Sequence stratigraphy of Holocene incised-valley fills and coastal evolution in the Gulf of Cádiz (southern Spain)

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Abstract

This first sedimentary interpretation of two incised-valley fills in the Gulf of Cádiz (southern Spain), which accumulated during the last fourth-order eustatic cycle in response to fluvial incision, changes of sea level, and correlative deposition, relates the filling of the estuarine basins and their barriers with four regional progradation phases, H_1 to H_4. The cases studied are the wave-dominated Guadalete, and the mixed, tide and wave-dominated Odiel-Tinto estuaries. The sequence boundary is a type-1 surface produced during the lowstand of the Last Glacial period ca. 18 000 ^{14}C yr BP. No fluvial lowstand deposits were found in the area. Due to rapid transgression the valley fills consist of transgressive and highstand sediments. The maximum landward advance of the estuarine barriers occurred ca. 6500–6000 ^{14}C yr BP during the maximum of the Flandrian transgression, but there is no evidence of sea level rising appreciably above the present. A large part of the estuaries was filled during H_1 (ca. 6500–4400 ^{14}C yr BP) but ravinement by shifting tidal inlets destroyed most of the coeval barriers. During the H_2 phase (ca. 4200–2550 ^{14}C yr BP) sedimentation was favoured by arid conditions and concentrated in the axial estuarine zones and the barriers. Between H_2 and H_3 prevailing winds changed from W to WSW, increasing spit growth to the east and south-east. Progradation of bay-head deltas and flood-plains during H_3 (ca. 2300–800 ^{14}C yr BP) and H_4 (500 yr ago to the present) further reduced the accommodation space in the largely-filled valleys, and sediment by-passed the estuaries and accumulated in the estuarine barriers as fast-growing spits. Arid conditions and increasing human activity have caused rapid coastal modifications.

Introduction

Several estuaries along the coast of the Gulf of Cádiz are partly enclosed by spits (Figure 1). The Holocene evolution of the coast has been the focus of many papers (e.g. Gavala y Laborde 1959, Dabrio & Polo 1987, Zazo et al. 1992). Radiocarbon dating of shells from the spits suggested a chronology of events of progradation and erosion (Zazo et al. 1994, Lario et al. 1995, Goy et al. 1996, Lario 1996).

In contrast, the filling of the estuaries has remained poorly understood despite a few publications (e.g. Borrego 1992, Borrego et al. 1993, Morales 1993). The first attempts to reconstruct the Holocene sedimentary evolution of an estuary from drill cores were those of Dabrio et al. (1995) and Goy et al. (1996) who concluded that the Guadalete estuary underwent flooding in the Early Holocene followed by a phase of open estuary and a later, relatively rapid filling related to sea-level changes and progradation of the Guadalete

