (Valdelagrana beach), oriented NNE to SSW, and the other located at the southwestern end (Cádiz-Sanctipetri), orientated NNW to SSE. The sandy spits border a lagoonal area. In the intertidal margin of this lagoon, there is an extensive system of muddy saltmarsh (Gutiérrez-Mas *et al*., 2009a) (Fig. 2B). During the Holocene, sedimentation was controlled by sea-level fluctuations, the tectonic structure and late tectonic readjustments of the Betic range, which has conditioned the depocentre location and isopach orientation (Gutiérrez-Mas *et al*., 2004). Following the Last Glacial Maximum, the Holocene transgression caused the coastline to retreat up to the Transgressive Maximum 6,500 to 6,000 years ago, which resulted in flooding of the current coastal environments. Recently, Alonso and Pages (2010) located the final of the Holocene transgression near 4,000yr BP. From 5,000 to 2,500yr BP, the climatic conditions changed to colder. Later, another colder period between 900 and 1,200yr BP generated a slight drop in relative sea level, as well as the progradation of coastal systems and the formation of the current sedimentary environments (Dabrio *et al*. 2000; Lario *et al*., 2002b; Gutiérrez-Mas, 2011).

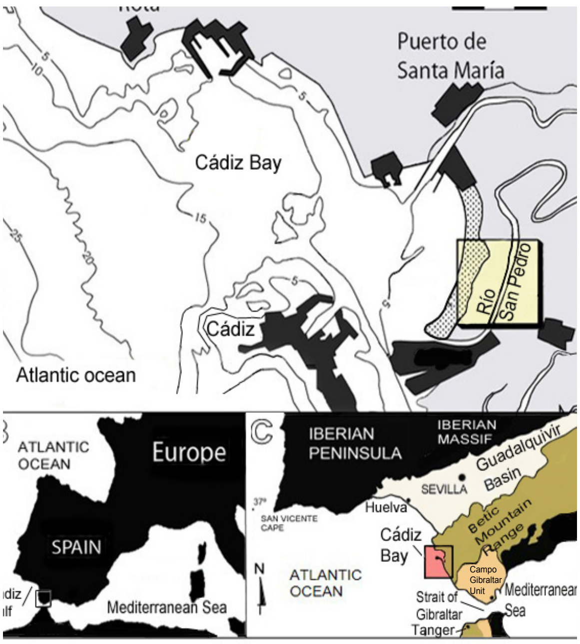


FIGURE 1. Geographical (A and B) and geological setting (C).

The hydrodynamic regime is controlled by a semidiurnal tide with a mean range of 2.2m and maximum of 3.7m (Álvarez *et al*., 2003). Although the zone is protected from storms, small waves act in combination with the tide. The direction of the waves depends on the dominant wind (W, WSW and E windy). The east wind is important, especially combined with spring tide, providing the highest wave height (0.1 to 0.2m) and short periods (1 to 3s).

METHODS

Field and laboratory work

Fieldwork was conducted during 2012 and 2013. It consisted of direct exploration of terrain, collection of sediments and fossils, and preparation of representative stratigraphic sections and geological profiles. Laboratory work consisted of textural analysis (through mechanical sieving with Udden-Wenworth scale), grain size distribution curve plotting and granulometric index calculation. Sand fraction components were observed by mean binocular magnifying glass and subsequent counting of terrigenous and biogenic grains.

Radiocarbon dating

Dating of interbedding bioclastic levels in the sandy mantle La Algaida was made using the ^{14}C method in three mollusc shell samples (*Glycymeris insubrica*, Brocchi, 1814). The analysis was carried out at the Dating Laboratory, Granada University (Spain). Calibration was performed using the CALIB 6.01 program and the

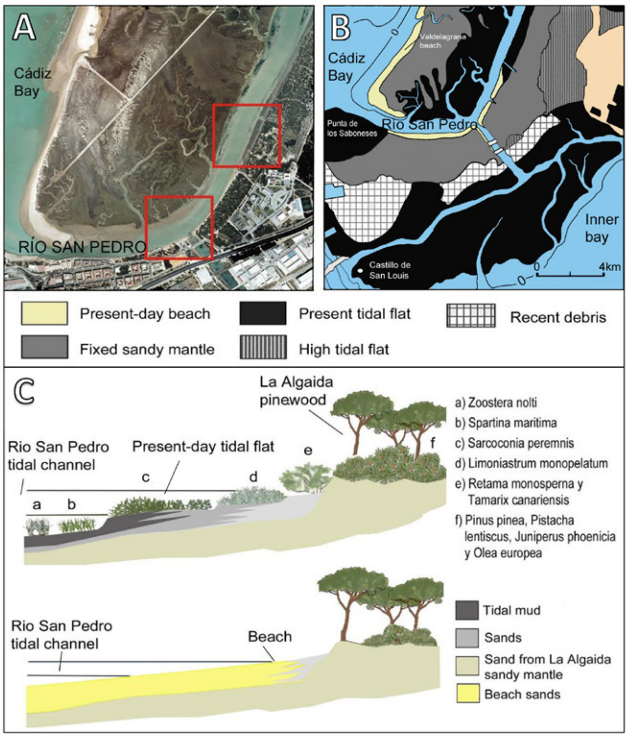


FIGURE 2. Environmental setting: A) Aerial image of the river mouth at the Río San Pedro Tidal Channel indicating two distinct sectors in this work. B) Geological map of the study zone. C) Environmental and sedimentary profiles, top: Nothern sector; bottom: Southern sector.

Marine09 curve (Reimer *et al.*, 2009). Marine reservoir effect (ΔR) values were provided by Monge and Matos (2009a and b), which were established for waters from southwest Portugal and areas of the Cádiz Gulf (ΔR=-160±80yr for samples from 1,000 to 2,000 years old, and ΔR=340±50yr for samples from 3,500 to 4,000 years old). In addition, several terrestrial seeds extracted from the sediments were dated by this method.

Photogrammetric analysis

Aerial orthophotography was examined to establish the temporal evolution of the sedimentary environments of the bank of the Río San Pedro tidal channel through the last 57 years. Images were obtained from the Environmental Information Net of Andalusia (REDIAM, 2012), regional government of Andalusia. Based on the geometric quality and spectral diversity criteria, 10 images, irregularly spaced in time, were selected (years 1956, 1977, 1984, 1997, 1998, 2001, 2004, 2006, 2008 and 2010). The positional mismatch correction was prepared through polynomial geometric transformation by the method of control points, using the photography from 2008 as the reference image because its better quality. Images were re-sampled at greater detail (0.5m). To establish morphological and environmental comparisons, cover and limit vectorisations were generated, followed by the overlapping of vectored elements on the reference image. Finally, the remote information was compared with field observations.

