Geomorphological and morpho-sedimentary features of a sand barrier in a tectonically asymmetrical estuary during the Late Holocene: La Algaida (SW Spain)

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A B S T R A C T

Analysis of a number of drill cores, geomorphic patterns, and radiocarbon assays on mollusk shells from La Algaida spit, in the estuary of the Guadalquivir River (SW Spain), has revealed the genesis and evolution of a sandy barrier located in a rather complex neo-tectonic setting: the geological boundary between the Alpine belt of the Baetic mountain ranges and the Hercynian massif. The development of this sandy barrier during the Late Holocene has been conditioned by the presence, on the eastern bank of the estuary, of a Plio-Pleistocene paleo-relief which forms part of a raised block in a set of reverse-fault systems with SW-NE alignment, the most conspicuous of which is that of the Lower Guadalquivir Fault (LFG). These systems have influenced the morpho-stratigraphic and geomorphological disposition of the Holocene sediments on both sides of the tectonic alignment. The evidence presented here indicates that La Algaida spit is part of this raised tectonic block. As signs of subsidence are negligible, the spit exhibits series of exposed progradation units which started to develop shortly after the spit itself emerged, in the form of a barrier island. By contrast, subsidence processes affecting the Doñana spit, on the western bank of the estuary, are clearly marked, as they were sustained and massive. This asymmetry explains the relatively meager thickness, 22 to 24 m, of the sedimentary formations constituting La Algaida. Deposits at this location began to accumulate in about 6000-5500 cal. BP, originally as part of extensive shoals lying on top of the Plio-Pleistocene paleo-relief. At present, the spit exhibits three exposed progradation units (PS). Punctuated by erosive discontinuities, these units, or phases, succeeded one another until the Roman period (PS1 and PS2); thereafter, a tombolo formed to connect the erstwhile barrier island with the mainland (PS3). The peculiar, tectonically conditioned, active asymmetry ─geomorphological as well as sedimentary─ in the Guadalquivir

estuary and its environs contradicts received geological understandings of the area, yet helps understand comparable transformations in other coastal areas of the planet.

Keywords:
Littoral geomorphology
Morpho-sedimentary infilling
Holocene
Guadalquivir estuary
South-west Spain

1. Introduction

The Holocene formations that shape the geography of present-day estuaries are extraordinary markers of the geodynamic processes that have been at work in coastal environments over the most recent thousands of years (Morales, 2022). Best known and most cited among these processes are those animated by rivers and the sea, which jointly impinge upon the geomorphological configuration of landscapes. Though less conspicuous in the literature, the processes derived from neo-tectonics affecting the same formations should not be neglected (Jackson, 2013), as such processes, including growth faults, have been shown to be significant contributors to subsidence and sedimentation (Dokka, 2011; Yeager et al., 2012). Neo-tectonics can be an important factor in the paleo-geography of an estuary, accounting for the extent to which it is filled in by sediments and explaining the location of depocenters, the markers of the local variations of sea level. It is important, too, in determining the geomorphological configuration that ensues in every phase of the process.

The Iberian side of the Gulf of Cádiz is punctuated by a number of estuaries. From west to east, the largest estuaries are those of the rivers Guadiana, Tinto-Odiel, Guadalquivir, Guadalete, and Barbate (Fig. 1). Of these five, the Guadalquivir estuary is by far the most extensive. In addition, it is distinct in that it lies in the area of transition between two very different geological domains: the Iberian massif and the Alpine belt of the Baetic mountain ranges, which is still active (González-Castillo et al., 2015). A rare case of morpho-structural asymmetry of this kind worldwide, the estuaries to the west of the Guadalquivir, pertaining to the rivers Tinto-Odiel and Guadiana, are part of the Iberian massif, whereas those lying further east, of the rivers Guadalete and Barbate, belong to the belt of the Baetic mountain ranges. Elsewhere on the planet, asymmetric domains of this kind are found on the Pacific coasts of America (Muhs et al., 1992; Ota and Yamaguchi, 2004) and in the Mediterranean basin (Vött, 2007; Mastronuzzi and Sansó, 2012), where neo-tectonic processes wield a powerful control over the morpho-stratigraphy and geomorphological configuration of transitional areas of this nature.

The Holocene formations in the lower Guadalquivir River Basin, namely an extensive marshland and two littoral spits, Doñana and La Algaida, have been studied in detail in terms of its geomorphological evolution (Zazo et al., 1994; Rodríguez-Ramírez et al., 1996; Rodríguez-Ramírez and Yáñez, 2008; Rodríguez-Ramírez et al., 2015), the sedimentary infilling (Lario et al., 2001, 2002; Pozo et al., 2010), and neo-tectonics (Salvany et al., 2011; Rodríguez-Ramírez et al., 2014). This multi-faceted and extensive research has focused essentially on the formations lying on the western bank of the estuary, that is, on the littoral spit of Doñana and the marshland. By contrast, the littoral spit of La Algaida, on the eastern bank of the estuary, has been given far less attention.

Although this spit has been argued for as the most likely location of the political center of the pre-Roman realm of Tartessus (Barbadillo-Delgado, 1951; Villarías-Robles and Rodríguez-Ramírez, 2019), fieldwork has to date resulted in no more than a chronological outline of its geomorphological formations (Rodríguez-Ramírez et al., 1996, 2016). This study worked on the assumption that the position of the La Algaida spit is homologous to that of the Doñana spit, and that the morpho-sedimentary and geomorphological configurations of the former have thus been conditioned by the same morpho-structural parameters as those constraining the latter.

Given these circumstances in the literature, the specific objectives of our study were: 1) to determine the conditions that resulted in the genesis and location of La Algaida spit in the Guadalquivir estuary in the course of the Late Holocene; 2) to analyze the geomorphological and morpho-sedimentary evolution of this spit; 3) to describe and interpreting its facies distribution; 4) to characterize the influence of marine and estuarine conditions on the spit based on its paleontological content; and 5) to establish a robust chronology in order to understand the different phases of evolution of this formation. In carrying out the study, we conceived of La Algaida as a distinct research case from that of the more studied Doñana spit, located on the western side of the estuary and in a neo-tectonic context of subsidence. Nevertheless, the case of La Algaida can be used as a model for research into comparable estuaries in tectonically asymmetrical settings elsewhere in the world.

2. Morpho-dynamic setting

The Guadalquivir Estuary, at the midpoint of the Gulf of Cádiz, in the Atlantic Ocean, spreads out across an area of 1,800 km^2 (Fig. 1). Because of its geo-biodiversity and cultural history, it is an environment that elicits considerable interest. Some 700 km^2 of the area is protected under the name "Espacio Natural de Doñana," which includes the renowned Doñana National Park, a UNESCOMAB Biosphere Reserve.

From a geomorphological standpoint, the Guadalquivir Estuary is flanked by the above-mentioned littoral spits, Doñana and La Algaida. The marshland behind them extends more than 80 km into the hinterland (Rodríguez-Ramírez et al., 2019). The Doñana spit, attached to the western bank of the estuary and oriented toward the SSE, is the largest coastal barrier in Spain; it is some 23 km long and 3.5 to 5.2 km wide, depending on the meridian. The Algaida spit, on the eastern bank of the estuary and oriented toward the NNE, is some 10 km long and 1.2 to 2.2 km wide. Both spits are largely covered by dune systems. Those spreading across the Doñana spit are particularly striking and active, to the extent that they only spare the most recent developments in the progradation of the spit in the form of successive littoral strands. The marshland behind the two spits features a number of levees and cheniers (Rodríguez-Ramírez and Yáñez, 2008), which are the byproduct of the intense fluvio-marine dynamics experienced by the estuary in the course of the Holocene. The sedimentary infilling of the estuary has been the work of the convergent rivers, chiefly the Guadalquivir advancing toward the ocean in the form of a large bird-foot delta in a low-energy environment.

At present, the hydrodynamic processes in the estuary are controlled by the fluvial regime, the tidal inflow, wave action, and drift currents. The Guadalquivir River is the axis of the largest fluvial network in SW Spain. The mean annual flow is 116.5 m^3/s (Confederación Hidrográfica del Guadalquivir, 2016), in the wintertime ordinarily rising to 5,000 m^3/s ─extraordinarily as much as 10,000 m^3/s─ before the large transformations in the river basin during the 20th century (Vanney, 1970). The average tidal range at the outlet of the river is 2 m, with a maximum of 3.86 m (Spanish Ministry of Fomento, 2005). Average wave height, generated by southwesterly winds, is 0.6 m, although occasional storm surges in the Atlantic may unleash highly destructive erosive processes on the seashores (Rodríguez-Ramírez et al., 2003). In addition, waves raised in succession may be part of longshore drift currents that result in net transport of sediments from W to E. This movement of marine sediments turns NE on the shores of Sanlúcar de Barrameda, thus conditioning the progradation of La Algaida spit (Fig. 1).

3. Tectonic setting

One of the distinguishing traits of the Guadalquivir estuary is its location in the area where the European and the African plates converge, making it an area of high tectonic activity (González Castillo et al., 2015) (Fig. 1). Ever since the Miocene, the lower Guadalquivir River Basin has been subject to a rather notable tectonic conditioning (Salvany et al., 2011). This conditioning has generated a specific morpho-sedimentary disposition throughout the Quaternary (Flores-Hurtado, 1993; Rodríguez-Ramírez et al., 2014). Newly continuous GPS data (2008–2013), gathered at the Topo-Iberia stations in the western Baetic mountain ranges, reveal a rather consistent westward motion of these ranges with respect to the relatively stable Iberian Massif foreland (González Castillo et al., 2015). These data have enabled researchers to recognize an area undergoing a contraction in the westernmost sector of the ranges. This contraction would have resulted in a deformation band affected mainly by folds, convergence toward the NW, and reverse faults that have been active at least since the Late Miocene. The most important of these faults is the Lower Guadalquivir River Fault (LGF) (Viguier, 1977; Armijo et al., 1977). Coupled with the mountain front of the Baetic ranges (Fig. 1B), this fault runs across the southernmost boundary of the Guadalquivir estuary. The line of convergence between the European and the African plates exhibits a dextral slip (Medialdea et al., 2009). In the Early–Middle Miocene, such a slip generated the radial arrangement of extensive allochthonous masses, known as "the Olistostrome Unit" (Torelli et al., 1997; Maldonado et al., 1999), in the Gulf of Cádiz, as well as in the Guadalquivir River Basin. The location of this formation on the Atlantic littoral of southern Iberia has been linked to the migration of the Alborán volcanic islet toward the west as a consequence of a formerly active subduction zone off the Mediterranean coast of Andalusia (Royden, 1993; Iribarren et al., 2007). Gutscher et al. proposed (2002) that this subduction is still active west of the Strait of Gibraltar.

