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Reconstructing the historical shoreline evolution of the Northern Bay of Cádiz (SW Spain) from geomorphological and geoarchaeological data

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ABSTRACT

During the last 3 ka, different human communities occupied the Bay of Cádiz (SW Spain), including Phoenician, Carthaginian, Roman, Medieval and Modern settlements. Traces of such historical occupations have been recognized along the bay from a geoarchaeological point of view. Some of them bear a palaeogeographical interest related to the historical location of the shoreline. At the same time, Holocene sedimentary units and geomorphological elements identified along the bay can be interpreted as evidences of its morphological evolution. The objective of the present paper is to represent all the available data about archaeological sites and geomorphology in the northern Bay of Cádiz, with the aim of combining both sources of data for elaborating a simple proposal of landscape evolution during the last 3 millennia. The base for mapping was multiple, from historical aerial photographs to satellite imagery and a digital terrain model with a maximum resolution of 0.35 m. .

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1. Introduction

The reconstruction of shoreline evolution is usually addressed by comparison of vertical aerial photographs and satellite imagery. This kind of data is mainly limited to the last decades due to the shortage of aerial images before the 1950s. However, the natural rate of shoreline trends in many cases is much slower, and hence prediction of future coastal trends needs to account for longer time scales, on the order of 10^2–10^3 years (French & Burningham, 2009). Sea-level changes, coastal beach and dune progradation phases, generation of successive beach ridges, lateral migration of fluvial channels on estuaries, or very high-energy coastal events (like tsunamis) are processes whose rates of occurrence fall within such a time range (Gracia, 2022). The study of this time period requires the use of different historical data sources (Nunn et al., 2021). Apart from historical maps, whose accuracy is often very low and unacceptable for a reliable analysis (Crowell et al., 1991; Gupta & Rajani, 2020), historical palaeo-shorelines and relative sea-level (RSL) positions can be established through the identification and analysis of archaeological sea-level markers (Fernández-Montblanc et al., 2018). Many examples exist along southern European coasts, due to a long history of coastal human occupation and urbanization, which produced a large number of coastal archaeological sites (Anthony et al., 2014; Aucelli et al., 2017).

The Bay of Cádiz, generated by Plio-Quaternary tectonics (Gracia et al., 2008) and located on the South Atlantic side of the Iberian Peninsula, is an excellent example of this case. The Bay is 30 km long in N-S direction and 15 km wide and is constituted by low relief and plains on very recent sedimentary coastal units (sand barriers, tidal flats, and salt-marshes), characteristic of a mesotidal coast (mean spring tidal range of 2.96; Benavente et al., 2007). Regarding the wave climate, this is a low-energy coast where the most energetic waves, linked to Atlantic storms, reach heights usually not greater than 4 m (Del Río et al., 2012). However, different very high-energy wave events have affected this coast historically, most of them interpreted as tsunamis (Gracia et al., 2022). Such events are related to the seismological activity of a set of faults located along the western side of the Gulf of Cádiz (De Martini et al., 2021).

Morphologically, the bay is composed of three embayments separated by rocky headlands and elevated areas. The present work is focused on the northern embayment, represented by the semi-confined tidal estuary of the Guadalete River (i.e. the second

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most important river in Andalusia, south Spain), formed by a N-S oriented outer sand barrier 7 km long (i.e. Valdelagrana spit-barrier, related to the prevalent southwards littoral drift) and a wide sheltered extension of salt marshes. The latter were transformed into salinas during historical times and finally desiccated in the 1950s for unsuccessful agricultural purposes (Gracia et al., 2017, 2022). The San Pedro River, a less important fluvial channel, is located in the southern sector of the salt marshes, today functioning as a tidal channel in its lower stretch. The Valdelagrana spit-barrier comprises a complex system of more than 20 Late Holocene beach ridges, according to Rodríguez Polo et al. (2009), and previously identified and grouped by Dabrio et al. (2000) into three main groups, each one associated with an episode of continuous coastal progradation.