RESULTS

Sediments, stratigraphic succession and age of deposits

The sandy deposits consist of fine sands with cross stratification and intercalations of lenticular shelly beds, 0.10 to 0.4m thick, at various topographic heights. The biogenic remains consist of *G. insubrica* valves from 3 to 6cm in size. The sand is siliciclastic, with quartz (65–85%), carbonate (10–25%) and scarce feldspar (<10%). The carbonates are, especially bivalve mollusc shells. The muddy deposits consist of phyllosilicates, including illite (60%), chlorite (15%), kaolinite (10%), smectite (7%), and interlayered illite–smectite (<5%).

A representative and schematic stratigraphic section shows from base to top, the following sedimentary succession (Fig. 3):

i) Fine sands with cross stratification and bioclastic intercalations. Visible thickness: 1 to 2m.

ii) Bioclastic layer with *G. insubrica* shells. Thickness: 0.4 to 0.5m.

iii) Fine sands with cross stratification. Foraminifera are significant microfossils comprising 6.3% (benthic 4.5%, planktonic 1.4%) of the sand grains of this unit. Variable thickness: 2 to 3m.

iv) Bioclastic bed containing complete or fragmented valves of *G. insubrica* some shells are articulated, and 2 to 5cm in size. This deposit contains mollusc valves embedded in a bioclastic–gravelly-sandy matrix and its base is erosive. Other macrofossils present include *Murex brandaris* (Linnaeus, 1758), *Ocenebra erinacea* (Linnaeus, 1758) and *Strombus*. Echinoderms, bryozoans, ostracods, corals, microscopic fish bones and sponge spicules are also present. Thickness: 0.5 to 0.6m. This bed has provided a ^{14}C age of 1,910±60yr BP, a calibrated age of 1,637±119yr BP and a calendar age of 313±119yr AD.

v) Fine sands with cross-stratification and bioclastic intercalations. Variable thickness: 5 to 7m.

vi) Fine sands with scattered *G. insubrica* shells. Thickness: 2 to 3m.

vii) Bioclastic–gravelly-sand with *G. insubrica* shells. Thickness: 0.4m. This bed has provided a ^{14}C age of

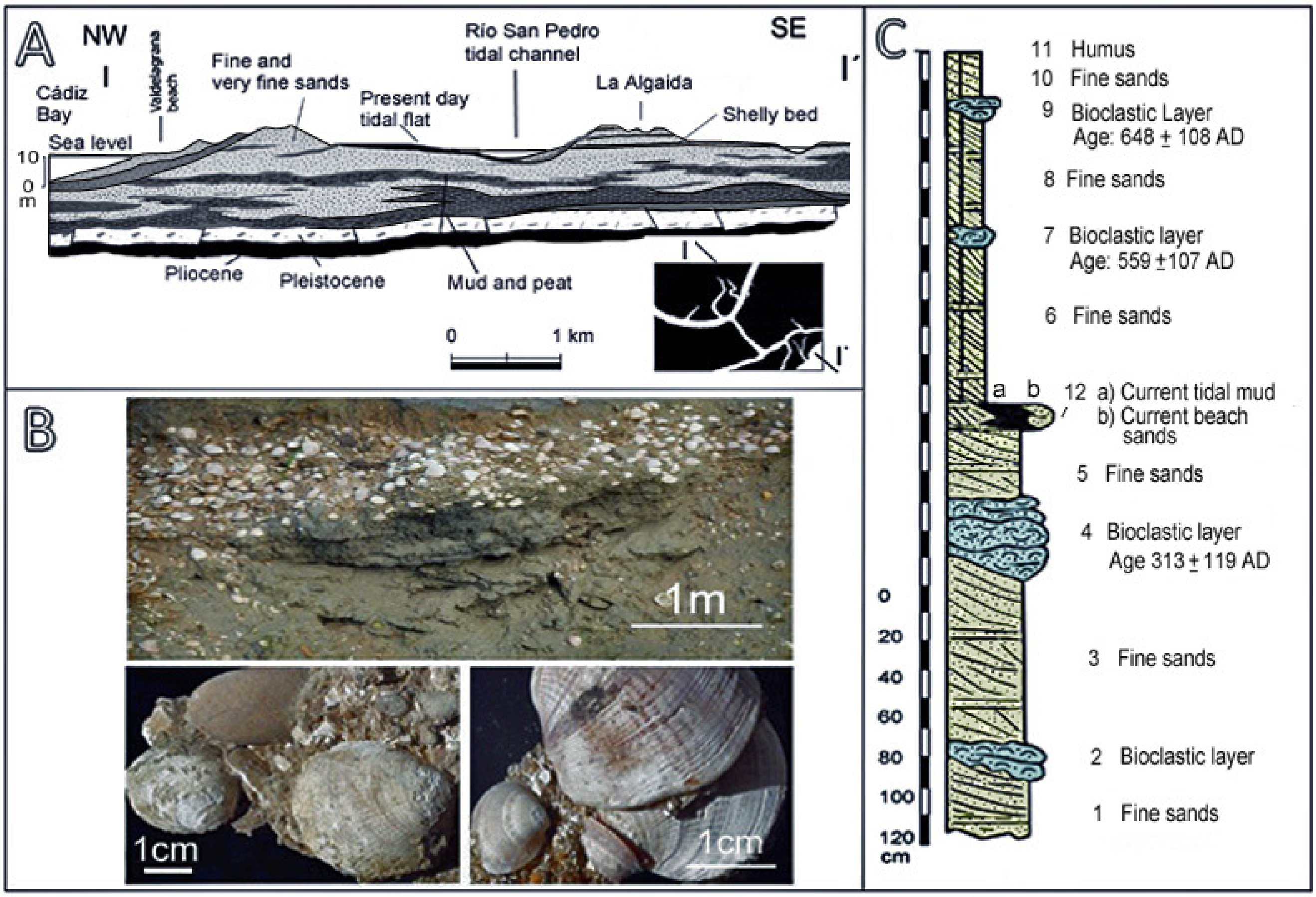


FIGURE 3. A) Schematic profile of the study area. B) Shell accumulation interbedded in La Algaida sandy mantle, and details of *Glycymeris insubrica* shells. C) General stratigraphic section of the study area and grain-size distribution from the main sedimentary units.