North of the LGF, in the foreland of the Iberian Massif, where the Doñana spit and most of the marshland of the lower Guadalquivir River Basin extend, the area features a complex system of N-S oriented faults that are joined by subordinate E-W oriented faults (Viguier, 1977; Armijo et al., 1977). A set of additional, secondary alignments, oriented NW-SE and NE-SW, has been identified by other researchers (e.g., Flores-Hurtado, 1993; Salvany, 2004); these secondary alignments crisscross the northern block of the LGF-affected area. The same researchers also recognized a regional tilting of the basin toward the SSE, which bears strongly on the sedimentary and geomorphological pattern of the Holocene formations in the basin. The overall effect of this process of subsidence is the accumulation of increasingly massive depocenters as one moves toward the southernmost sector of the estuary and its vicinity. South of the LGF, in the mountain frontal areas, where La Algaida spit lies, recent geological structures and seismicity have resulted in moderate deformation from compressional stress, aligned roughly NW–SE to WNW–ESE (González Castillo et al., 2015).

4. Materials and methods

4.1. Geomorphology

We analyzed aerial photographs, generated by photogrammetric flights over Spain in 1956 and 1957 by U.S. planes, so as to reconstruct the general geomorphological features of the natural configuration of the lower Guadalquivir River Basin up to that date, before the large transformations in the area that took place over the following decades. We then analyzed in detail topographic data in a digital model from a Light Detection and Ranging (LIDAR) survey from 2018, in addition to the use of the program Global Mapper. Our aim was to gather precise geomorphological information on the different formations recognized in the 1956/7 photographs. We supplemented the analysis of these photographs and that of the 2018 LIDAR model with direct observations in the field.

4.2. Lithostratigraphy

In 2021, we drilled the spit deposit to obtain two cores, A1 and A2, for the purpose of accessing the sedimentary configuration and facies of the Holocene formations under study (Fig. 1). Core A1, to a depth of 27 m, was extracted at 36º51´42.85´´N and

6º18´38.47´´W, while core A2, to a depth of 29 m, was dug out at 36º52´27´´N and 6º17´28´´W (Fig. 1). In addition, we analyzed two other cores, A3 and A4, from a previous construction project that required geotechnics. Core A3, to a depth of 10 m, had been obtained at 36º52´57.34´´N and 6º16´56.79´´W, while core A4, to a depth of 14 m, had been extracted at 36º49´51.05´´N and 6º19´12.56´´. All four boreholes were drilled by a direct circulation rotary method, with continuous core sampling.

We identified the sedimentary facies and then described the morphology, geometry, and relationships of these facies to one another. The elevations in the facies refer to the mean sea level (msl) in the Gulf of Cádiz. We performed grain-size analyses using conventional sieving for particle sizes >2 mm and utilized a Malvern Mastersizes 2000 laser diffraction particle analyzer for smaller fractions, from 2 mm down to 2 µm. We then applied Shepard's sediment classification to grain-size results (Shepard, 1954) in order to describe sediment texture, including sand, silt, and clay fractions.

4.3. Paleontology

We used the general qualitative taxonomy applicable to malacofauna (Gofas et al., 2017) on sediment samples from the cores, 14 from A1 and 19 from A2. We washed the samples, around 12 cm^3 per sample, employing a 1 mm sieve. Although a large part of the remains thus retrieved turned out to be fragmented and worn out, we nevertheless sought to identify the malacofauna that were found to the species level as far as possible. Of note in the samples was also the relative abundance of other groups, including scaphopods, corals, and bryozoans.

We performed microfossil analyses on 21 sediment samples from A1 and 34 from A2. We weighed dried samples, wet-sieved them over a 63-μm mesh, and dried them in an oven at 40°C. We then dry-sieved the samples over a mesh (>125-μm) in order to study planktic and benthic foraminifera.

We used the presence of specific planktic foraminiferal species, which are commonly used as bio-stratigraphic markers, in order to date Pliocene sediments. For benthic foraminiferal analyses, we obtained sub-samples containing at least 300 benthic foraminifera by using a micro-splitter. In addition, we differentiated Pliocene from Holocene benthic foraminifera on the basis of shell preservation and presence or absence of Pliocene planktic foraminiferal biomarkers. Poorer shell preservation (i.e., yellowish and frosty shells) and presence of Pliocene planktic biomarkers was indicative of Pliocene fauna, whereas Holocene fauna was characterized by better shell preservation (i.e., glassy shells) and the absence of Pliocene planktic foraminiferal species. We also differentiated Holocene marine from Holocene estuarine fauna by the ecology of each benthic foraminiferal species. Marine species included miliolids, keeled *Elphidium* spp., *Ammonia beccarii*, *Asterigerinata* spp., *Cibicides* spp., *Cibicidoides* spp., *Rosalina* spp., and other marine species (Murray, 1991, 2006; Mendes et al., 2004). Estuarine species included *Ammonia tepida*, *Haynesina germanica* and unkeeled *Elphidium* spp. (Murray, 1991, 2006; Debenay, 1995, Blázquez and Usera, 2010; Pérez-Asensio and Aguirre, 2010; Pérez-Asensio and Rodríguez-Ramírez, 2020). Finally, we calculated benthic foraminiferal abundance (N/g) by totaling the number of benthic foraminifera per gram of dry sediment. We computed the planktic/benthic ratio (P/B) as the score of [P/(P+B)] x 100.

4.4. Dating

We obtained eight radiocarbon dates from mollusk shells at the Accium BioSciences Accelerator Mass Spectrometry Laboratory (Seattle, USA), in addition to the use of published radiocarbon data (Rodríguez-Ramírez et al., 1996) (Table 1). Shells were selected that showed minimal, or no, transportation, and which had been preserved as articulated valves in the sedimentary record. For calibration of the radiocarbon data, we relied on version 8.2 of the CALIB program (Stuiver & Reimer, 1993), in addition to the calibration dataset of Heaton et al. (2020). Uncertainties in the calibrated ages are expressed in Table 1 as 2σ errors. We made corrections for the reservoir effect by using the ΔR values recommended by Soares (2015). He suggests a ΔR value of −108 ± 31 14C yr for the late Holocene on the Andalusian coast of the Gulf of Cádiz, except for the years 4400–4000 14C yr BP, for which he recommends a ΔR value of +100 ± 100 14C yr.

5. Results

5.1. Geomorphology

Analysis of the 2018 LIDAR images, along with the 1956/7 aerial photographs, enabled us to define in detail the geomorphological configuration of the research area (Fig. 2). We discovered that La Algaida spit is made up of morpho-sedimentary systems showing a three-phase succession of progradation. The oldest system identified (PS1), covered by an aeolian mantle of scant morphology, acted as a barrier island, to which the subsequent systems of progradation (PS2 and PS3) adhered.

These three systems of progradation turned out to be marked out from one another by erosive discontinuities that left geomorphological traces in the development of the littoral strands. The strands of the PS1 system prograded successively toward the NE, surrounding the central area of the barrier island and causing this island to grow toward the S. The most recent system (PS3) made it possible for the island to connect with the mainland in the last phases of progradation by means of a tombolo, thereby transforming the island into a spit. The littoral strands of PS2 and PS3 exhibit a series of dunes, with a foredune morphology, that relate to the erstwhile shorelines. Toward the hinterland of the spit, these dunes evolve into parabolic dunes, reaching a maximum elevation of some 15 m. At present, the spit is surrounded by marshland on three sides away from the ocean; dynamically speaking, it is a relict formation.

5.2. Lithostratigraphy and paleontology in the cores

5.2.1. Pre-Holocene deposits

Below -15.5 m in core A1 and -18 m in core A2, we found sands, sandy silts, and yellow clayey silts (Fig. 3). These same facies were found below -8 m in core A4 and below -6 m in core A3. In core A1, we retrieved sandy silts consisting of 15-25% sand, 55-65% silts, and 15-18% clay, and ochre in color (10YR6/8). Interspersed in the silts were thin deposits of more sand, lithified by carbonate. At the top, were carbonated nodules, very dusty and edaphic in nature. There were abundant remains of malacofauna, mainly of Ostreidae and Pectinidae, rather reworked. At the point of contact with the overlying gray sands in the core, there was a concentrated layer of pebbles of various kinds (including carbonate and quartzite), some of which were large (10 x 5 cm), and showed clear signs of reworking and transportation. These facies included the planktic foraminiferal species *Globoconella puncticulata* and *Globorotalia margaritae*, suggesting an early Pliocene age between 4.52 and 3.81 Ma (Lourens et al., 2004; Pérez-Asensio et al., 2018). Also present in these facies, were poorly preserved benthic foraminiferal species, such as *Nonion faba* and *Ammonia beccarii*, typical of early Pliocene inner-middle shelf environments from the lower Guadalquivir River Basin (Murray, 1991, 2006; Pérez-Asensio et al., 2012). The relatively high P/B ratio values (~40% on average) (Fig. 3) are consistent with a fully marine early Pliocene inner-middle shelf setting.