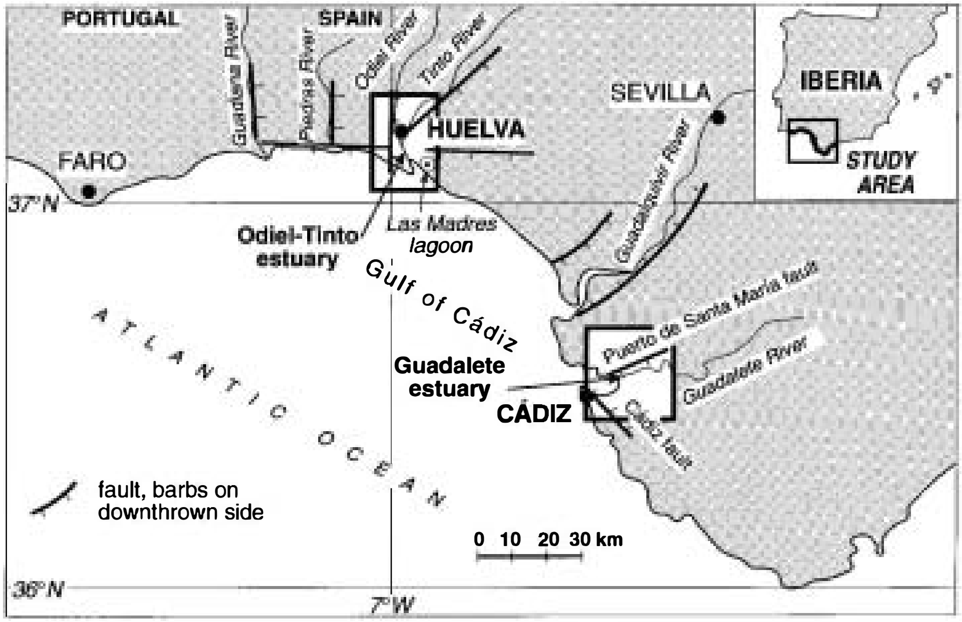

Figure 1. Map showing study areas and main faults controlling localities for fluvial valleys and estuary settings along the coast of the Gulf of Cádiz.

river delta after 6450 ^{14}C yr BP. To obtain a more detailed view of the importance of valley fills as records of coastal evolution and of climate changes, the area has been re-studied in the framework of a project including the analysis of aeolian deposits nearby (Zazo et al. this issue).

The aim of this paper is to present the results of the study of drill cores from two incised-valley fills in the Gulf of Cádiz: the wave-dominated Guadalete estuary and the mixed, tide- and wave-dominated Odiel-Tinto estuary, with its associated Las Madres coastal lagoon and peat bog. The results make it possible to interpret the sedimentary evolution of the incised-valley fills as a function of first the glacio-eustasy factor (global sea-level rise) and then the minor relative changes of sea level after the maximum of the Flandrian transgression. This interpretation also relates, for the first time in the area, the filling of the estuarine basins and the development of spits at the mouths of the estuaries. It proposes a more detailed version of the coastal evolution of the Gulf of Cádiz during the Holocene.

Geological setting

The Gulf of Cádiz (southern Iberian Peninsula) opens towards the south-west and the Atlantic Ocean (Figure 1). The morphology of the coasts of south-western Europe and north-western Africa, greatly reduces the effective fetch of Atlantic gales, and only wave fronts and surges moving towards the north-east are able to reach the shore of the gulf. Daily winds blowing mainly from the sea also generate wave fronts which progress roughly in the same direction. Most of the wave fronts approach the coast obliquely and induce strong longshore transport. This produces littoral drift directed towards the east and south-east on the Spanish side of the gulf. The drift is demonstrated by direct observation, measurements of sand transport, and the occurrence of spit barriers (Zazo et al. 1992).

The coast of the Gulf of Cádiz can be described as semidiurnal mesotidal with mean tidal ranges of 2.1 m and a variation up to 0.45 m between successive flood or ebb tides (Borrego et al. 1993). Wave energy is medium, because 75% of the waves do not exceed 0.5 m in height. These conditions favour the development of broad littoral lowlands, usually sheltered by spits, where tidal flats and fresh-water marshes extend several kilometres inland.

Two major Holocene phases of coastal progradation have been widely recognised in southern Spain after the transgressive maximum (ca. 6500 ^{14}C yr BP) in the area (Zazo et al. 1994, 1996a, Lario et al. 1995). In the most complete case (Almería, SE Spain), they include four spit systems currently referred to as H_1, H_2, H_3, and H_4 (Zazo et al. 1994). The first major progradation phase comprises the spit units H_1 and H_2. The second major phase includes the spit units H_3 and H_4. The complete set of spit systems crops out only in the Mediterranean coasts of Almería (Zazo et al. 1996b, Goy et al. 1996) and the Balearic Islands (Goy et al. 1997). The complete suite has not been observed so far on the Atlantic coast, where no physical record of H_1 has been located in outcrops. However, as discussed below, there is circumstantial evidence of its deposition.