1,670±60yr BP, a calibrated age of 1,391±107yr BP and a calendar age of 559±107yr AD.

viii) Fine sands with scattered shells. Thickness: 1 to 2m.

ix) Bioclastic-sands with embedded *G. insubrica* shells. This shelly bed has provided a ^{14}C age of 1,590±60yr BP, a calibrated age of 1,202±108yr BP and a calendar age of 648±108yr AD.

x) Fine sands with interbedded *G. insubrica* shells (calendar age of 648±108yr AD). Thickness: 1 to 1.5m. Terrestrial seeds included inside in articulate valves of *G. insubrica* provided a calendar age later at 1950 AD.

xi) Modern humus layer covered by Mediterranean forest and scrub.

xii) a) Mud and sandy mud, with crustacean burrows. This muddy bed is representative of the modern saltmarsh on the Río San Pedro channel bank. Thickness: 0.5 to 0.8m. From its stratigraphic position, above unit 10, an age less than 648yr AD is deduced for this bed. b) Well-sorted sands with shell fragments, representative of the modern beach in the bank of this channel. Variable thickness.

Environmental and photogrammetric units

From sedimentary and photogrammetric analysis, two depositional environments are distinguished in the bank of the Río San Pedro tidal channel:

a) In the northern sector (Fig. 4), a well-developed saltmarsh (unit 12a), characterised by the presence of a mud bed 0.5 to 0.8m thick, occurs. This mud bed is covered by halophyte vegetation, which includes, from lower to higher tidal zones, *Spartina maritime* (Curtis, 1787), *Zostera noltii* (Hornemann, 1832), *Sarcocornia fruticosa* (Scott, 1977) and *Sarcocornia perennis* (Scott, 1977). In the zone only flooded by high spring tides, *Halimione portulacoides* (Aellen, 1938) is present. Landward, the saltmarsh ends with an escarpment, which is covered by both Mediterranean scrub and halophyte vegetation.

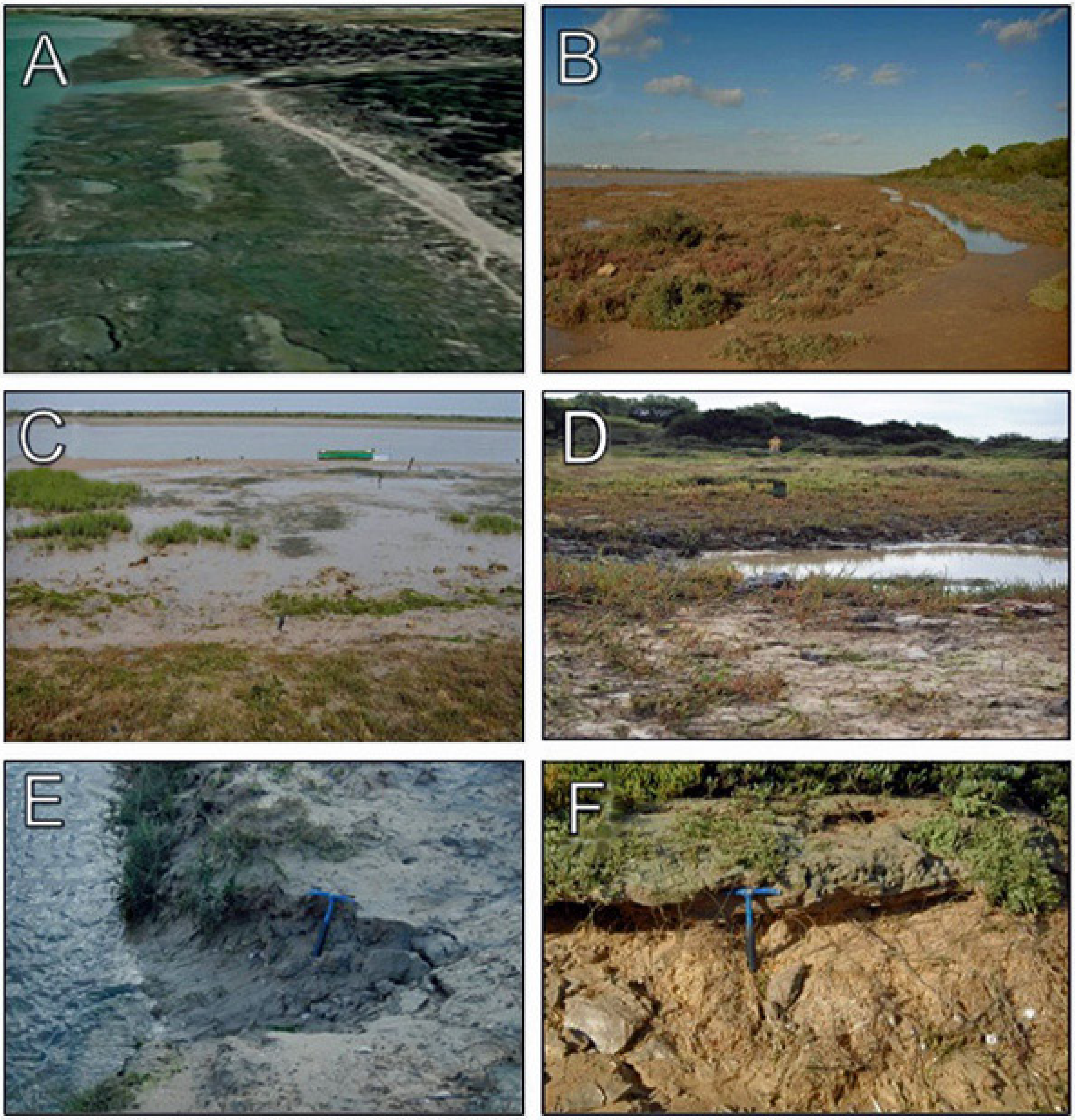


FIGURE 4. Images of the northern sector of the study zone: A) Aerial view of the zone. B) General view of the high saltmarsh. C) View of the low saltmarsh. D) The boundary between the high saltmarsh and the Mediterranean forest. E) Erosion of the tidal muddy layer at the edge of the saltmarsh. F) Muddy tidal bed overlying older sands.

This escarpement is less abrupt than that observed in the southern sector. The transition between the littoral environment and Mediterranean forest is gradual. In the high saltmarsh, there are shrubs, while in higher zones, beyond tidal influence, pinewood appears.

b) In the southern sector (Fig. 5), closer to the river mouth, there is a beach (unit 12b) Of fine sands over the sandy substrate of the La Algaida sands. Landward, the beach ends with a small cliff formed in La Algaida sands. The transition between this littoral environment and the Mediterranean pinewood is abrupt. This transition zone contains only isolated pines, and the Mediterranean scrub and typical vegetation of high saltmarsh are absent. The transition zone is environmentally deteriorated and occurs in the same zone where washover fan deposits are present.