In core A2, the clayey silts consisted of 5-10% sand, 70-75% silts, and 18-20% clay, and were ochre brown in color (7.5YR7/8). These silts reached a depth of -21,8 m, below which we found ochre (10YR6/8) sands (2-10% gravel, 45-70% sand, 10-35% silts, 10-15% clay), with lithified layers by carbonate in them. We identified no malacofauna in these sands, suggesting they may have been the product of a fluvial overflow.

The ochre clayey silts contained from 40 to 75% Pliocene faunal remains, consisting of early Pliocene planktic foraminiferal biomarkers (*G. puncticulata*, *G. margaritae*) and inner-middle shelf benthic foraminifera (*Nonion faba*, *Ammonia beccarii*) (Murray, 1991, 2006; Lourens et al., 2004; Pérez-Asensio et al., 2012, 2018). This finding, along with that of a very low occurrence of benthic foraminiferal (N/g) (Fig. 3), suggests that the sample was made up of reworked Pliocene fauna that had been transported to the core site by fluvial dynamics. The source of this transported early Pliocene fauna could be the sands farther down the core, which showed higher percentages of Pliocene fauna and higher N/g. The lower stratigraphic position of the ochre clayey silts below the Holocene facies indicates that these silts were deposited during the Pleistocene and that early Pliocene foraminifera were transported to the site in the process.

5.2.2. Gray sands facies

We encountered gray sand facies between approximately -9 m and -15.5 m in core A1, between -12 m and -18 m in core A2, and between -4 m and -8 m in core A4 (Fig. 3). In these facies, coarser layers alternated with finer ones. The coarser layers were characterized by their gray color (10YR7/1) and medium sands (5-10% gravel, 40-50% sand, 30-40% silts, 5–8% clay) that included carbonated dispersed pebbles of small size (maximum 2 x 1 cm) with quartzite. The finer, interspersed layers consisted of sandy silts of varying thickness, from 1 to 10 cm, and darker gray in color (10YR5/1). The silt component was appreciably larger: 3-5% gravel, 20-35% sand, 35-55% silts, 5–8% clay.

Dispersed within them we found remains of malacofauna, some showing clear signs of much reworking, while others were in good condition and far less reworked, especially in the darker gray-colored silty clays. We were able to recognize a number of various species, including *Ostrea* sp., *Corbula gibba*, *Cerastoderma* sp., *Chlamys* sp., *Tellina* sp., *Nassarius* sp., *Clathroscala cancellata*, *Turbonilla* sp., *Murex* sp., and *Turritela* sp., among fragments of corals and colonies of bryozoans.

In core A1, the foraminiferal data show an average P/B ratio of 7%, with an N/g of 35, and a composition of 74% marine fauna to 24% estuarine fauna (Fig. 3). Core A2 yielded an average P/B ratio of 18%, an N/g of 96, and a composition of 53% marine fauna and 43% estuarine fauna (Fig. 3). In both cores, coarser layers produced more marine fauna and lower N/g, whereas finer layers contained more estuarine fauna and higher N/g (Fig. 3).

Judging by the dates obtained for the samples from cores A1 and A2, these gray sand facies would date from c. 5500 to c. 3600 cal BP (Table 1). These facies are the first formations of the Quaternary to rest directly on the Plio-Pleistocene paleo-relief.

5.2.3. Yellow sands facies

The base of the yellow sands facies was found at -9 m in core A1, -12 m in core A2, and 2 m in core A4 (Fig. 3). They consisted of layers of coarse sands with abundant gravel that include interspersed packages of silty sands. The coarsest layers were comprised of rough, ochre yellowish-colored (10YR8/6) sands (20-30% gravel, 50-60% sand, 5-10% silts, 2-3% clay), with pebbles of various kinds, carbonated and quartzite, some of them as large as 6 x 8 cm in size. While in core A1 we discovered a larger concentration of gravel at a depth of -2 to -5 m, in core A2 we found a comparable concentration at a depth of -1 to -8 m. The interspersed layers of siltier sands had, in most cases, decimeter thicknesses, were light yellow in color (10YR8/3), and contained a rather high amount of silt, the total composition being 5-10% gravel, 30-40% sand, 35-45% silts, and 2-3% clay.

There were abundant remains of malacofauna, showing clear evidence of transportation and wear, as though they were no more than sedimentary debris. We were able to identify a number of species, most readily those with robust shells, better equipped to sustain wear. However, in the siltier layers we found remains that, though of smaller species, were better preserved. The species identified include *Glycimeris* sp., *Pecten* sp., *Chlamys* sp., *Petricola* sp., *Tellina* sp., *Corbula* sp., *Chamelea* sp., *Cerithium* sp., *Nassarius* sp., *Murex* sp., *Turritella* sp., *Clathroscala cancellata*, and scaphopods.

Foraminiferal data showed similar average values for marine (~70%) and estuarine (~30%) fauna in both cores, although the P/B ratio and N/g were lower in core A2 (Fig. 3). In both cores, the coarser and finer layers showed similar values for marine (~70-75%) and estuarine (~25-30%) fauna, as well as similar P/B ratios (~3-6%) (Fig. 3). However, the N/g was higher in the finer layers in both cores (Fig. 3).

These yellow sand facies would date from c. 3600-3000 cal BP in core A2 and from c. 3600-1700 cal BP in core A1 (Table 1). In core A4, these facies were generated by the most recent progradation.

5.2.4. Aeolian yellow sand facies

We discerned an initial *Aeolian yellow sand* segment, which extended to a depth of -1.5 m in cores A1 and A2, and to a depth of just -0.5 m in core A4. In this top segment, the facies were light yellow in color (10YR8/4) medium sands (78-82% sand, 10-15% silts, 2–5% clay), very well sorted and containing no fossils. In core A2, these sands transitioned to deeper layers through a 15 cm-thick layer of dark brown (5YR4/6) silty sands of an edaphic nature, which contained organic matter in abundance.

5.2.5. Clayey facies

In core A4, we found clayey facies from an elevation of +2 m down to a depth of -4 m, while in core A3, they ranged from the surface down to -6 m (Fig. 3). They were gray-greenish (10YR6/1) clayey silts (40–55% silt, 25–35% clay, 1-5% sand) with some rather meager, sandier deposits interspersed throughout. In core A4, these clayey silts appeared to separate the fine yellow sands from the gray sands. The malacofauna included mostly *Cerastoderma* sp., *Ostrea* sp., and *Tellina* sp., the latter in the sandier deposits. In core A3, these clayey sands rested directly on the Pliocene substructure, the malacofauna consisting mostly of *Cerastoderma* sp. and *Scobrucoloaria plana*, with concentrations of remains particularly abundant from -1 to -2 m.

6. Discussion

6.1. Pre-Holocene formations (>11.7 ka) and tectonics

The paleogeography of the research area has been strongly conditioned by the geological structures of the lower Guadalquivir River Basin (Fig. 1B and 4), where the Alpine belt of the Baetic mountain ranges meets the Hercynian massif of the Iberian Peninsula, and where the NW front of the Baetic ranges is still active. This front includes a deformation band affected by reverse faults (González-Castillo et al., 2015), such as the lower Guadalquivir River Fault (LGF) (Fig. 1B and 4). Such reverse faults mark the boundary between two very different domains: a raised block, south of the faults, and a sunken block, north of the faults.

Researchers have long assumed that the La Algaida spit, like the Doñana spit, formed part of the sunken block, north of the LGF (Rodríguez-Ramírez et al., 2014). However, the cores extracting sedimentation from La Algaida spit and its milieu, described above, showed a shallow Pre-Holocene substratum from the Plio-Pleistocene at depths below msl in the Gulf of Cádiz of -16 in A1, -18 in A2, -6 m in A3, and -8 m in A4, all of which pertain to the raised block (Fig. 4). None of these formations is nowadays visible above sea level in the immediate vicinity of the spit.

Generally speaking, these formations define a platform-like paleo-relief which rests upon Miocene formations located farther south and spreads out under the spit. As one moves toward the N or W—that is, toward the sunken block north of the LGF—this paleo-relief rapidly loses elevation. This is consistent with the findings from other cores drilled in terrains where deposits from the Holocene are remarkably large (Rodríguez-Ramírez et al., 2014) (Fig. 4). The analysis of three cores from points off the north and west of La Algaida spit, described in Salvany et al. (2011), revealed the presence of the Plio-Pleistocene formations at great depths, below massive deposits from the Late Pleistocene and the Holocene (Fig. 4C). Such a significant contrast in depth between the two series of cores, on and off the spit, dramatically highlights the prominence of the paleo-relief that lies under the spit. Underneath the spit, the paleo-relief is found at comparatively rather shallow depths.

A system of faults and alignments oriented NNE-SSW (IGME, 1988), shapes the orographic configuration of the eastern side of the Guadalquivir estuary, which includes prominent hills and valleys. The hills can be as high as 70 m, while the valleys were flooded by the ocean until a few centuries ago (Rodríguez-Ramírez et al., 2015), when they became the marshes that characterize the area today. The Pliocene paleo-relief that extends underneath would have been subject to the same system of alignments. In effect, both the LFG, along with other reverse faults with a similar SW-NE orientation (González-Castillo et al., 2015), and the array of NNE-SSW faults would have favored the formation of such a paleo-relief. The NNE-SSW faults would have moved slightly toward the north of the LGF, at the same time causing their own transit toward the sunken block, where the depocenter of the Holocene formations lies (Fig. 1B and 4A). This dynamic, in turn, would explain the odd meander that the Guadalquivir River traces near its mouth, turning northwards on a short detour, and thereafter head sharply south.

During periods of low sea level, such as the MIS2 Last Glacial Maximum (Dabrio et al., 2000), the subterranean paleo-relief would have stood high above sea level, like a hillock overlooking the eastern side of the Guadalquivir paleo-valley, subject to the regular action of the sea waves and the occasional flooding of transgressive events.