Relevant coastal settlements in this northern bay date back to the Phoenicians (almost 3 ka BP; Bernal-Casasola et al., 2020), with Cádiz considered one of the oldest cities in Western Europe (Niveau de Villedary, 2019). For centuries the bay was densely occupied by humans and modified through the development of infrastructure and agricultural and fishing activities. Many historical settlements of Phoenician, Roman, Medieval and Modern age have been identified and studied along the bay during the last decades (Alonso et al., 2009; López-Sánchez et al., 2019). The use of historical settlements as indicators for reconstructing the changing palaeogeography of the Bay of Cádiz has been addressed only recently in several works, mainly proposing very general palaeogeographical approaches without a detailed cartographic base (Alonso et al., 2009, 2015; Caporizzo et al., 2021; Fernández-Montblanc et al., 2016, 2018; Gracia et al., 2017; Gracia & Alonso, 2009).

The recent evolution of the relative sea level in the marshes of the northern Bay of Cádiz was assessed by Caporizzo et al. (2020), by combining data from boreholes and the application of a glacial and hydro-isostatic adjustment model (GIA): the ANICE-SELEN coupled ice-sheet – sea-level model (De Boer et al., 2014). Subsiding rates for this zone, due to sediment compaction, were estimated in 1.4 mm/yr for the deepest point (dated at 3.1 ky BP) and 0.47 mm/yr for the youngest one, dated at 2.0 ky BP (Figure 1).

This trend is similar to other proposals made for the region, describing a rapid postglacial sea level rise until about 6.5 ka BP, with a later deceleration and very minor or slight oscillations or in the last 3–2 ka BP (Boski et al., 2002; García-Artola et al., 2018).

The present work aims to present a high-resolution geomorphological map of the northern Bay of Cádiz with an up-to-date inventory of historical settlements and their characterization, fundamental for any palaeogeographical reconstruction of the historical evolution of the bay. The article includes a proposal of morphological evolution of the zone from the antiquity until the present time.

2. Materials and methods

The first step consisted in a systematic review of previous archaeological works made on the bay along the last decades. Every report, paper or book was consulted and checked. The experience of the authors helped to classify the sites according to their main palaeogeographical relevance. A simplified table was made including the name, historical period and typology of all the sites.

The geomorphological map was made using a work of photo-interpretation of current and historical aerial orthophotographs, the study of a current digital terrain model based on LiDAR (Light Detection and Ranging) data, and field work to confirm the nature of the different landforms recognized on the ground.

2.1. Photo-interpretation

The geomorphological map considered as its main sources the images captured by a photogrammetric flight carried out in 1945–1946 by the US Army Map Service (American flight series A) on 25/07/1946 over the Bay of Cadiz. Stereoscopic photointerpretation of the different forms, together with the revision of previous works, helped to the interpretation of the nature of each form and select the associated symbol to be included in the map. By doing so, it was possible to represent the most pristine state of the bay for which graphic documents are available. This made it possible to identify numerous coastal and fluvial forms which are essential for studying the evolution of the area and which, today, have disappeared due to the expansion of the main urban settlements or agricultural activities: abandoned channels, fluvial levees, ponds and wetlands, etc. Ancient littoral ridges were already mapped in detail in previous works (like Rodríguez Polo et al., 2009); starting from that, the authors proceeded to a revision and a more accurate representation of those relict morphological elements. At the same time, the state of low tide present at the time the orthophotos were taken allowed the mapping of all the forms present in the intertidal zone.

The images from other later photogrammetric flights, like the so-called 'Interministerial' (June 1978) and 'Costas' (August 1990) flights, commissioned by the Spanish National Geographic Institute (IGN), and 'PNOA 2019' (18/07/2019), carried out by the Spanish National Aerial Orthophotography Plan (PNOA), were used as complementary information. These images have a higher spatial resolution (0.35 metres) compared to the American Series A flight (1 m), which allowed for a better recognition