Based on sedimentary and environmental criteria, five environmental units and photogrammetric covers have been characterized. These covers are separated by different color lines, and numerated from 1 to 5 (Fig. 6A).

FIGURE 5. Images of the southern sector of the study zone: A) General view of the beach in the left bank of the Río San Pedro tidal channel; notice the washover fans invading La Algaida pinewood. B) Berm formed on the limit between the foreshore and backshore. C) Río San Pedro beach at high tide. D) Washover fans in La Algaida pinewood, with some isolated pines. E) Erosive scarp formed in the high part of the beach. F) Erosive scarp and shells of *Glycymeris insubrica*.

i) *Sandy mantle*. This unit is a sandy formation of Late Holocene age and is representative of the sandy substrate of the La Algaida pinewood. The sandy substrate is essentially composed of fine and very fine sand (97.7%), gravel (0.7%) and silt and clay (1.2%). The sands have massive structure or tangential cross-lamination. These sands appear throughout the study area, from the lowest to the highest saltmarsh zones, and even in the high saltmarsh and Mediterranean vegetation. In the inner saltmarsh, where muddy deposits and halophyte vegetation are absent,

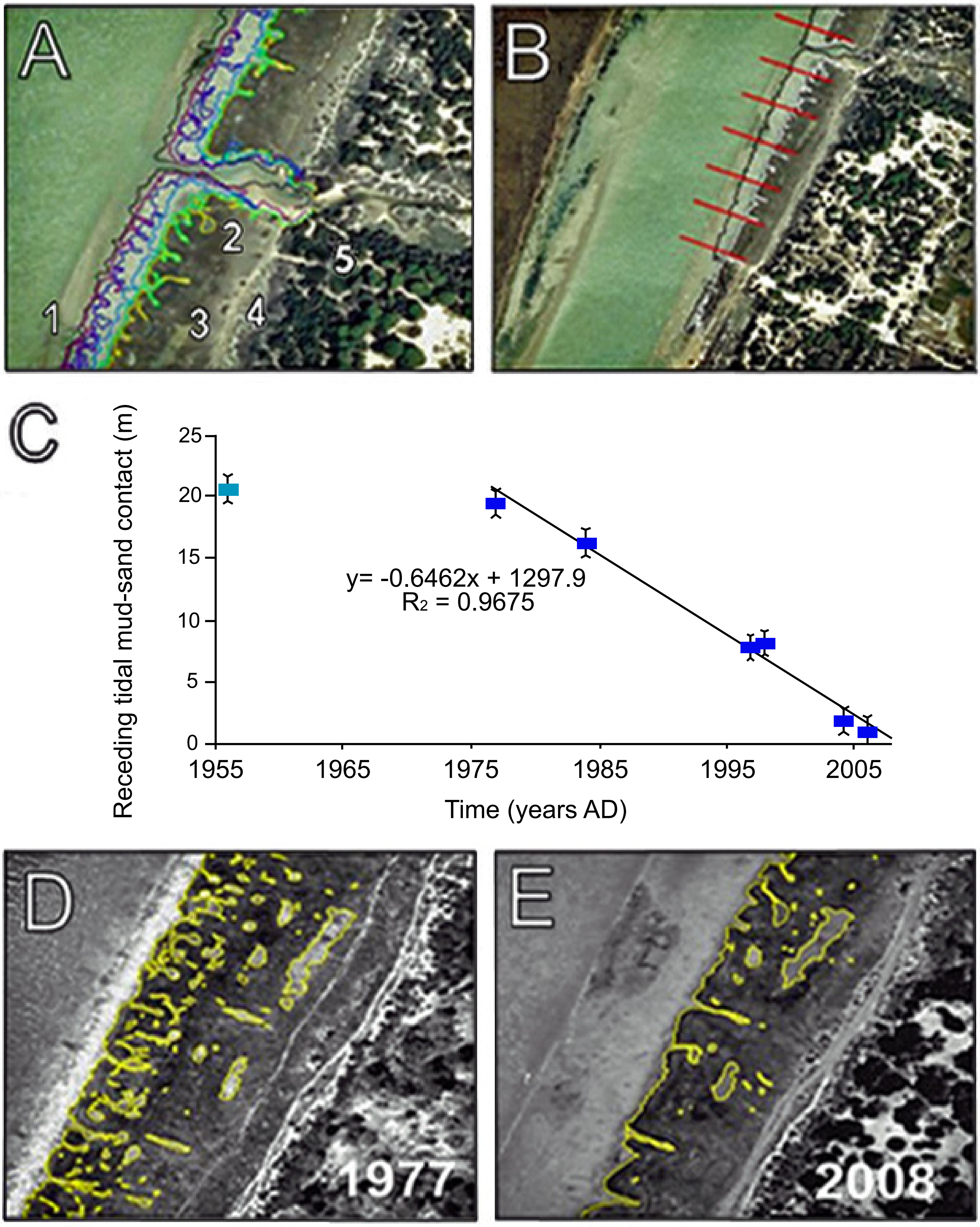


FIGURE 6. Northern sector: A) Orthophotography (year 2008), showing the sand-mud contact-line corresponding to different years (1956: black, 1977: purple, 1984: blue, 1998: dark green, 2004: light green and 2008: yelow). 1: Sandy mantle; 2: Tidal mud with bioturbation and halophyte vegetation; 3: Tidal pools and tidal creeks; 4: High saltmarsh; 5: Pinewood and Mediterranean vegetation. B) Transects used to measure saltmarsh retreat (year 1956: red, year 2008-reference image: cyan). C) Retreat of the saltmarsh edge from 1955 to 2008. D) Tidal pools and tidal creeks (yellow) in 1977. E) Tidal pools and tidal creeks (yellow) in 2008.

the sands are present and bioturbated by crustacea. These sands are reworked by active sedimentary processes, and used to build the present environments.

ii) *Muddy saltmarsh*. Silty–sandy-mud, bioturbated by crustacea, algae and halophyte vegetation, is present from the mean low tide edge to the mean flood tide edge. Landward, the sand content increases up to 95%, as evidenced by the grey shade or colour gradation in the photographic images (Fig. 4A, B and C).

iii) *Tidal pools and tidal creeks*. Tidal pools are ellipsoidal depressions of variable size, from 0.5 to 200m^2, excavated in the tidal mud in zones where halophyte vegetation is poor, in the saltmarsh in the northern portion of the study zone. They are generally flooded, even at ebb, and colonized by algae. During rainy weather, the pools collect fresh water. Tidal creeks are small tidal channels, elongated incisions (up to 0.5m deep), hierarchically connected where the tidal flow is concentrated.

iv) *High saltmarsh*. It is the highest part between spring and mean high tidal limits (Fig. 4B). It is composed of fine muddy sand and covered by halophyte vegetation, especially *Limoniastrum monopetalum* (Boiss, 1848) scrub. Sand content ranges from 88 to 95%, and gravel (primarily *G. insubrica* shell fragments) contributes 3 to 19%.

v) *Pinewood and Mediterranean vegetation*. This zone is the highest sector of the area and is never flooded, even during spring flood tides. The substrate consist of sands with abundant bivalve shells and root remains. The sands are stabilised by La Algaida pinewood and Mediterranean shrubbery (Fig. 4D).