6.2. From shoal to barrier island (6000-5500 to 3600 cal BP)

Unlike the formations to the north of the LGF, in which Holocene sedimentation is remarkably thick (Salvany et al., 2011; Rodríguez-Ramírez et al., 2014), the eastern side of the Guadalquivir estuary, south of the fault, where La Algaida spit is located, contains relatively thin Holocene deposits, amounting to as little as 22 m in core A1 and 24 m in core A2 (Fig. 4). The difference between the two locations, north and south of the LGF, highlights the sedimentary asymmetry affecting the coastal formations of the Late Holocene in the area. Whether marshes or sandy barriers, their morphology and magnitude clearly depend on which side of the LGF these formations lie on (Fig. 4).

As the sea level rose over the course of the MIS1 transgression, the Guadalquivir River Valley became increasingly flooded by the ocean, while the Plio-Pleistocene relief was gradually submerged and thereby became subject to the intense erosion generated by the marine dynamic. Characterized by low bathymetry and located at the outlet of the river, this relief would have served as threshold and trap for the sedimentary package of the maritime transgression as this package moved progressively toward the east during the sustained sea-level rise. Both the incessant erosive retreat of the coastline and the high availability of sediments favored this process.

The earliest facies from the Holocene deposited on top of such a structural high ground from the Plio-Pleistocene are rather coarse. They include a bed of pebbles of a diverse nature dragged from surfacing formations in the vicinity, as if constituting a marine transgressive lag. At the present-day mouth and its coastal environs, there are considerable littoral outcrops of calcarenites from the Plio-Pleistocene, many of which exhibit the morphology of shore platform (Fig. 1), and which, over thousands of years, fed large amounts of coarse sediments to the Holocene formations. Judging by radiometric assays on samples collected from the earliest of these formations resting on the Plio-Pleistocene paleo-relief, this process would have initiated in the time span from 6000 to 5500 cal BP (Table 1) (Fig. 5a), or possibly some time earlier, during the phases that preceded the transgressive maximum established for the Gulf of Cádiz (Zazo et al., 2008; Rodríguez-Ramírez et al., 2015). Oceanic flooding of the paleo-relief would have taken place at the same time.

Following the coarse bed, various facies of gray sands and silts came to rest on the paleo-relief, accumulating over a period from about 5500 cal BP to about 3600 cal BP (Table

1). The malacofauna and foraminifera identified in the cores suggest a semiconfined, subtidal-intertidal milieu for the period, strongly indicative of an extensive shoal subject to river inputs while protected from the marine dynamics by means of a system of swash bars, the setting being an ebb tidal delta under strong influence of the swell (Fig. 5a, 6Aa and 6Ba). Within this semiconfined environment, the foraminiferal data show that less sheltered areas (core A1 site) (Fig. 3) had higher energy and received higher inputs of marine sediment than more sheltered areas (core A2 site). This is indicated by evidence including: (1) a lower P/B ratio, suggesting that less-resistant, delicate planktic foraminiferal shells were preferentially destroyed (Kucera, 2007; Pérez-Asensio et al., 2017; Pérez-Asensio, 2021); (2) lower N/g (i. e., more sediment supply); and (3) more abundant marine fauna in core A1 than in core A2 (Fig. 3).

While the siltiest deposits are indicative of phases of less energy affecting the environment, the sandiest, coarsest deposits would have been the work of events of higher energy, such as storm surges in wintertime, nowadays a frequent event in the Gulf of Cádiz (Rodríguez-Ramírez et al., 2003). This interpretation is supported by a higher number of marine benthic foraminiferal fauna and a lower N/g in the coarser layers, alongside a conversely higher number of estuarine benthic foraminiferal fauna and a higher N/g (Fig. 3) in the thinner layers. Dabrio et al. (2000), Lario et al. (2002), and Boski et al. (2008) independently argue that the time span 5500-3600 cal BP was also the primary phase of sedimentary accretion in the estuaries across the Gulf of Cádiz, when the most notable systems of littoral spits formed and started to prograde.

The yellow sand facies that followed this period are consistent with a foreshore-backshore environment that was more exposed to the open sea, as indicated by the high abundance of marine benthic foraminifera (~70%) found in cores A1 and A2. Such facies would have been the product of a system of swash bars marking out the sea front of the ebb tidal delta, and thus subject to rather intense swell dynamics (Fig. 5a, 5b, 6Ba and 6Bb). Impelled by the longshore drift current, these swash bars would have migrated progressively toward the inner side of the estuary, where they would stabilize as extensive shoals and eventually surface to become littoral strands. The outcome of such a development, that is the formation of La Algaida as a barrier island, would date to the year 3600 cal BP or thereabouts (Table 1) (Fig. 5b). Progradation of this barrier island toward the ocean would explain the lower N/g and P/B ratios recorded in the more proximal core A2 (Fig. 3), suggesting higher sediment supply at this site. Sedimentological and geomorphological research into the estuary (Rodríguez-Ramírez et al., 1996; Lario et al., 2002; Rodríguez-Ramírez et al., 2015; Pérez-Asensio and Rodríguez-Ramírez, 2020) has revealed a transition to a more confined estuary in the years from c. 3400 to c. 3000 cal BP, when abundant sedimentation occurred far inland from the ocean by marine processes (Lario et al., 2001; Rodríguez-Ramírez et al., 2014, 2015, 2016).

As a barrier island in the Guadalquivir estuary, La Algaida was separated from the mainland by two ocean inlets (Menanteau, 1979, Rodríguez-Ramírez et al., 1996), which were also outlets of the Guadalquivir River: a very broad inlet, between the barrier island and the Doñana spit to the west, and a narrower inlet between the island and the Miocene reliefs to the south (Fig. 5b). These inlets left evidence of their presence in both the succeeding littoral strands surrounding La Algaida and the Doñana spit (Rodríguez-Ramírez et al., 2016). The flood-and-ebb tidal delta thus became split into two sectors according to the two inlets, with each sector separated from the other by the barrier island. This kind of dynamic system, comprising channels, shoals, and swash bars, has also been recognized in other estuaries in the Gulf of Cádiz at the earliest stages of the Holocene evolution (Morales et al., 2006).

The sedimentation revealed by cores A1 and A2 indicates that such primeval sedimentary developments in La Algaida, following the transgressive maximum, pertain to what we refer to as "Prograding Unit 1 (PS1)" (Fig. 2), the oldest constituent of the barrier island (Fig. 2, 5, and 6). The first sediments making up PS1 accumulated in the form of slightly sloping depositional surfaces oriented toward the E-NE. This orientation resulted from both the previous paleo-topography from the Pliocene, some 3 m deeper in core A2 than in core A1, and the powerful migration of the sedimentary systems in the same direction (Fig. 4B). Due to these conditions, the earliest deposits in the Holocene at the La Algaida site yield older dates in core A1 than in core A2.

The emerging island, at present the most stable sector in the spit as well as the best protected from wintertime storm surges, features the archaeological site of El Tesorillo, which includes evidence of occupation from both the post-Tartessian, or Turdetanian, period in the 5th to 2nd centuries BCE, and the Roman imperial period from the mid-1st century BCE to the 4th century CE (Esteve-Guerrero, 1952; Blanco-Freijeiro and Corzo-Sánchez, 1983; López-Amador and Ruiz-Gil, 2010) (Fig. 2).

In the course of these formative developments, La Algaida was set in an estuary that was clearly dominated by a swell conditioned by intense drift currents along the coast, following a SW-NE direction on its eastern side and a NW-SE direction on its western side (Fig. 5). In the course of the Holocene, the disposition of these currents has facilitated incessant sedimentation toward the inner side of the estuary. Convergence of these currents at the site of the structural high ground from the Plio-Pleistocene, where La Algaida formed, resulted in the emergence of the two-sector, swell-dominated flood-and-ebb tidal delta noted above, and the development of significant sandy barriers. This kind of complex process, affecting swell-dominated estuarine systems (Roy et al., 1980), has been recognized in other estuaries along the Gulf of Cádiz, including those of the rivers Guadalete and Guadiana (Morales et al., 2001, 2006), as well as other estuaries around the world (Dalrymple et al., 1992).

6.3. From barrier island to spit (3600 to 1700 cal BP)

Following the stabilization of the barrier island c. 3600 cal BP, from c. 3000 cal BP onwards the subsequent progradation units, PS2 and PS3, developed in the same swell-dominated estuarine system (Fig 5). These prograding littoral systems fed on the evolution of the swash bars in the two ebb tidal deltas that had formed in the two river outlets. Almost the entire uppermost record of the yellow sand facies in core A1 dates from this period, specifically from c. 3000 cal BP to c. 1650 cal BP (Table 1). In other estuaries on the Gulf of Cádiz this kind of development pertains to a phase of greater confinement, which has been determined to have begun after c. 3400-3000 cal BP (Zazo et al., 1994; Rodríguez-Ramírez et al., 1996; Lario et al., 2002; Rodríguez-Ramírez et al., 2015; Camacho et al., 2016; Pérez-Asensio and Rodríguez-Ramírez, 2020).

Prograding Unit PS2 developed as a build-up on PS1; a series of erosive scarps marks the geomorphological and sedimentary discontinuity between the two units (Fig. 2 and 5). The same geomorphological evidence makes it clear that Unit PS2 advanced mostly toward the NW and the SE from an older sedimentary structure. PS2 progradation resulted in a large geomorphological expansion over the length of the barrier island. Further evidence of this process is provided by the successive littoral strands that mark out the spit on its westernmost side. Many of the formations that this process generated find themselves disjoined from one another by erosive scarps caused by the lateral migration of the fluvio-tidal channels in which the migration erosively incised La Algaida (Rodríguez-Ramírez et al., 2016). In turn, as in other estuaries along the Gulf of Cádiz (Morales et al., 2006), the intense wave dynamics caused the migration of the swash bars in the ebb tidal delta toward the backshore (Fig 5 and 6). By pushing the main fluvio-tidal channels toward the barrier inland, the continuous migration of the swash bars ended up eroding the boundaries of the island until they finally collapsed, allowing for the progradation of the system. More distal secondary channels then became functional and the process started anew.