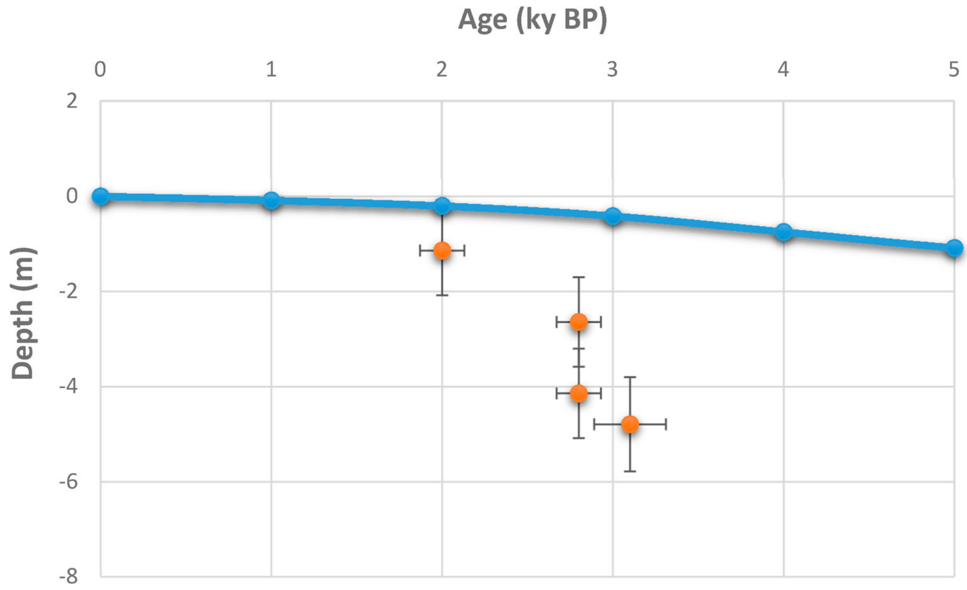

Figure 1. Late Holocene relative sea-level curve trend for the northern Bay of Cádiz, based on depositional sea-level markers identified in boreholes made on the salt marshes (blue dots) and the GIA sea level model ANICE-SELEN proposed for the Gulf of Cádiz (modified from Caporizzo et al., 2020).

and delimitation of some coastal shapes. All these images were consulted in the Spanish Digital Photo Library of the National Centre for Geographic Information (CNIG) and helped to solve some local indefinite forms, too vague or unclear in the American flight photos.

2.2. Terrain model

The digital terrain model was created using LiDAR data taken from the IGN's Download Centre. Specifically, the data provided by the PNOA in its first national coverage was used. This data was acquired in 2015 and has a density of 0.5 pts/m^2. The development of a terrain model (DTM) helped to better define the limits of certain coastal landforms which, in aerial photography, can be easily confused. Thus, the contours of current and relict dune ridges, tsunami or storm overwash fans and the boundaries of marshes, pediments, alluvial fans and fluvial terraces were mapped on the basis of a digital terrain model with a spatial resolution of one metre. In addition, this model made it possible to clearly distinguish the different marsh horizons (high, medium and low), the delimitation of which can be complicated by photo-interpretation.

2.3. Map elaboration

The map, both its digitization and the layout process, was carried out using QGIS software version 3.28.4. This free software has the necessary digitization tools to produce a highly detailed cartography. In order to obtain a cartography without topology errors, we chose to draw all the polygonal shapes of the geomorphological map in a single vector layer, on which the different shapes were traced with the help of the tools 'split spatial objects', 'fill ring', 'add polygon', as well as the vertex modification tool. In the same way, the advanced digitizing functions were activated, which avoid polygon overlapping errors. All these shapes were drawn using as a guide a terrain model generated from LiDAR data as well as the images of the different flights mentioned above. For LiDAR data processing, LAStools software from Rapidladso was used, executed via command line. The map was made with a high level of precision and detail, especially those shapes referring to coastal environments such as tidal channels, marshes, beaches and dunes and to fluvial environments, since both are considered fundamental to reconstruct the geomorphological evolution of the study area. Soft colours were chosen, so that the darkest colours are associated with the most ancient, relict forms, while the lighter colours are linked to the most recent or presently active forms. At the same time, the colours of the forms that make up each geomorphological unit were chosen to be coherent. For that purpose, general symbol and colour recommendations proposed by the Spanish Geological Survey for elaborating the national geomorphological map at scale 1:50.000 (Suárez Rodríguez et al., 2005) was mostly followed: the morphostructural units take ochre colours, the fluvial units take green colours, the coastal sandy areas take yellow and brown colours and the marshy environments take blue colours. In order to give a greater geographical context to this area of limited extension, it was decided to include the city of Cadiz, as well as a location map showing the Bay of Cadiz as a whole in its current state.