Morphological and environmental variations

Several morphological and sedimentary variations through time are detected in the current tidal channel bank. In the northern sector, the photogrammetric analysis indicates a decrease in the area of the tidal mud bed and a retreat of the saltmarsh. The mean retreat rate between the years 1977 and 2008 was 0.65m/year (Fig. 6C). The dismantling of the upper mud bed has resulted in exhumation of the sandy substrate and widening of the channel mouths, where, fed from the exhumed sands, small tidal deltas have developed. The size and form of the tidal pools have persisted over at least the last 50 years. In the year 1977, the tidal pools occupied a surface of 1,648m^2 (6.7% of the saltmarsh), while in the year 2008, these pools occupied a surface of 582m^2 (3.6% of the saltmarsh) (Figs. 6D and E). The reduction of tidal pools is most likely linked to the saltmarsh retreat because the pools facilitate the erosion of the tidal mud and the halophyte vegetation of the saltmarsh.

In the southern sector the saltmarsh is not present. Instead, in the channel shore, there is a narrow sandy beach, which abuts directly on a pinewood or an erosive scarp 1 to 2.5m high in La Algaida sands, visible along the beach edge (Fig. 5C, D, E and F). The scarp appears clearly in the images of the years 1956 and 1977 (Fig. 7A and B), which show a mean landward retreat of 11m (0.5m/yr). In subsequent images (Fig. 7C, D and E), the scarp is partially affected by the construction of a breakwater and an artificial beach. Subsequently, there is a clear decrease in the width of the beach (0.5m/yr between 1984 and 2001) and an increment of the tip. These processes seems to have been intensified in recent years (in some places, up to 3m/yr between 2006 and 2010). Overall, the foreshore zone has decreased progressively from a width of 50m in 1977 to less than 21m at present, even disappearing next to the defence breakwater. Moreover, there has been a lateral displacement of the channel axis towards the SE (Fig. 8A). Between 1977 and 1998 this displacement was 24m (1.25m/yr), and from 1998 to 2008 14m (1.4m/yr). Concurrent with the scarp retreat, reduction of the foreshore width and displacement of the channel axis, the channel width in some areas narrowed by between 20 and 25m, due to the accretion of a sandy bar in the right bank of the channel (Fig. 8B).

Owing to the displacement of the tidal channel toward the SE and the scarp retreat, the Mediterranean forest zone retreated by 8.4m between 1956 and 1977 (a mean retreat rate of 0.4m/yr) and 8.7m between 1977 and 1984 (1.24m/yr). From 1984 to present, the process slowed markedly, with an average retreat of 5.1m (0.21m/yr). The areal loss of forest mass from 1956 to the present was 4,750m^2 along 215m of shoreline (mean retreat of 22m in 52 years) (Fig. 7F).

DISCUSSION

Origin of La Algaida sands and Glycymeris shell accumulations

Sandy sediments under La Algaida pinewood have textural and grain-size features similar to the modern littoral deposits, such as the coastal dunes and backshore deposits. These deposits are characterised by the predominance of fine sand (99.5%), absence of gravel and mud, and high sorting. La Algaida sands may be old coastal dunes, stabilised by the Mediterranean forest. The main difference between La Algaida sands and the modern coastal dunes is the high foraminiferal content of the former, which is similar to that found in neritic sediments (Gutiérrez-Mas *et al*., 2009a).

The origin of the *Glycymeris* shell accumulations intercalated within the sands (Fig. 3B) can be related to a