Each unit is separated from the adjacent ones, either by an erosional surface intersecting beach ridges, or by a gap in sedimentation recorded as a prominent swale (Zazo et al. 1994). It is interesting to note that the formation of the gap separating the two major phases of progradation coincides with notable modifications in some parameters of the coastal dynamics, such as a reversal of the coastal drift on Spanish Mediterranean beaches (Goy et al. 1986), changes in direction of prevailing winds both on Mediterranean and Atlantic coasts (Zazo et al. 1996a, Goy et al. 1996), and increased rates of filling in estuaries (Lario et al. 1995, Lario 1996).

Our database of radiometric data with normalised ages has been enlarged noticeably (Table 1). This allows us to refine the previously proposed ages of coastal progradation phases and intervening gaps. The new limits for progradation of the spit units are: H_1: ca. 6500 to 4400, H_2: ca. 4200 to 2550, H_3: ca. 2300 to 800 ^{14}C yr BP, and H_4: 500 years ago to the present. Accordingly, the gap separating the two major phases of progradation lasted from ca. 2550 to 2300 ^{14}C yr BP.

As shown below, the rivers flowing into the Gulf of Cádiz during the drop of sea level caused by the Last Glacial period excavated valleys. Sediments accumulated in the valleys during the succeeding rise of sea level. A part of the incised valley of the Guadalete river evolved into a wave-dominated estuary, whereas the estuarine part of the Odiel and Tinto rivers was mixed, tide- and wave-dominated. At present, both estuaries are largely filled with sediments.

We use the concepts and definitions of incised-valley systems, valley-fill, estuary fill, and estuary model as described by Allen (1991), Dalrymple et al. (1992, 1994), Allen & Posamentier (1993, 1994), and Zaitlin et al. (1994), and the concepts related to sequence stratigraphy of Mitchum et al. (1977), Roy (1994), Vail et al. (1977), and Van Wagoner et al. (1988).

Techniques

The first step was to identify and map marine and coastal deposits and to integrate them into a series of morpho-sedimentary units, taking into account the available sedimentological, faunal and tectonic data, radiometric dating, and archaeological information. Outcrops and drill cores were used to study the lithology and facies, including some sedimentary structures, and to collect samples for laboratory analyses such as detailed sedimentology, environmental magnetism, ^{14}C dating, stable carbon and oxygen isotopes, and palaeontology (pollen, microfauna, and macrofauna).

Samples from spit deposits were collected by excavating 1 to 1.4 m down into the swales separating beach ridges in order to reach the upper foreshore or berm facies (close to mean sea level: MSL). Shells of the mollusc *Glycymeris glycymeris* tend to accumulate here and are relatively common. Ages and rates of progradation were calculated from radiometric dating of mollusc samples collected across the spits. We designed the sampling patterns according to detailed mapping of the units, in order to identify and eliminate the reworked shells.

Samples from both estuaries and the peat bog were obtained from cores of drill holes bored to 8 m depth with manual and percussion mechanical drills and to 40 m with conventional mechanical rotation drilling. Sampling intervals ranged from 0.1 m in Las Madres to 0.2 m in Guadalete. Sample depths refer to surface elevations of drill sites, which are between 0 and 2.00 m above MSL. Several trenches dug in the Las Madres peat bog allowed to collect samples at elevations of 5.00, 4.60 and 4.40 m above MSL (Table 1).

A Coulter LS 130 counter was used for grain-size analyses. Measurement of environmental magnetism (Lario 1996) included low and high-frequency magnetic susceptibility, anhysteretic remanent magnetisation, isothermal remanent magnetisation, and saturation isothermal remanent magnetisation. The results obtained were inconclusive and therefore they have not been shown in this paper although we have used them to get additional information about the source of sediments.