2.4. Fieldwork

Work made in the field consisted in a systematic inspection of most archaeological sites and geomorphological elements in the zone. This helped to verify previous interpretations in remote sensed images and focused on the recognition of littoral ridges, identifying the nature of the sediments associated with Holocene deposits, fluvial palaeochannels and terraces, and tsunami deposits in areas where photo-interpretation and digital terrain model studies were not sufficient for their correct identification. The possible palaeogeographical relevance of each archaeological site was evaluated (artificial channels, bridges, harbours, fishing industries, or hydraulic mills).

3. Results and discussion

The map of the northern Bay of Cádiz shows a complex set of historical relict landforms, mainly of fluvial and coastal origin, overlapped by a number of human infrastructures (e.g. railways, highways and roads, bridges, salinas, harbours, urban settlements, etc.). A total number of 71 archaeological sites located at or near the littoral zone have been recognized based on the literature and included in the map. In order to facilitate the reading of the chart, the sites are referenced by numbers, while their name, nature/typology and age are detailed in Table 1. A hyperlink has been included in most entries, which allows accessing to the web page of the Andalusian Institute for Historical Heritage, where a complete file can be consulted for each site. The files include information like location, nature, description, protection level, sources of information (bibliography related to the study of the site) and other additional information. Any archaeological site file can be accessed at https://guiadigital.iaph.es/inicio. Nevertheless, due to the very different levels of record and research achieved in all the sites, some of the data are not included in that web page. For those cases, additional information is indicated at the end of the table.

Historical changes in this coastal zone are mainly recorded in littoral ridges, salt marshes and fluvial deposits. According to Figure 1, relative sea-level oscillations in the last 2 ka BP were negligible, less than 0.5 mm/yr in Roman times, and lesser in the following periods. Climate changes recorded in southern Europe during the last two millennia could have affected the behaviour of sea level at a regional scale. Following Losada et al. (2011), a slight relative drop would have occurred during the barbarian invasions (1.5–1.2 ka BP), with a later minor rise during the Medieval warm period (1.0–0.7 ka BP), another drop in correspondence with the Little Ice Age (0.5–0.15 ka BP) and finally the contemporary sea level rise due to global warming. However, the supposed minor sea level oscillations associated with this climatic evolution have not been demonstrated to date and probably lie within the range of error inherent to the methods used for inferring historical sea levels from borehole analysis.

Littoral ridges in Valdelagrana spit-barrier formed during different prograding episodes in the last millennia, with complex inter-relationships (Dabrio et al., 2000; Del Río et al., 2015; Rodríguez Polo et al., 2009). Since the Mid-Holocene eustatic sea-level highstand was reached in the Gulf of Cádiz, at about 5.3–4.8 ka BP, sea level has remained broadly stable until present, favouring coastal progradation and generation of successive beach ridges (Caporizzo et al., 2020; Dabrio et al., 2000). The oldest one is dated to 3.5 ka (Zazo et al., 1994), and together with other chronological constraints of the ridges derived from radiocarbon dating (Arteaga et al., 2008, and the previously cited works), allowed Alonso et al. (2015) to propose a palaeogeographical reconstruction of the coastal evolution of Valdelagrana spit-barrier in the last three millennia. Very energetic events (i.e. strong storms and especially tsunamis) conditioned such evolution by producing breaching episodes that relocated the Guadalete River mouth and led to the generation of new sets of littoral ridges. The geometry of each set of ridges allowed to reconstruct the main energetic events that affected this coast during the last 3 millennia (Alonso et al., 2014, 2015). Apart from other geoarchaeological markers, historical washover deposits associated with the last 1755 AD tsunami event can be recognized in the beach ridges and marshes behind the present dunes. The most outstanding example is Valdelagrana spit barrier, where up to 5 relict washovers can be identified (Gracia et al., 2022; Luque et al., 1999, 2002). All this information has been incorporated into the map included in the present work.