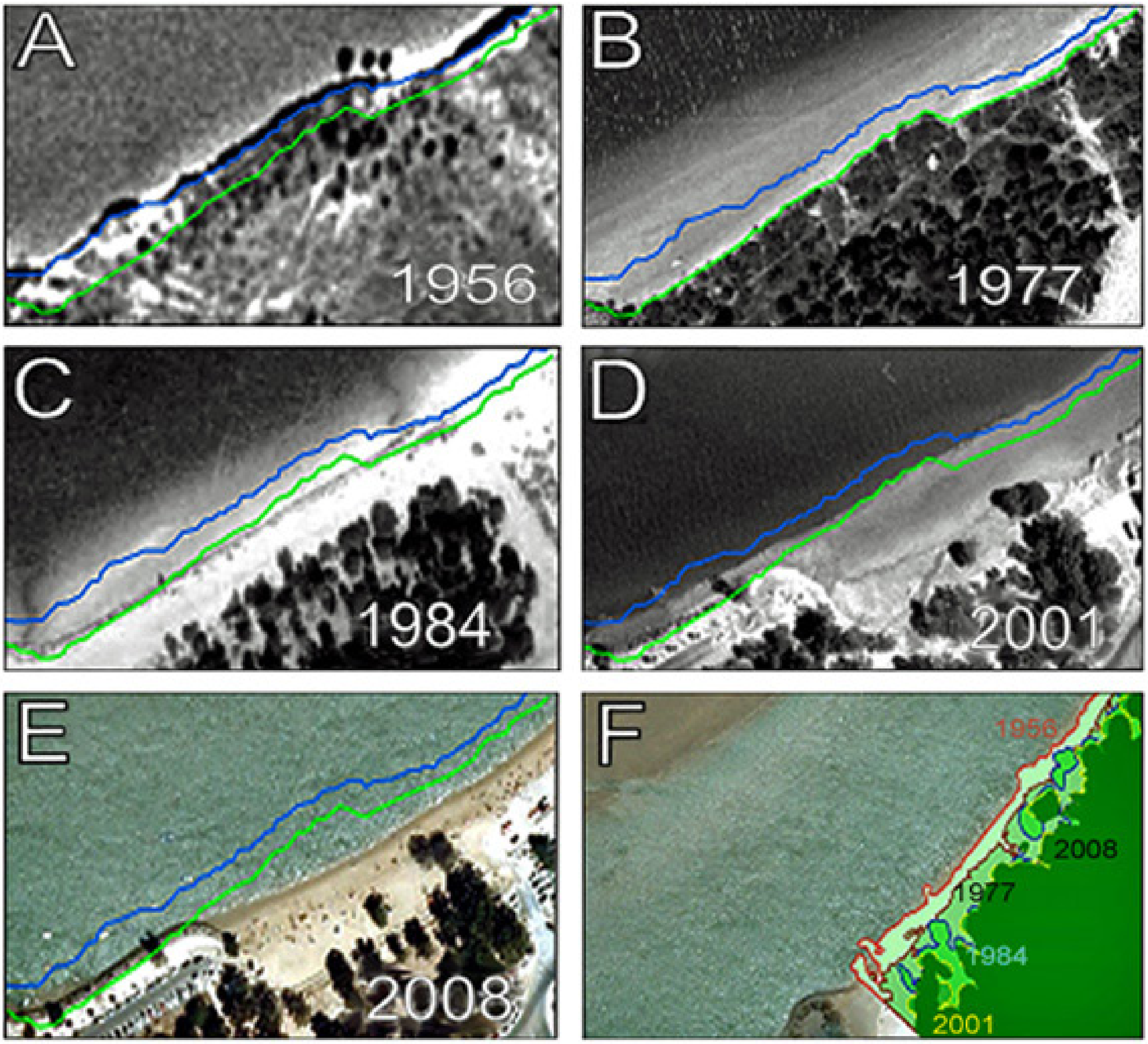


FIGURE 7. Temporal evolution of the beach in the left bank of the Río San Pedro tidal channel (Southern sector). Erosive scarp lines are included (blue: 1956, green: 1977): A) year 1956; B) year 1977; C) year 1984; D) year 2001; E) year 2008; F) retreat of the Mediterranean forest in: 1956, 1977, 1984, 2001 and 2008.

small relative sea-level rise followed by a slight sea-level fall, this would explain why these deposits are located in areas higher than the current sea-level. Successive variations in water temperature could also have caused the displacement of the *Glycymeris* habitat (Sivan *et al.*, 2006; Gutiérrez-Mas, 2011).

Another possible origin of the bioclastic accumulations could be a tsunami or a major storm action. In Cádiz Bay, several historic tsunamis have been documented (Campos, 1991; Ribeiro, 1995; Luque *et al.*, 2002a and b; Silva *et al.*, 2005). The main cause of this activity is the high seismicity in the SW margin of the Iberian Peninsula, due to its position close to the Eurasian–African plate boundary (Grimison and Chen, 1986), which has given rise to large earthquakes and tsunamis, such as the Lisbon earthquake and tsunami (1755 AD) (Zitellini *et al.*, 1999; Solares and Arroyo, 2004). Several littoral deposits are actually attributed to the action of this tsunami, for example, the washover fans in the nearby Valdelagrana beach (Borja *et al.* 1999; Dabrio *et al.*, 1998, 2000; Luque *et al.*, 2002a and b). In the Formosa barrier island in the Algarve (Portugal), great waves of this tsunami generated large washover fans and shelly deposits (Andrade, 1991; Andrade *et al.*, 2004). The high content of marine microfossils, such as benthic foraminifera (*Ammonia becarii, Cibicides lobatulus, Nonion pompiloides, Nonion boneanum, Cassidulina laevigat, Cassidulina obtuse)* and planktonic foraminifera

(*Globigerina aequilateralis, Globigerina bulloides, Globigerina apertura, Globigerina concinna, Globigerina quinqueloba, Globigerina sp.*), suggests that La Algaida sands were subjected to an intense remobilisation by great waves (Gutiérrez-Mas *et al.*, 2009b; Gutiérrez-Mas, 2011). The age of the lower shelly beds approximately coincides with some historically documented tsunamis. If the calendar age of the shelly deposits are considered, the lower shelly bed from La Algaida has an age (313+119AD) coincident with a historically documented earthquake and tsunami occurred between 350 and 395AD, which destroyed the old roman city of Bolonia (Baelo Claudia) near to Tarifa (Galbis, 1932, 1940). Respect to the higher shelly layers, their calendar age (648+108AD), is near to several earthquakes and tsunamis ocurred in the SW of the Iberian Peninsula between VIII and X centuries (Galbis, 1932, 1940).

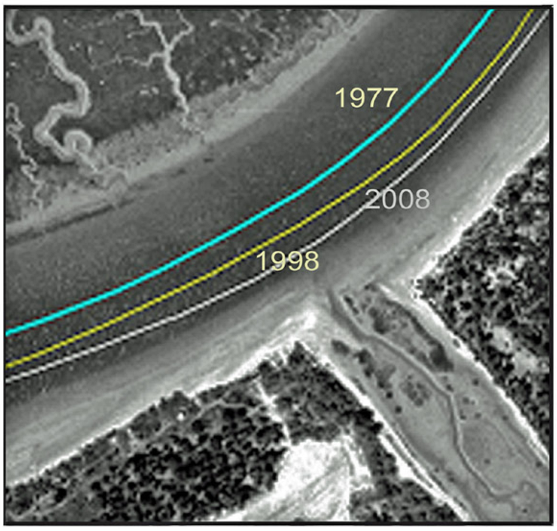
Depositional environments and sedimentary processes

i) In the northern sector, the depositional regime is dominated by mud supply and is characterised by the presence of a well-developed saltmarsh (Fig. 4F). The deposition of mud from suspension and flocculation cause the aggradation of the saltmarsh and facilitates the development of the typical halophyte vegetation of the saltmarsh (Fig. 4B and C).

Erosional processes are also present in this sector, as is evident from the dismantling of a portion of the saltmarsh of the tidal muddy bed and the halophytic vegetation loss (Fig. 4E). The result is the disappearance of the muddy layer and the exhumation of the sandy substratum, which occurred between 1977 and 2008 (Fig 6C). Another erosive effect is the widening of small tidal creeks. The results indicate that tidal pools are relatively stable and their sizes and shapes have persisted over at least the last 50 years. Nevertheless, although changes have not been detected, these pools are a decisive factor in the recent evolution of the saltmarsh because, when the erosive front reaches the zone where they are located, the retreat speed of the tidal mud layer increases dramatically. The mean retreat rate of 0.65m/yr between 1977 and 2008 can be explained by this mechanism (Fig. 6D and E). However, between 1956 and 1977, the retreat was slower and, moreover, the saltmarsh area increased. This different retreat rate between the periods 1956–1977 and 1977–2008 could be atributed to the presence of the tidal pools. The slower saltmarsh retreat observed during 1956–1977 occurred in a period when the saltmarsh was more extensive and the tidal pools were less abundant in the external parts of the saltmarsh, retarding the erosion. When the erosive process reached the area where tidal pools were more abundant, the retreat speed increased considerably.

ii) In the southern sector, where erosion and sediment transport are the main processes, the depositional regime is dominated by accommodation. This environment supports a higher water energy level than the northern sector and is characterised by the presence of a sandy beach made of erodes La Algaida sands.