Ages expressed in ^{14}C yr BP are normalised and corrected for the marine reservoir effect. In the North Atlantic this effect has been calculated to be between −400 and −500 years (Stuiver et al. 1986, Bard 1988, Shouton et al. 1990). In our study area, the reservoir

Table 1. Database of ^{14}C samples and results. The ^{14}C ages are corrected for reservoir effect (–440 ± 85 yr BP.

Estuary	Sample code	Locality	Material	Depth (m)	Laboratory code	^{14}C age (yr BP)	Error (±)	δ^{13}C‰ (PDB)	Reference
GUADALETE									
Drill core	PSM104/C0	Guadalete tidal flat	plant debris	4.80	GX-20913(*)	3505	55	–25.50	Goy et al. 1996
Drill core	PSM104/C3	Guadalete tidal flat	shell	8.30	GX-20914(*)	5445	105	0.50	Goy et al. 1996
Drill core	PSM104/C5	Guadalete tidal flat	shell	11.55	GX-20925(*)	5980	95	1.00	Goy et al. 1996
Drill core	PSM104/C9	Guadalete tidal flat	shell	15.20	GX-20916(*)	7180	100	-0.30	Goy et al. 1996
Drill core	PSM104/C11	Guadalete tidal flat	shell	20.00	GX-20917(*)	7400	95	-0.10	Goy et al. 1996
Drill core	PSM104/C15	Guadalete tidal flat	shell	21.50	GX-20918	7600	100	-0.10	Goy et al. 1996
Drill core	PSM104/C20	Guadalete tidal flat	peat	24.77	GX-20919	8915	100	–28.40	Dabrio et al. 1995
Drill core	PSM104/C21	Guadalete tidal flat	peat	24.95	GX-20920	9495	340	–27.80	Dabrio et al. 1995
Drill core	PSM102/18	Guadalete tidal flat	shell	3.00	GX-21802(*)	5965	125	0.90	
Drill core	PSM102/3	Guadalete tidal flat	shell	8.50	GX-21803(*)	5980	105	0.80	
Drill core	PSM105/3	Guadalete tidal flat	shell	6.00	GX-21840	110	135	–1.60	
Drill core	PSM105/4	Guadalete tidal flat	shell	1.60	GX-21804(*)	210	100	–3.00	
Drill core	PSM105/5	Guadalete tidal flat	plant debris	1.00	GX-21839	275	155	–27.70	
Drill core	PSM106/5	Guadalete tidal flat	plant debris	2.00	GX-21841	5240	690	–31.70	
Drill core	PSM107/1	Guadalete tidal flat	plant debris	28.80	GX-21842	9620	170	–28.20	
Drill core	PSM108/6	Guadalete tidal flat	shell	6.80	GX-21805(*)	2545	100	–1.70	
Drill core	PSM109/4	Guadalete tidal flat	plant debris	27.80	GX–21843	9620	260	–29.70	
Drill core	PSM109/7	Guadalete tidal flat	shell	9.50	GX-21806(*)	3770	105	–1.30	
Drill core	PSM110/1	Guadalete tidal flat	shell	3.80	GX-21807(*)	5310	100	–2.10	
Drill core	PSM110/2	Guadalete tidal flat	shell	5.00	GX-21808(*)	5740	100	0.40	
Trench	C–3	Valdelagrana spit	shell	0.00	R-2182	1880	100	1.43	Zazo et al. 1994
Trench	C-4	Valdelagrana spit	shell	0.00	R-2208	2705	100		Zazo et al. 1994