Regarding historical human interventions, in the last 50 years, the building of dams in the Guadalete River basin, the construction and lengthening of the jetties located at the mouth of the Guadalete River, and land reclamation performed in 1976 for building shipyard facilities to the south of San Pedro River, resulted in accelerated coastal erosion, especially in the southern sector of the Valdelagrana barrier (Martínez del Pozo et al., 2001). Recently, shoreline erosion has decreased and a certain equilibrium has been achieved (Del Río et al., 2015).

Salt marshes have recorded a continuous silting by sediments of fluvial and tidal origin. During the last 2 ka, different periods of deforestation favoured the increase of fluvial sediment yield to the coast (Alonso et al., 2015). The change from an original embayment controlled by tides to the presently prevailing fluvial environment has been reconstructed from the analysis of different cores excavated from the salt marshes

Table 1. List of archaeological sites located on the northern Bay of Cádiz.

No.	Name	Period	Typology
1	La Cartuja	Ist–16th centuries AD	
2	La Corta[a]	Ist–18th centuries AD	
3	Azud de la Corta	20th century AD	
4	Villares	Ist–7th centuries AD	
5	Hijuela de Las Coles	Ist–12th centuries AD	
6	Cortijo Matavaca	Roman s.l.	
7	Bajo de la Galera	16th century AD	
8	Zarandilla	Roman s.l.	
9	Buenavista[b]	2nd–Ist centuries BC. 12th century AD	
10	Las Cumbres	8th century BC	
11	El Portal	12th–18th centuries AD	
12	Ermita de la Piedad	18th century AD	
13	Doña Blanca	8th century BC	
14	La Martela	3rd century BC	
15	La Dehesa	1st century AD	
16	Puerto Franco	15th century AD	
17	San Ignacio	1st century AD	
18	Corta de 1648	17th century AD	
19	Tesorillo	1st century AD	
20	Las Quinientas	3rd century BC–1st century AD	
21	La Angelita[c]	1st century AD	
22	El Pinar[c]	1st century AD	
23	Caño del Molino	18th century AD	
24	Molino del Caño	19th century AD	
25	San José	16th century AD	
26	Corta de 1722	18th century AD	
27	Barjas	Roman s.l.	
28	Roalabota	3rd century BC–1st century AD	
29	Puerto 19	6th century BC	
30	Portus gaditanus[c]	Ist century AD	
31	Puente Puerto SM[c]	1st century AD	
32	Molino de Charles de Varela	15th century AD	
33	Coto de la Isleta[c]	1st century AD	

(*Continued*)

Table 1. Continued.

No.	Name	Period	Typology
34	Bolaños 4	1st century AD	
35	Bolaños 5	1st century BC	
36	Cjo de Frías	1st century AD	
37	Cjo Frías 3	Roman s.l.	
38	Bolaños 2	Roman s.l.	
39	Bolaños 1	1st century AD	
40	Santa Catalina-La China	1st–18th centuries AD	 
41	La Laja	18th century AD	
42	Bolaños 3	Roman s.l.	
43	Bolaños 6	Roman s.l.	
44	Arroyo de la Zarza	1st century AD	
45	Zarza	1st century AD	
46	Cerro de la Tinaja	1st century AD	
47	Torre Baja	Roman s.l.	
48	Molino de Goyena	Contemporary	
49	Cerería	1st century AD	
50	Pago Machichi	1st century AD	
51	Olivar de los Valencianos	1st century AD	
52	Cerro Ceuta	1st century AD	
53	La Arriaga	Roman s.l.	
54	Cantera Lavalle	1st century	
55	Casines	1st century	
56	Gadir-Gades-Cádiz	9th century BC	
57	Gallinero	Roman	
58	Puerto Real	15th century AD	
59	Urb. Julián Besteiro	Roman s.l.	
60	El Pinar	Roman s.l.	
61	El Retamar	Roman s.l.	
62	Torrealta	1st century AD	
63	Puente Melchor	1st century AD	
64	Huerta del Olivar-Olivar II	1st century AD	

(*Continued*)

Table 1. Continued.