The most recent evidence of the development of Unit PS2 seems to be the littoral strands of Los Prados, in the southeast (Fig. 2). These strands are the product of activity in the fluvio-tidal inlet channel east of the barrier island. It seems that this activity lasted until around 2050-1750 cal BP (Rodríguez-Ramírez et al., 2016), that is, until the first centuries of the Common Era. Writing in the late first century BCE about the uncertainty regarding the location of the pre-Roman city of Tartessus, Greek geographer-historian Strabo of Amasya (Str. 3.2.11; 1966) pointed out that the river *Baetis*, later Guadalquivir River, had two outlets or mouths, which suggests that the eastern tidal inlet of the ocean was still active at that time. Some fifty years later, geographer Pomponius Mela, a native of southern Iberia, apparently corroborated Strabo's testimony, writing (3.1.5; 1987) that the river *Baetis* reached the Atlantic Ocean by means of two large channels flowing from a large lake located not far from the sea, each of the channels being as large as the river itself before flowing into the lake.

Thereafter, a sand bar, or tombolo, formed south of the barrier island, a development of progradation phase PS3, resulting in the connection of the island with the mainland (Fig. 5d and 6Ab). Prograding Unit PS3 turned out be the most extensive in La Algaida, and more generally in the Gulf of Cádiz (Dabrio et al., 2000; Lario et al., 2002; Camacho et al, 2016).

Over the past two millennia, progradation of the sandy barrier on the western bank of the estuary has been remarkable (Rodríguez-Ramírez et al., 1996, 2016), causing the Doñana spit to grow nearly 10 km in length and 4 km in width (Fig. 2 and 5). This process has been favored over these past two millennia by less intense subsidence of the Doñana spit (Rodríguez-Ramírez et al., 2014), while at the same time it has hindered the progradation of La Algaida.

During this last phase in the evolution of the Guadalquivir estuary, the littoral strands on the Doñana spit register a clearly marked erosive discontinuity in connection with a tsunami in the second or the third century CE (Rodríguez-Ramírez et al., 2016). La Algaida, however, has thus far failed to yield any evidence of this event, possibly due to the intensity of agriculture practices on the spit over the past two thousand years, which may have disfigured geomorphological patterns. In any event, attempting to correlate secondary patterns of progradation between the two spits seems an impossible task: La Algaida is subject to intense fluvio-tidal dynamics on the inner side of the Guadalquivir estuary, whereas Doñana is conditioned by the dynamic processes at work in the open sea.

In core A4 (Fig. 3), the transition of the facies from gray sands to estuarine clays substantiates the posited twofold process of ever greater confinement in the area of the paleo-estuary and subsequent closure of the eastern outlet of the Guadalquivir River. The facies of yellowish sands overlying the clays reveal both the migration of the tombolo eastward, energized by the swell, and the gradual collapse of the ebb tidal delta at this location (Fig. 5e, 6Ad, and 6Ae).

Thereafter, progradation continued on the western side of the spit only. The progressive displacement of the western channel of the estuary toward the NW facilitated this development (Fig. 5e). The considerable growth of the Doñana spit since the beginning of the Common Era, coetaneous with the PS3 phase in La Algaida spit, increasingly isolated the latter from the dynamic processes at work in the ocean (Rodríguez-Ramírez et al., 2016) (Fig 5). The end product of this development was the final disconnection of La Algaida from such processes and its resultant location in the shallow, more restrained water dynamics of the inner side of the estuary, a circumstance which selected sedimentation for clays as opposed to sands. At present, La Algaida is a relict component in the geomorphological dynamics of the Guadalquivir estuary and its environs (Fig. 2 and 5f).

As sedimentation accrued to La Algaida in the course of the three phases of progradation that it experienced during the Late Holocene, the substratum from the Plio-Pleistocene underwent a slight isostatic subsidence. The offset in the largest depocenter ranges from 8 to 10 m, as sedimentation in cores A1 and A2 reveals when compared with sedimentation in cores A4 and A3 (Fig. 1D).

6.4. The "island of Cartare" in the First Millennium BCE

The two outlets or mouths of the Guadalquivir River mentioned by the geographer-historian Strabo in the late first century BCE circumscribed an island which Strabo's sources (chiefly Posidonius of Apamea and Artemidorus Ephesius) (García y Bellido, 1993) believed had been the location of the city of Tartessus (Str. 3.2.11; 1966). The sedimentary, geophysical, and geomorphological evidence discussed above would appear to indicate that this island was La Algaida in the PS2 phase of progradation (Fig. 5c). Posidonius of Apamea and Artemidorus Ephesius spent some time in the area early in the first century BCE (García y Bellido, 1993). In his poem *Ora Maritima* (205-295; Avienus in Gavala y Laborde, 1959), the fourth-century CE Roman author Rufus F. Avienus conveyed an old tradition, likely from as early as the sixth century BCE, that this island was called "Cartare," a place-name of Phoenician etymology which means "the island of the city". Elements of this tradition included at least a portolan chart, or rutter, from a long-distance seafarer, probably Greek (Peretti, 1979; Villalba i Varneda, 1986; Domínguez Monedero, 1996, 2013; Villarías-Robles and Rodríguez-Ramírez, 2019). Indeed, the rutter-like narrative taken by much of Avienus' poem suggests that the island, visible from the sea, stood close to the outlets of the river. The river surrounded the island after flowing from the hinterland into a lake called "*Lacus Ligustinus*." The geography of the outlets and their vicinity was complex; the poem reads that, east of the island, the river distributed part of its flow into the nearby lands by means of three inlets. South of the island, after an apparently sequential bifurcation within a delta ("*ore bis gemino*," "through a twice two-fold outlet"), the eastern channel rejoined the western channel and then flowed into the ocean.

The complexity of “a twice two-fold outlet” to the south of the island mentioned in *Ora Maritima* indicates that the channels making up such an outlet were then part of a small tidal delta located at the tombolo, which centuries later would connect the former island to the mainland, north of Sanlúcar de Barrameda.

6.5. La Algaida vs Doñana

In summary, the genesis and evolution of the two littoral spits flanking the estuary of the Guadalquivir River rest upon two fundamental, structural conditions other than the fluvio-marine dynamic constraints of the area: on the one hand, the presence of a Plio-Pleistocene paleo-relief in the estuary functioning as a sedimentary threshold (Fig. 5); on the other, the asymmetry of the subsidence processes at work on both sides of the Baetic front (Fig. 4). As part of the raised tectonic block, south of the LGF, La Algaida was not affected by these subsidence processes, or at least not to the degree of intensity that these processes affected the sunken block, north of the fault, where the Doñana spit is located.

As in other estuaries along the Gulf of Cádiz located in zones of little or no subsidence, such as the estuaries of the rivers Tinto-Odiel and Guadalete (Dabrio et al., 2000; Goy et al., 2003), progradation in La Algaida spit during the Holocene has resulted in a system of successive prograding units that are now exposed above ground. By contrast, the Doñana spit, north of the LGF, underwent transgressive retrogradation in the first sedimentary phases of the Holocene due to the sustained, massive subsidence of the sedimentation. Such was the magnitude of this subsidence that these early deposits remain below ground at present, covered by subsequent formations which, in a reversed trend, prograded. The product of this back-and-forth process over the course of the Holocene has been referred to as a retro-aggradational system (Rodríguez-Ramírez et al., 2014). In effect, the exposed Holocene formations in La Algaida spit are much older than those above sea level in the Doñana spit, even though the latter is far more extensive. This is a clear sign of the sedimentary and geomorphological asymmetry registered on either side of the Baetic mountain ranges. The initial sedimentary phases in the Doñana spit match progradation phases PS1 and PS2 in the La Algaida spit. As mentioned above, less intense subsidence processes in the Doñana spit since c. 2000 cal BP facilitated progradation of this spit over the same time span (Rodríguez- Ramírez et al., 2014). This 2000-year progradation correlates with Phase PS3 in La Algaida spit.

It is not easy to find another case in the scientific literature of so clearly a marked asymmetry between two littoral spits located in the same estuary. The most similar, but not quite identical, scenarios at hand are located in the Mediterranean basin and on the coasts of North America. In many littoral areas of the Mediterranean basin, recent research (Rodríguez-Estrella et al., 2011; Spampinato et al., 2011) has revealed processes of subsidence and tectonic uplift in the course of the Holocene that have generated massive depocenters. In the Cascadian subduction zone of the Pacific Plate, investigation into tectonic activity has enabled researchers such as Nelson et al. (2006) to propose rates of subsidence and uplift for the Quaternary formations. Along the U. S. Atlantic Coast, researchers such as Fiaschi and Wdowinski (2020) have concluded that subsidence of littoral barriers and beaches harbors potentially serious problems for the human communities settled in those areas, including an increasing rate of sea level rise that may make the threat of flooding ever more ominous. In the case of subsidence in the area of the Guadalquivir estuary, however, sea level rise does not seem to pose the same type of threat in the short term, unless present-day climate change dictates otherwise by compounding the sea-level effect of subsidence.

7. Conclusions

The formation and disposition of a Plio-Pleistocene paleo-relief by the mouth of the Guadalquivir River have been favored by a system of faults with SW-NE and NNE-SSW orientation; this paleo-relief is located in the raised tectonic block of the fault system. La Algaida spit rests on such a paleo-relief.

In the first half of the fourth millennium BCE (6000 to 5500 cal BP), the sedimentation of the first Holocene formations took place. These early deposits consisted mostly of sandy facies that punctuated the evolution of a flood-and-ebb, fluvio/tidal delta under strong swell influence; this process was conditioned by both the Pliocene paleo-topography and the intense wave dynamics.

About the year 3600 cal BP, the evolution of the deltaic system caused the budding barrier island to finally emerge. In the first millennium BCE, this island would be known by Phoenician and Greek seafarers, merchants, and colonists as “Cartare island.” It was separated from the mainland by means of two inlets, which were also outlets of the Guadalquivir River.