Between the years 1977 and 2008, the lateral migration of the Río San Pedro channel toward the SE occurred at a rate of 1.24m/yr (Fig. 8A). This migration was due to the erosion of the left bank of the tidal channel that produced erosive scarps in the high part of the beach (Fig. 5C, E and F), tidal penetration over the pinewood (washovers) (Fig. 5D and F) and loss of forest mass (Fig. 7F). The lateral migration of the tidal channel is attributed to the channel



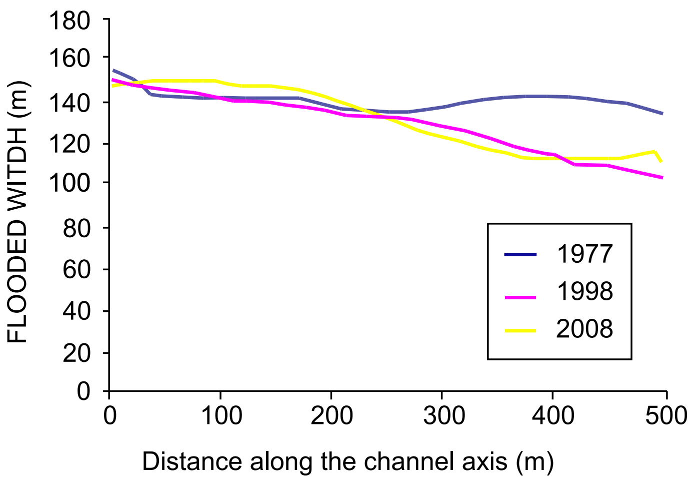


FIGURE 8. Southern sector. A) Displacement of the tidal channel axis in: 1977 (blue), 1998 (yellow) and 2008 (white), B) Temporal-spatial evolution of the channel width (mesured from the west).

curvature and the consequent bidirectional erosive action of the tide (Davis and Dalrymple, 2012). The relatively high water energy of this environment and the presence of an important sand source, La Algaida sandy mantle, are the main factors controlling the existence of this beach on the left bank of Río San Pedro.

In the images that were taken in 1956 and 1977 (Fig. 7A and B), before the human intervention in the river mouth zone, a marked erosive scarp is observed, which experienced a mean landward retreat of 11m (0.5m/yr) during this period. The sand eroded from La Algaida sandy mantle was redistributed in the intertidal zone, which had an average width of 49.5m in 1977. In 1984, a defensive breakwater was built (Fig. 7C) that partially stopped the supply of sand to the beach from La Algaida sandy mantle, which would explain the decrease of the beach width. From 2006 to 2010, the decrease of the beach width continued (Fig. 7D and E). One consequence of the beach retreat was the loss of forest mass, caused by the grater tidal landward penetration (Fig. 7F), as explained above.

Evolutionary stages

If the environmental and depositional changes are considered, several evolutionary stages can be described in the Río San Pedro tidal channel (Fig. 9):

i) *Youth stage*. The youth stage is represented by the beach environments present along the shore of Río San Pedro in the southern sector of the study zone (Fig. 9A). Although the waves are not high, the environment supports a relatively high water energy level, enough to prevent the deposition of the fine sediments in suspension. The only sediments in this area are sands sourced from the erosion of La Algaida sandy mantle (Unit 5). Erosion activity occurs through the combined action of the tide and small waves, which produce a saw effect that effectively erodes the sandy scarp present in the high zone of the beach. The sand extracted from La Algaida sandy mantle is later deposited on the current beach, which is continuously renewed. In the southern sector, aerial images and seed ages, indicate that the erosive scarp was present in the year 1956, showing that the processes of tidal channel displacement and erosion of the left bank started before that date. The mix of elements of different ages (*G. insubrica* age: 648±108yr AD; seeds age: later than 1950 AD) indicate sediment remobilization, consequence of an intensive erosive action.

ii) *Maturity stage*. The maturity stage is represented by the current saltmarsh located in the north of the study zone (Fig. 9B). The progressive retreat of the beach and coastal pinewood increases the area flooded by tides. The limit of the landwards penetration of the tide is controlled by the maximum local tidal range (3.7m) and, more specifically,

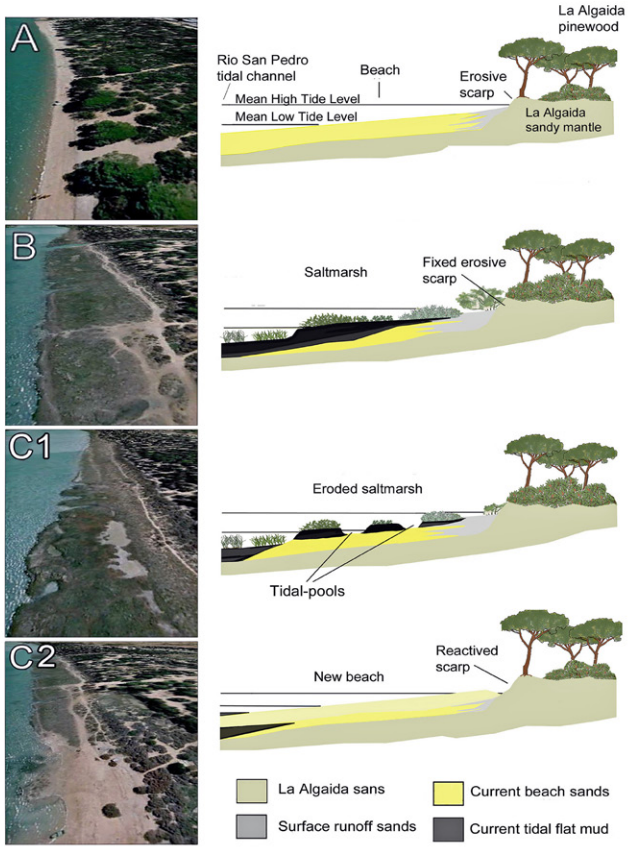


FIGURE 9. Main stages of the environmental and sedimentological evolution: A) Youth stage. B) Maturity stage. C) Reactivation stage. C1: Initial reactivation, C2: Advanced reactivation.

the topographic height reached by the sea during the spring tides in the present eustatic conditions. Additionally, the sandy nature of the substrate facilitates the erosion of the scarp located in the high part of the beach, resulting in coastal pinewood retreat.