No.	Name	Period	Typology
65	Miramundo	1st century AD	
66	Huerta San José	Roman s.l.	
67	Villanueva	1st century AD	
68	Cortadura	19th century AD	
69	Molino de Guerra	17th century AD	
70	Matagorda	17th century AD	
71	Fuerte San Luis	18th century AD	

Symbols: Artificial channel; Bridge; Diversion dam; Fishing industry; Fortification; Harbour; Hermitage; Necropolis; Pottery industry; Road; Salina; Settlement; Water mill.

[a]Cobos Rodríguez et al. (2021).
[b]Mata Almonte and Lagóstena Barrios (1997).
[c]López Amador and Pérez Fernández (2013).

(Caporizzo et al., 2021; Dabrio et al., 2000). In the mid-1950s, an attempt was made for desiccating the northern Bay of Cádiz for agricultural purposes through the excavation of a net of draining channels. Cropping failed in this zone due to the high salinity of soils associated with former salt marshes, and most desiccated fields were abandoned; at the same time, tidal flooding has not affected the zone ever since (Gracia et al., 2017). A former palustrine area developed in the marshes, near the Guadalete River mouth and identified in different historical maps, was recently (last 30 years) transformed into an industrial salt harvesting exploitation.

The fluvial changes recognizable in the area are represented by abandoned channels, levees and scroll bars, mostly associated with the lateral migration of the Guadalete River. The San Pedro River, located to the south, is an ephemeral channel without discharge enough to develop such fluvial dynamics; consequently, no scroll bars or abandoned channels have been identified in relation to its recent evolution. Detailed mapping of the historical forms and deposits of the Guadalete River shows that it consists of lateral migration of its channel and frequent episodes of meander capture, usually by means of neck cut-off processes. However, this evolution has been complicated by several historical human interventions in the zone, mainly consisting of the connection of both river channels (Guadalete and San Pedro) through artificial shortcuts excavated on the salt marshes existing between them. The oldest known intervention took place in the 1st century A.D., when the Roman ruler of the zone, *Lucius Cornelius Balbus*, decided to rectify the last stretch of the Guadalete River and open it directly to the sea, in order to facilitate the access to El Puerto de Santa María village and also to control maritime trade taxes. Other later interventions, like those of 1648, 1722, and 1742 (Pérez, 2018), aimed at letting trading boats coming from the continent along the Guadalete River reach the sea through the San Pedro River, without passing by the control existing at El Puerto de Santa María village, and avoiding the payment of customs duties (Iglesias, 2020).

The location, nature and age of the different archaeological sites and their position in relation to the present fluvial and coastal environments have been used for proposing the reconstruction of the morphological evolution of the northern Bay of Cádiz during the last two millennia. Figure 2 shows this attempt, based on the results obtained in this work and also on previous works already cited. This evolution represents a substantial advance with respect to other previous proposals about the palaeogeographical evolution of the northern Bay of Cádiz, like Alonso et al. (2001, 2004, 2009, 2014), Caporizzo et al. (2021), Del Río et al. (2015), Gallardo et al. (2000), Gracia and Alonso (2009), or Gracia et al. (1999, 2000, 2005, 2017). The high resolution achieved by the map, together with a complete revision and evaluation of the palaeogeographical potential of the 71 archaeological sites represents a significant upgrade on the reconstruction of the morphological evolution and knowledge of the human occupation of this territory during the last two millennia.