Shortly after the emersion of the barrier island, a number of units of sedimentary progradation developed in succession. The first unit (PS1), which grew until around 3000 cal BP, gave the island its earliest form. Thereafter, a second unit (PS2) was initiated and spread, causing the island to expand considerably toward the W and the SW. A third and final unit (PS3) began to unfold in the first two centuries CE, bringing as a result the closure of the eastern inlet and the formation of a tombolo that connected the former barrier island with the mainland.

The singular morpho-structural traits of the Lower Guadalquivir River Basin have largely influenced the geomorphological and morpho-stratigraphic characteristics of the Quaternary formations in the area. The system of faults and alignments has given form to a somewhat asymmetric estuary in terms of variables such as the sedimentary infilling and the geomorphological configuration. These variables relate, firstly, to the presence of a Plio-Pleistocene relief in the estuary which functioned as a sedimentary threshold for La Algaida spit, and secondly, to the asymmetry of the processes of subsidence at work on both sides of the Baetic front. As part of the raised block, south of the LGF, La Algaida avoided most of this subsidence, whereas the Doñana spit, north of the LGF, underwent subsidence on a large scale. The present result is that while La Algaida exhibits the entire progradation system of the Holocene as prograding units that are exposed sub-aerially, in the case of Doñana these formations are buried below sea level. These initial sedimentary processes in Doñana correlate with progradation phases PS1 and PS2 of La Algaida. By contrast, in phase PS3, subsidence processes in Doñana were less intense, allowing progradation to run a course homologous to the progradation then affecting La Algaida.

Asymmetric sedimentary processes, in combination with the dynamics of neo-tectonics, make the Guadalquivir estuary and its coastal surroundings a peculiar case for geomorphological research, and hence a potential reference for future studies elsewhere on the planet. Although many coastal areas around the world are subject to processes of subsidence and uplift, few, if any, have been considered thus far for hypothetically comparable conditions of asymmetry impinging upon littoral formations that lie so close to each other.

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Figure and table captions

Figure 1.- A.- Location of the research area. B.- Tectonic setting (GMF: Guadiamar Fault. GF: Guadalquivir Fault. LGF: Lower Guadalquivir Fault). C.- Geomorphological outline with location of cores (A1, A2, A3, A4).

Figure 2.- Geomorphology of La Algaida spit. Location of cores A1, A2, A3, and A4, and dates obtained by Rodríguez-Ramírez et al. (1996).

Figure 3.- Stratigraphy, lithology, dates, benthic foraminiferal abundance (N/g), planktic/benthic ratio (P/B), and distribution of foraminifera in cores A1 and A2.

Figure 4.- **A**.- Location of cores and tectonic setting and probable extension of Plio-Pleistocene paleo-relief. **B**.- Lateral and vertical succession of sedimentary bodies of La Algaida spit in relation to the Lower Guadalquivir River Fault (LGF), the Plio-Pleistocene paleo-relief, and the spit of Doñana. (*Y.S.F.*: Yellow sand facies. *G.S.F.*: Gray sand facies). **C**.- Correlation of analyzed cores in this work with those of Salvany et al., (2011): (SL, CM, and MA).

Figure 5.- Evolution of La Algaida from a shoal and swash bars systems to barrier island and spit. Probable extension of paleo-relief.

Figure 6.- **A**.- Evolution of the sedimentary transection of the tombolo of La Algaida: a.- Displacement toward the E of swash bars overlying gray sand facies, b.- Emergence of tombolo, closure of fluvio-tidal channel, and infilling of estuary, c.- Displacement of the sedimentary body of the tombolo over the estuary, d.-Progradation of tombolo toward the ocean, e.- Isolation of tombolo from the marine dynamics. **B**.- Evolution of the sedimentary transection of the central body of La Algaida: a and b.- Displacement toward the E of swash bars overlying gray sand facies, c.- Genesis of barrier island (PS1), d.- Progradation of sedimentary systems PS2 and PS3, e.-Collapse of the spit by a receding sea and infilling of estuary.

Table 1: Database of ^{14}C results after using the Marine 20 curve (Heaton et al., 2020) and the program CALIB rev. 8.2 (Stuiver and Reimer, 1993). Eight radiocarbon dates were obtained from mollusk shells at the Accium BioSciences Accelerator Mass Spectrometry Laboratory (Seattle, USA). Other published radiocarbon data were also used (Rodríguez-Ramírez et al., 1996).