When the erosive action of tides and waves creates enough accommodation, the environmental energy decreases, and the erosive action is reduced. Under those conditions, the environment is homeostatically readjusted, resulting in a new depositional equilibrium, deposition of tidal mud from suspension and cessation of erosion. Subsequently, halophyte vegetation colonises the tidal mud, developing a saltmarsh.

The muddy saltmarsh is unconformably laying on La Algaida sands, whose youngest shelly bed is dated in 648±108AD. Therefore, the muddy bed is younger than the sands and older than, at least, 57 years.

iii) *Reactivation stage*. Although the northern saltmarsh is essentially controlled by deposition, it also displays erosive features that indicate energetic reactivation in the environment. These features include the presence of abundant tidal creeks and tidal pools, the dismantling of the tidal mud layer under the halophyte vegetation, saltmarsh retreat and the exhumation of the sandy substrate (Fig. 9C1). These features indicate a tangible energetic reactivation of the tidal environment and a significant decrease of its areal extent.

In zones experiencing intense reactivation, the saltmarsh could disappear, and, instead, a new beach similar to the one present in the southern sector of the study area might appear (Fig. 9C2). This reactivation process is controlled by the local maximum tidal range during spring tide (3.7m high), which limits the height and inland extension of the tidal flood. The erosion process can only progress if sea-level changes or human intervention affects local hydrodynamics.

Large tsunami waves also have the capacity to cause erosive reactivation in the littoral environments. These events develop their energy in coastal zones, producing important and durable depositional changes along coastlines. The depositional impact of the tsunami following the 1755 Lisbon earthquake can still be observed in the Formosa barrier-island system (Algarve), Huelva Estuary, Doñana marshes and Cádiz Bay (Dabrio *et al.*, 1998, 2000; Borja *et al.*, 1999; Luque *et al.*, 2002a and b; Andrade *et al.*, 2004; Morales *et al.*, 2008). The erosive features present in this environment could be caused by an oceanographic event such as the 1755 tsunami. These erosive morphologies were enough to allow a quicker action of the normal hydrodynamic agents on the zone.

Factors controlling the depositional regime and morphological evolution

The depositional regime and the sedimentary and morphologic evolution of the studied environments are controlled by several factors:

i) *Hydrodynamic regime*. This regime is essentially controlled by the tides, although the waves have an important erosive effect. The data indicate a progressive decrease of the saltmarsh width due to the combined action of the tidal flow, small waves, the displacement of the tidal channel toward the SE and retreat of the beach and forest mass.

ii) *Sediment source and depositional regime*. In the northern sector, the sediment supply essentially comes from tidal flows, that provide fine sediment in suspension. In this zone, sand contributions are small because the erosion processes are restricted to the saltmarsh. Additionally, sediments deposited at a low rate from suspension prevent the remobilisation of fine sediments and the growth of the mud bed. Another factor controlling the saltmarsh retreat is the small thickness of the mud bed, that facilitates the erosion and dismantling of the bed. Tidal pools and tidal creeks increase the erosion speed of the saltmarsh, while halophyte vegetation stabilises the deposits producing bioturbation, incorporating organic matter and altering the hydrodynamic regime.

In the southern sector, the depositional regime is dominated by accommodation. The sedimentary contributions come from older units, with La Algaida sandy mantle sourcing most of the sand to the modern beach. While the environment is dominated by erosion, sand contributions to the beach continue. If the energy decreases, the erosive processes also decrease, stopping the sand contribution to the current beach.

iii) *Other factors* can also control the evolution of the zone. For instance, climate changes and water temperature variations can cause habitat displacement and changes in the ecosystem. Small sea-level fluctuations can control sedimentary evolution. A slight sea-level rise and a subsequent sea-level fall in a colder periode could explain the topographic position of the high shelly deposits several meters above the current sea level.

Additionally, the geological location of the Cádiz Bay, close to the Eurasian–African plate boundary, accounts for the relatively high seismic activity in the Cádiz Gulf, as major earthquakes and tsunamis in the region suggest. Several deposits are attributed to tsunami action, including the shelly beds interspersed in La Algaida sandy mantle.

CONCLUSIONS

Sedimentary and photogrammetric analysis of the left bank of Río San Pedro tidal channel (Cádiz Bay, SW Spain) has established the factors that control the evolution of this especially vulnerable environment. The data indicate that erosional processes, that dismantles the mud bed that underlies the saltmarsh, results in the loss of halophyte vegetation and exhumation of the sandy substrate. The retreat rate of the saltmarsh was 0.65m/yr from 1977 to 2008. However, between 1956 and 1977, this rate was smaller and, locally, there was even an increase in mud deposits.

In the southern sector, the tidal channel experienced an important lateral displacement process towards the SE, with an average rate of 1.24m/yr between 1977 and 2008. The beach width has decreased progressively from 50m in 1977 to 21m presently, even disappearing along the defensive breakwater.

Three evolutionary stages have been established: a) a youth stage, represented by beach environments under a relatively high hydrodynamic regim, with the only sediments being the sands sourced from the sandy mantle of La Algaida; b) a maturity stage, represented by the saltmarsh, deposition of mud from suspension, and halophyte vegetation, both stages were development between 648±108AD and 1950–56AD; and c) a reactivation stage, represented by erosive features in the saltmarsh, such as tidal pools, tidal channel, etc., that indicate the reactivation of an energetic environment. by an oceanographic event such as the 1755 tsunami, that facilitated the action of the normal hydrodynamic agents.

Several factors control the sedimentation in Cádiz Bay: i) the hydrodynamic regime is dominated by the tides, and subsidiary waves; ii) its proximity to an important sand source, such as the sandy mantle of La Algaida; iii) the small thickness of the tidal mud bed, because of the low sedimentary rate; iv) the low contribution of suspended fine sediments and organic matter; v) the presence of tidal pools and tidal creeks, which facilitate erosion; vi) the bioturbation caused by animals, algae and halophyte vegetation, which deforms the sediments, stabilises the bottom, and alters the hydrodynamic regime; vii) the geological location of Cádiz Bay, close to the Eurasian–African plate boundary, that accounts for the relatively high seismic and tsunami activity.

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