Since the Mid-Holocene eustatic sea-level highstand, sea level remained in a more or less stable situation until present, favouring coastal progradation of sedimentary systems. The southward growth of the first sets of ridges caused the migration of the Guadalete River mouth in the same sense partly enclosing the bay and favouring its filling with fine sediments to

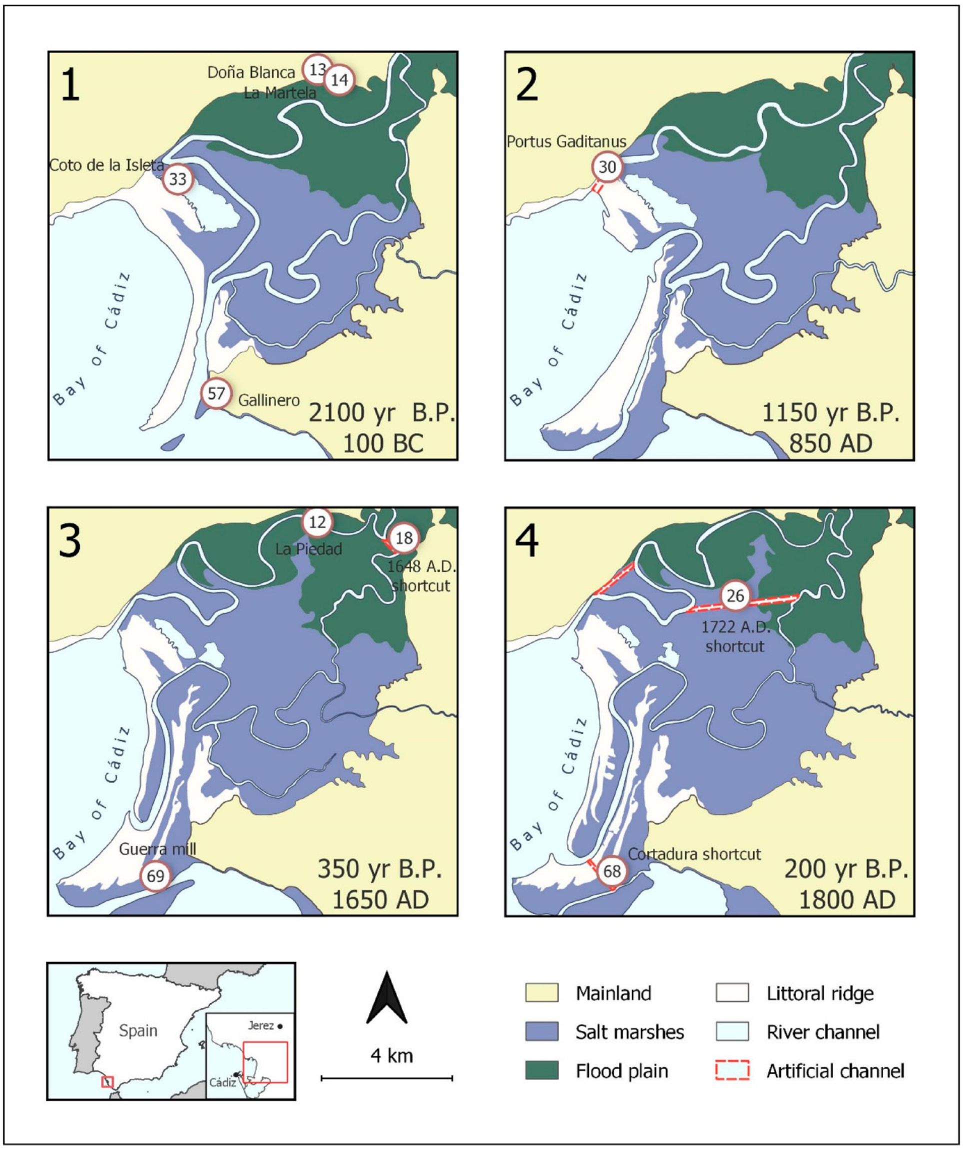

Figure 2. Palaeogeographical evolution of the northern Bay of Cádiz based on the geoarchaeological map presented in this work and also on different previous works and proposals.

form extensive salt marshes (Figure 2.1). During Phoenician and early Roman times the Guadalete River developed a sedimentary plain with several fluvial branches, forming a tide-dominated delta plain (Dabrio et al., 2000); Doña Blanca and La Martela sites confirm this occupation of the plain, close to navigable channels. Climate oscillations and different high-energy events possibly were the main drivers that conditioned the successive phases of growth of the Valdelagrana spit barrier, by means of generation of new sets of littoral ridges (Del Río et al., 2015; Gracia et al., 2022).