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Figures and tables

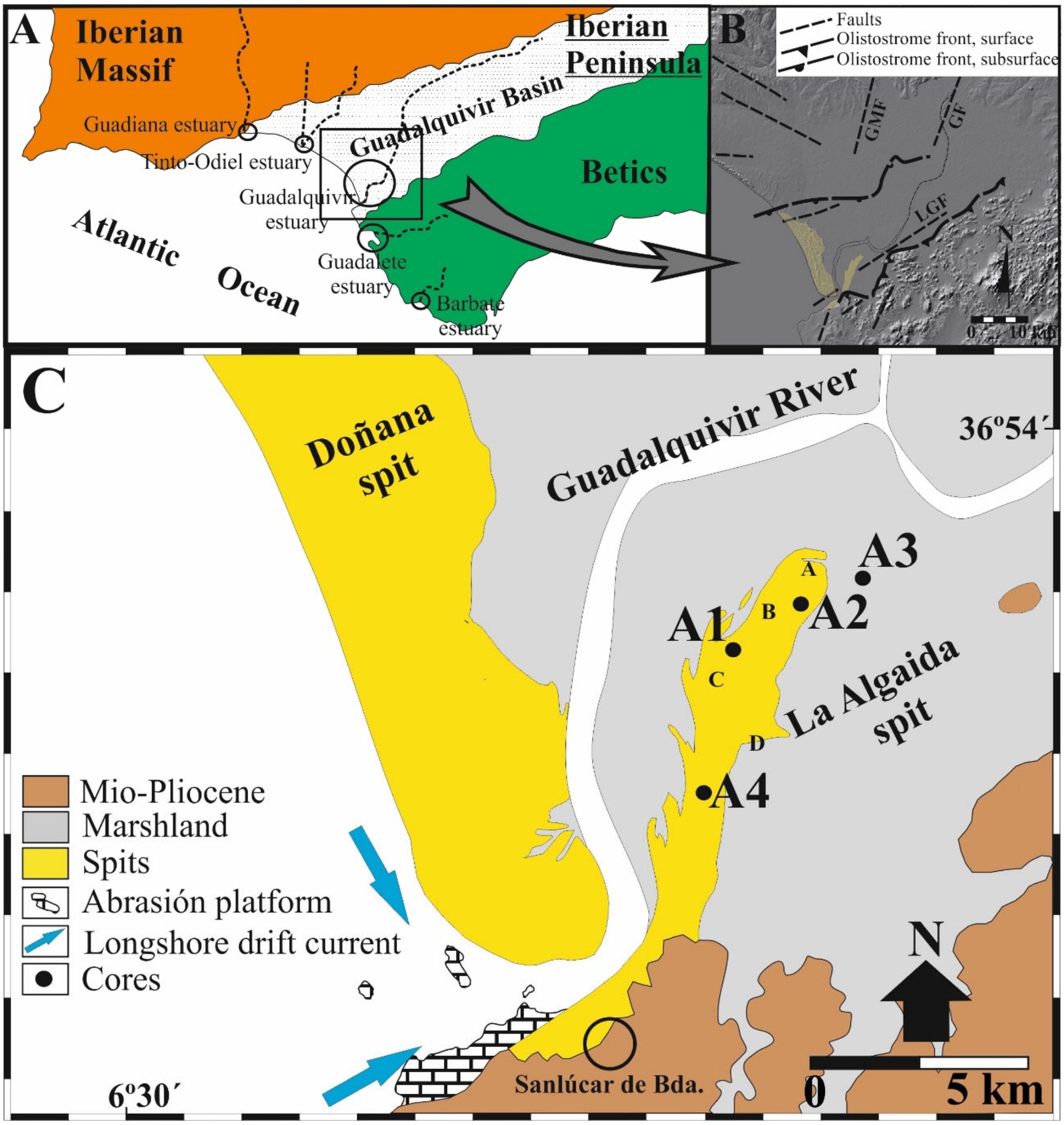

Figure 1.-

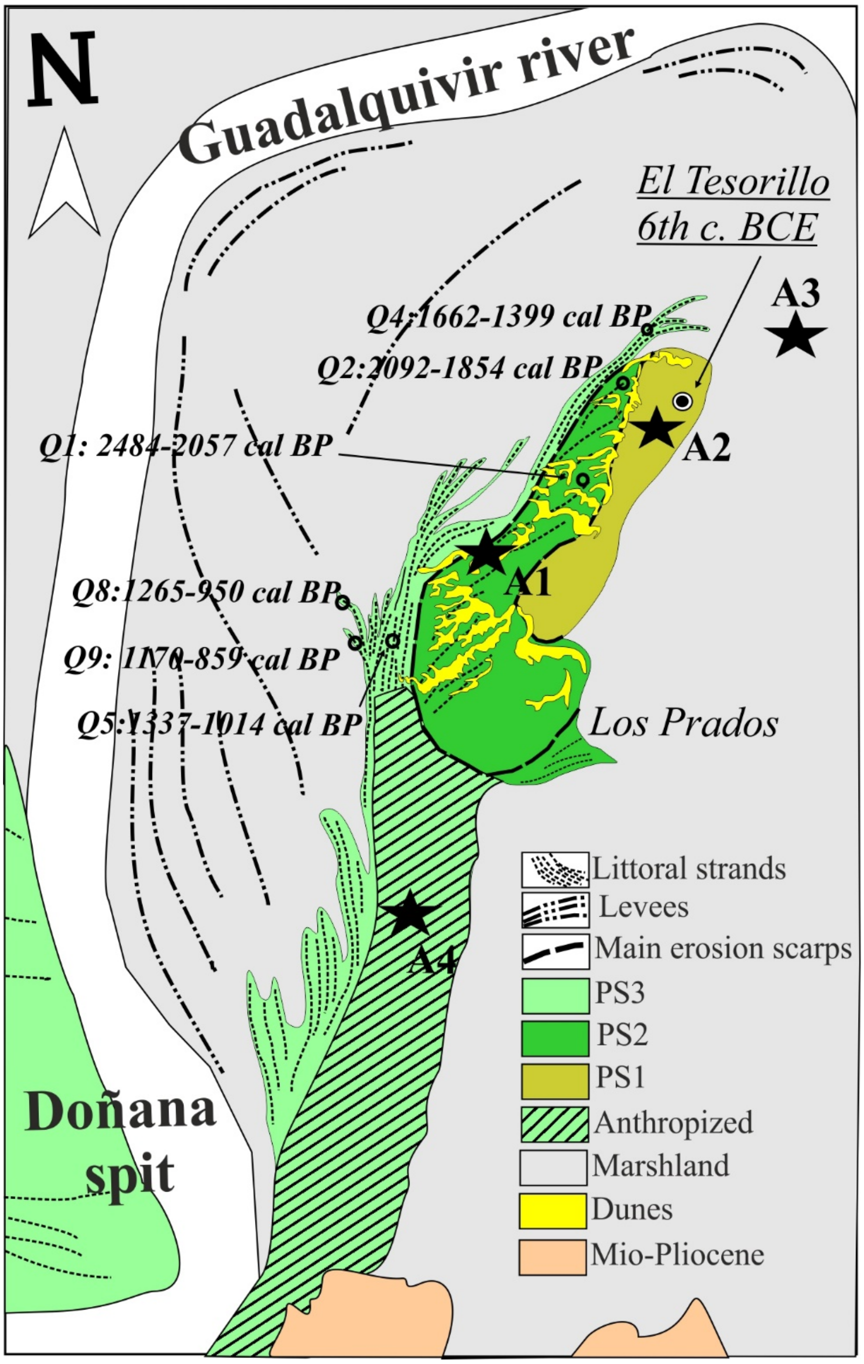
N
Guadalquivir river
El Tesorillo
6th c. BCE
A3
Q4:1662-1399 cal BP
Q2:2092-1854 cal BP
A2
Q1: 2484-2057 cal BP
A1
Q8:1265-950 cal BP
Q9: 1170-859 cal BP
Q5:1337-1014 cal BP
Los Prados
A4
Doñana
spit
Littoral strands
Levees
Main erosion scarps
PS3
PS2
PS1
Anthropized
Marshland
Dunes
Mio-Pliocene

Figure 2.-

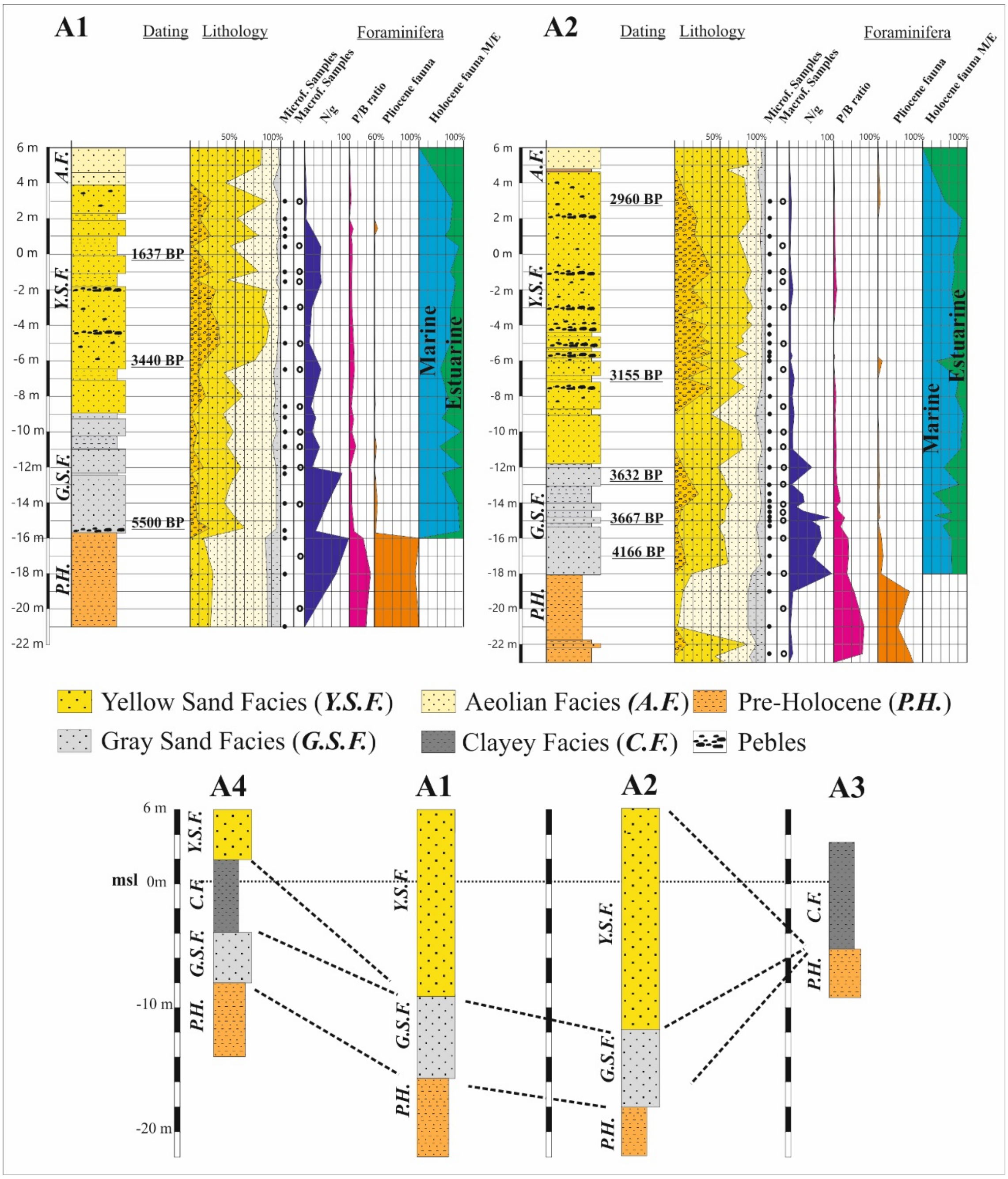
A1
Dating
Lithology
Foraminifera
Microf. Samples
Macrof. Samples
N/g
P/B ratio
Pliocene fauna
Holocene fauna M/E
50%
100%
100
60%
100%
100%
6 m
4 m
2 m
0 m
-2 m
-4 m
-6 m
-8 m
-10 m
-12m
-14 m
-16 m
-18 m
-20 m
-22 m
A.F.
Y.S.F.
G.S.F.
P.H.
1637 BP
3440 BP
5500 BP
Marine
Estuarine
A2
Dating
Lithology
Foraminifera
Microf. Samples
Macrof. Samples
N/g
P/B ratio
Pliocene fauna
Holocene fauna M/E
2960 BP
3155 BP
3632 BP
3667 BP
4166 BP
Marine
Estuarine
Yellow Sand Facies (Y.S.F.)
Aeolian Facies (A.F.)
Pre-Holocene (P.H.)
Gray Sand Facies (G.S.F.)
Clayey Facies (C.F.)
Pebles
A4
A1
A2
A3
6 m
msl 0m
-10 m
-20 m
Y.S.F.
C.F.
G.S.F.
P.H.

Figure 3.-

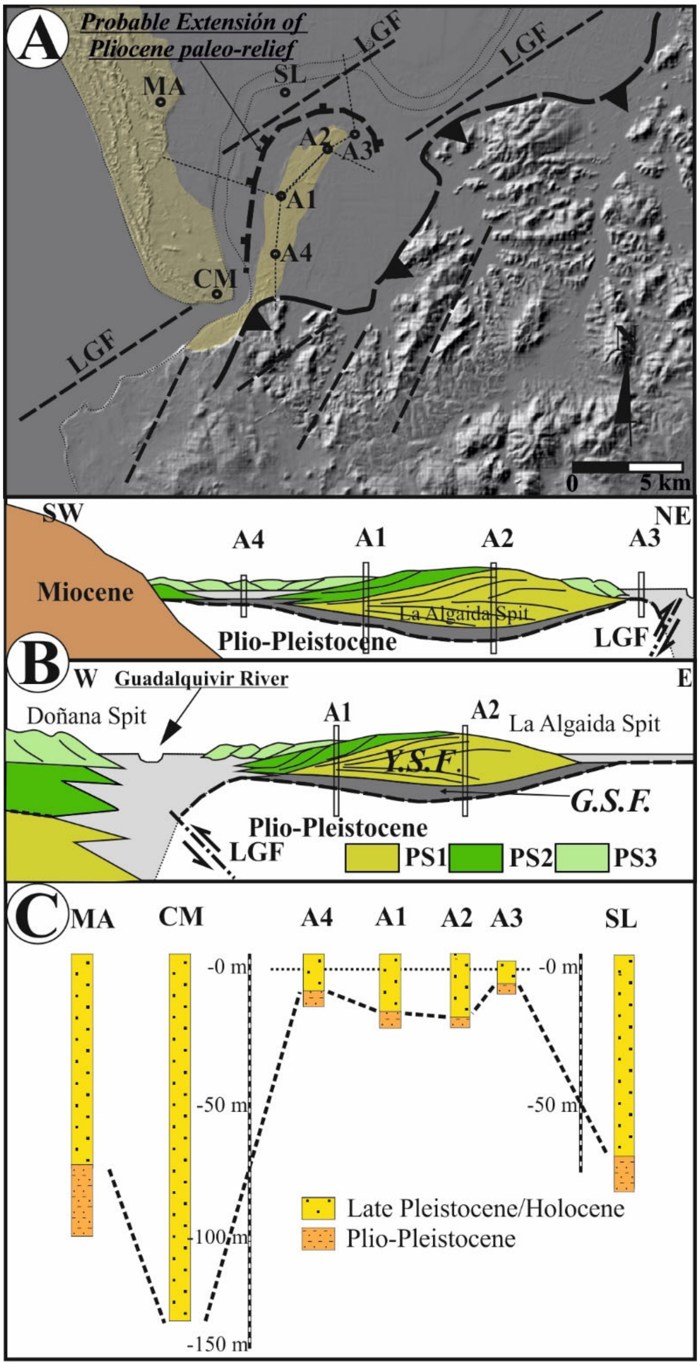
A
Probable Extensión of Pliocene paleo-relief
LGF
MA
SL
A2
A3
A1
A4
CM
0
5 km
SW
NE
A4
A1
A2
A3
Miocene
La Algaida Spit
Plio-Pleistocene
LGF
B
W
Guadalquivir River
E
Doñana Spit
A1
A2
La Algaida Spit
Y.S.F.
G.S.F.
Plio-Pleistocene
LGF
PS1
PS2
PS3
C
MA
CM
A4
A1
A2
A3
SL
-0 m
-50 m
-100 m
-150 m
-0 m
-50 m
Late Pleistocene/Holocene
Plio-Pleistocene