Trench	C–5	Valdelagrana spit	shell	0.00	R-2181	1830	100	1.42	Zazo et al. 1994
Trench	C-6	Valdelagrana spit	shell	0.00	R-2186	1680	100	1.48	Zazo et al. 1994
GUADALQUIVIR									
Drill core	P13–1	Lucio del Pescador	twigs	7.30	UtC-4028(*)	2490	60		
Drill core	P13–2	Lucio del Pescador	shell	7.30	UtC-4031(*)	2490	105	–2.90	
ODIEL-TINTO									
Drill core	SN9/1	Odiel tidal flat	shell	22.00	GX-21809	8340	105	–3.20	
Drill core	SN9/2	Odiel tidal flat	shell	18.80	GX-21810	6630	105	0.70	
Drill core	SN9/3	Odiel tidal flat	shell	15.50	GX-21811	6825	105	-0.30	
Drill core	SN9/4	Odiel tidal flat	shell	13.80	GX-21812	5675	100	–1.20	
Drill core	SN9/5	Odiel tidal flat	shell	13.05	GX-21813	5870	100	–1.00	
Drill core	SN9/6	Odiel tidal flat	shell	9.75	GX-21814	2050	100	–2.20	
Drill core	SN9/7	Odiel tidal flat	shell	5.50	GX-21815(*)	960	100	-0.50	
Drill core	SN11/1	Odiel tidal flat	plant debris	2.60	GX-21816(*)	150	45	–26.20	
Drill core	SN11/2	Odiel tidal flat	shell	3.30	GX-21817(*)	215	95	–2.00	
Drill core	SN11/3	Odiel tidal flat	shell	7.60	GX-21844	1780	255	–1.30	
Drill core	SN11/4	Odiel tidal flat	shell	10.00	GX-21818(*)	3295	105	–1.40	
Drill core	SN11/5	Odiel tidal flat	shell	15.20	GX-21819(*)	6715	115	0.30	
Drill core	SN11/6	Odiel tidal flat	plant debris	24.00	GX-21820(*)	25340	400	–27.40	
Drill core	SN11/7	Odiel tidal flat	plant debris	25.20	GX-21821(*)	30705	400	–26.70	
Drill core	SN11/8	Odiel tidal flat	plant debris	25.45	GX-21845	26210	+4740 –2960	–28.20	
Trench	PU95-1	Punta Umbría spit	shell	0.00	GX-20907	2875	110	1.50	Goy et al. 1996
Trench	PU95-2	Punta Umbría spit	shell	0.00	GX-20908	3115	115	1.80	Goy et al. 1996
Trench	PU95-3	Punta Umbría spit	shell	0.00	GX-20909	1460	110	1.80	Goy et al. 1996
Trench	H94-1	El Acebuchal (Saltés I.)	shell	0.00	UtC-4182(*)	5100	110	1.75	
Trench	H94-2	El Acebuchal (Saltés I.)	shell	0.00	UtC-4185(*)	1900	105	1.33	
Trench	H94-3	La Cascajera (Saltés I.)	shell	0.00	IRPA-1157	2705	90	1.74	
Trench	H94-4	La Cascajera (Saltés I.)	shell	0.00	IRPA-1158	2675	90	1.82	
Trench	H94-5	La Cascajera (Saltés I.)	shell	0.00	UtC-4190(*)	1290	105	1.55	
Trench	H94-6	La Cascajera (Saltés I.)	shell	0.00	UtC-4186(*)	1360	100	1.58	
Trench	H94-7	La Cascajera (Saltés I.)	shell	0.00	UtC-4187(*)	1300	115	1.36	
Trench	H94-8	Punta Arenilla spit	shell	0.00	IRPA-1164	2950	95	1.49	
Trench	H94-9	Punta Arenilla spit	shell	0.00	IRPA-1156	3220	95	1.30	