About 2000 BP an artificial channel was opened in the northern area to facilitate ship navigation and to control trade (Gracia & Alonso, 2009). Archaeological remains at Portus Gaditanus (Figure 2.2) confirm this opening (López Amador & Pérez Fernández, 2013), apart from other minor geomorphological indicators (Del Río et al., 2015). The cutting generated a complex estuary with two active mouths. The northern, artificial one has kept its location invariant until present, due to continuous dredging works. This favoured a period of very rapid coastal progradation of the Valdelagrana spit barrier, due to the direct sediment discharge to the spit head through the artificial channel. The commercial competition between cities connected by the Guadalete River led to the excavation of a second channel, called San Pedro River, in the seventeenth century (Figure 2.3), in order to facilitate ships to avoid passing by El Puerto de Santa María village and the payment of pass taxes.

In the eighteenth century, this second connection was artificially closed and a new cut was excavated in 1722 in the inner marshlands that made the Guadalete River flow to the sea entirely through the northern mouth (Figure 2.4), leaving the San Pedro River completely inactive until present (Baldera & Falcon, 1987), only affected by tidal fluctuations. This actuation increased the water depth at El Puerto de Santa María harbour, of growing importance for its commercial activity with America by that time. Apart from the local effects caused by the 1755 tsunami (Gracia et al., 2022), the last intervention represented in Figure 2.4 is the opening of an artificial channel in the southern historical ridges, in order to prevent the French army to reach the city of Cádiz during the Napoleonic wars, in the early nineteenth century.

4. Conclusions

The northern Bay of Cádiz is an outstanding example of the complex interaction between natural processes and human settlements and interventions along a history of more than 3.0 ka. As an estuary system, the area has experienced natural changes related to marine (e.g. tides and sediment supply by tidal currents) and fluvial processes (e.g. river channel migration, flooding episodes, historical variations in the fluvial sediment yield, etc.). The broadly stable position of sea level during the last two millennia has facilitated the prevailing trend of the confining spit-barrier of the bay to progradation. Several historical high energy wave events (e.g. strong storms and tsunamis) conditioned the geometry and evolution of the prograding littoral ridges in the spit, whose local effects can still be recognized in the salt marshes behind the present dunes.

The coexistence of two river channels in the northern bay complicated the morphological evolution of the salt marshes upon which both rivers flowed. The northern one, the Guadalete River, showed a very high dynamism with intense lateral migration and meander capture episodes. The progressive silting of the sheltered salt marshes was accelerated by the increasing sediment supplied to the zone by the Guadalete River. These processes have changed the original marine embayment, initially subject to the prevalence of tidal dynamics, to a more recent fluvial plain, only affected by river flooding episodes.

Human interventions have significantly increased the complexity of this evolution: River channel diversions (since Roman times), artificial connection between both rivers (especially in the XVII and XVIII centuries), desiccation of the salt marshes (in the middle 1950s), apart from other local works (e.g. salt marsh reclamation for building a shipyard, groynes, construction of salt harvest pans, groin installation and harbour expansion), and regional developments (i.e. construction of several dams in the Guadalete River basin), have completely altered the historical natural dynamics and trends of the beaches, dunes and salt marshes of the northern Bay of Cádiz.

The present contribution represents the first approach to this complex interaction and evolution using high-resolution mapping. The relevance of the present contribution mainly lies in the spatial contextualization of the different archaeological sites and historical settlements in this dynamic and rapidly changing environment. Nevertheless, the authors are aware of the difficulty of reconstructing such historical changes with detail. Future research on historical documents, new cores drilled in the marshes, and compilation and detailed analysis of historical maps, will provide new data and valuable information for improving the geoarchaeological map and refining the evolutionary model presented in this paper.

Software

The whole map, both its digitization and the layout process, has been carried out using Qgis software. For LiDAR data processing, LAStools software from Rapidladso has been used, executed via command line.

Social media

The present work is focused on explaining the evolution of the Bay of Cadiz since historical times, an area where human occupation in the last 3000 years has played an important role in the modelling of the terrain, resulting in the landscape that we contemplate today.

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No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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