Figure 4.-

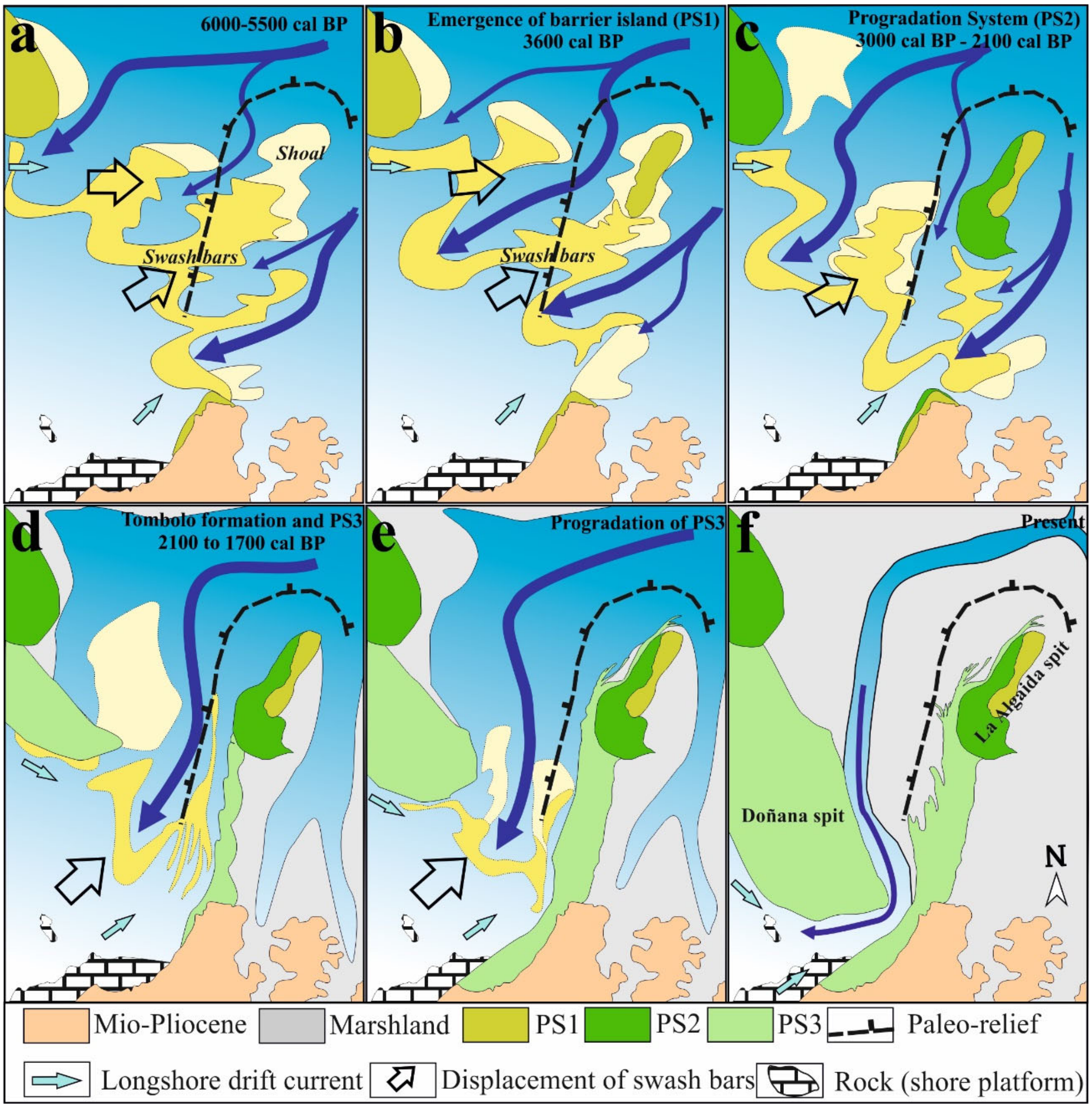
a
6000-5500 cal BP
Shoal
Swash bars
b
Emergence of barrier island (PS1)
3600 cal BP
Swash bars
c
Progradation System (PS2)
3000 cal BP - 2100 cal BP
d
Tombolo formation and PS3
2100 to 1700 cal BP
e
Progradation of PS3
f
Present
La Algaida spit
Doñana spit
N
Mio-Pliocene
Marshland
PS1
PS2
PS3
Paleo-relief
Longshore drift current
Displacement of swash bars
Rock (shore platform)

Figure 5.-

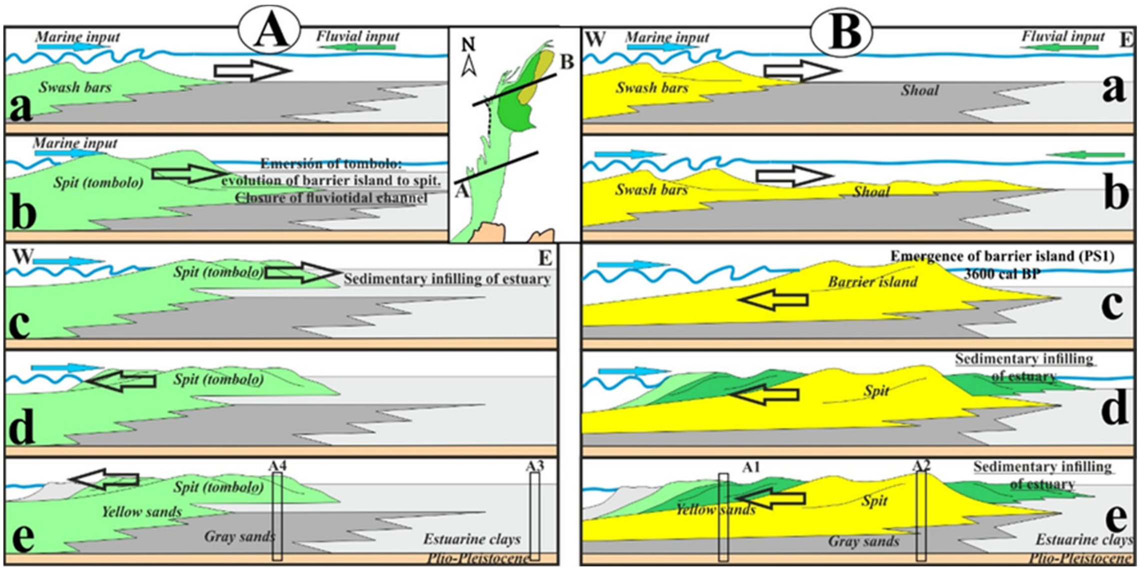
A
B
Marine input
Fluvial input
Swash bars
Shoal
a
b
c
d
e
N
W
E
Spit (tombolo)
Emersión of tombolo:
evolution of barrier island to spit.
Closure of fluviotidal channel
Sedimentary infilling of estuary
Emergence of barrier island (PS1)
3600 cal BP
Barrier island
Spit
Sedimentary infilling
of estuary
Yellow sands
Gray sands
Estuarine clays
Plio-Pleistocene
A1
A2
A3
A4

Figure 6.-

Location	**Depth**	**Lab. Ref.**	**^{14}C yr BP**	**pMC**	**^{14}C cal yr BP (2σ intervals)**
A1	-6 m		1955±52	78.40±0.5	**1804 - 1501**
A1	-12 m	D-AMS 033548	3647±54	63.51±0.42	**3723 - 3146**
A1	-21.5 m	D-AMS 033549	5032±64	53.45±0.42	**5628 - 5316**
A2	-3 m	D-AMS 033668	3255±58	66.68±0.48	**3249 - 2706**
A2	-13.5 m	D-AMS 033669	3417±52	65.35±0.42	**3424 - 2860**
A2	-18.5 m	D-AMS 033670	3806±54	62.26±0.42	**3918 - 3357**
A2	-21 m	D-AMS 033671	3834±64	62.05±0.50	**3966 - 3373**
A2	-23 m	D-AMS 033672	4211±56	59.20±0.42	**4454 - 3849**
Q1(a)	-0.6 m	B-88022	2487±70	--	**2484 - 2057**
Q2(a)	-0.5 m	R-2284	2233±29	--	**2092 - 1854**
Q4(a)	-0.4 m	R-2262	1865±35	--	**1662 - 1399**
Q5(a)	-0.3 m	B-88021	1530±70	--	**1337 - 1014**
Q8(a)	-0.4 m	R-88020	1450±70	--	**1265 - 950**
Q9(a)	-0.2 m	B-88019	1340±60	--	**1170 - 859**

Table 1