Table 1. Continued.

Estuary	Sample code	Locality	Material	Depth (m)	Laboratory code	^{14}C age (yr BP)	Error (±)	$\delta^{13}C$‰ (PDB)	Reference
Trench	LM-4-C6	Las Madres peat bog	peaty sand	+5.00	LGQ-1021	960	200		Zazo et al. 1996b
Trench	LM-4-C7	Las Madres peat bog	peaty sand	+4.60	LGQ-1022	1090	170		Zazo et al. 1996b
Trench	LM-4-C8	Las Madres peat bog	peaty sand	+4.40	LGQ-1023	1150	190		Zazo et al. 1996b
Drill core	LM1b/M11	Las Madres peat bog	peat	+2.00	UtC-4029	2550	60		Zazo et al. 1996b
Drill core	LM1b/M14b	Las Madres peat bog	organic mud	+1.30	UtC-4027	3520	60		Zazo et al. 1996b
Drill core	LM1b/M16b	Las Madres peat bog	organic mud	+0.55	UtC-4030	4450	70		Zazo et al. 1996b
Drill core	LM1/M8	Las Madres peat bog	peat	0.70	UtC-4023	5480	60		Zazo et al. 1996b

Key to laboratories: GX: Geochron Laboratories, Krueger Enterprises, Inc., Cambridge (USA); IRPA: Institut Royal du Patrimoine Artistique, Brussels (Belgium); LGQ: Laboratoire du Geologie du Quatemaire, CNRS, Marseille (France); R: Centro di Studio per la Geodinamica Applicata a la Stratigrafia Recente, CNR Dipartamento Fisica, Universita 'La Sapienza', Roma (Italy); UtC: Utrecht, Van der Graaff (Netherlands). Asterisks (*) indicate AMS analysis. Depths of drill core samples in metres below the high-tide mark, considered as MSL. This is also the case in Figures 3, 4, 5, 8 and 9. However, some drill sites in these figures are actually at elevations up to 1.3 m above MSL. This introduces small errors. Depths of samples collected in trenches refer to MSL. Values marked + in Las Madres peat bog indicate elevations above MSL.

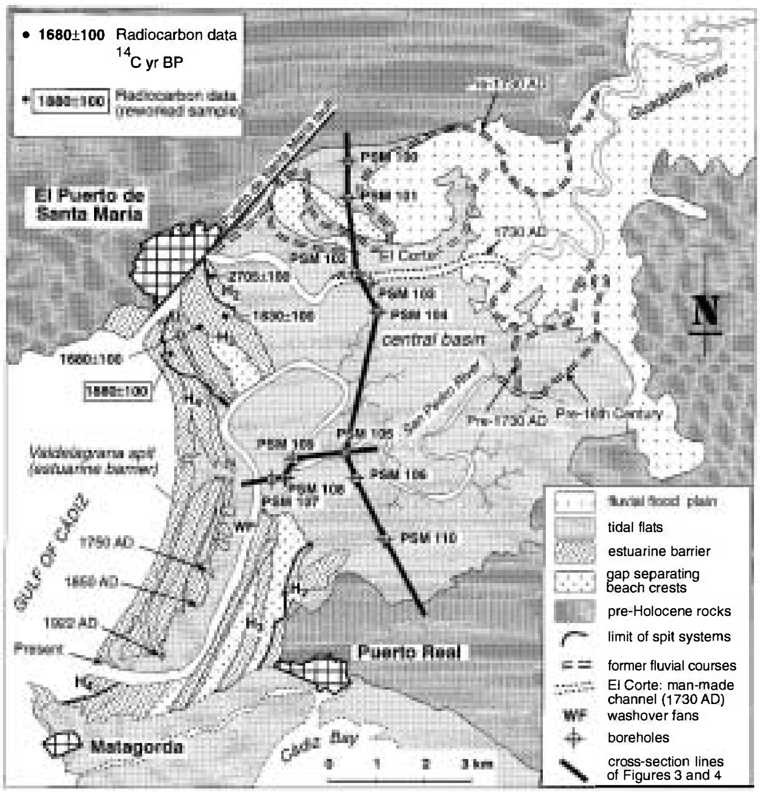

Figure 2. The Guadalete estuary and Valdelagrana spit system. Note the breached relatively small Valdelagrana spit that existed in the second half of the 18th century and three washover fans ca. 3.5 km west of drill site PSM 110, which may be related to the 1755 Lisbon earthquake. (PSM: Puerto de Santa Maria drillings).

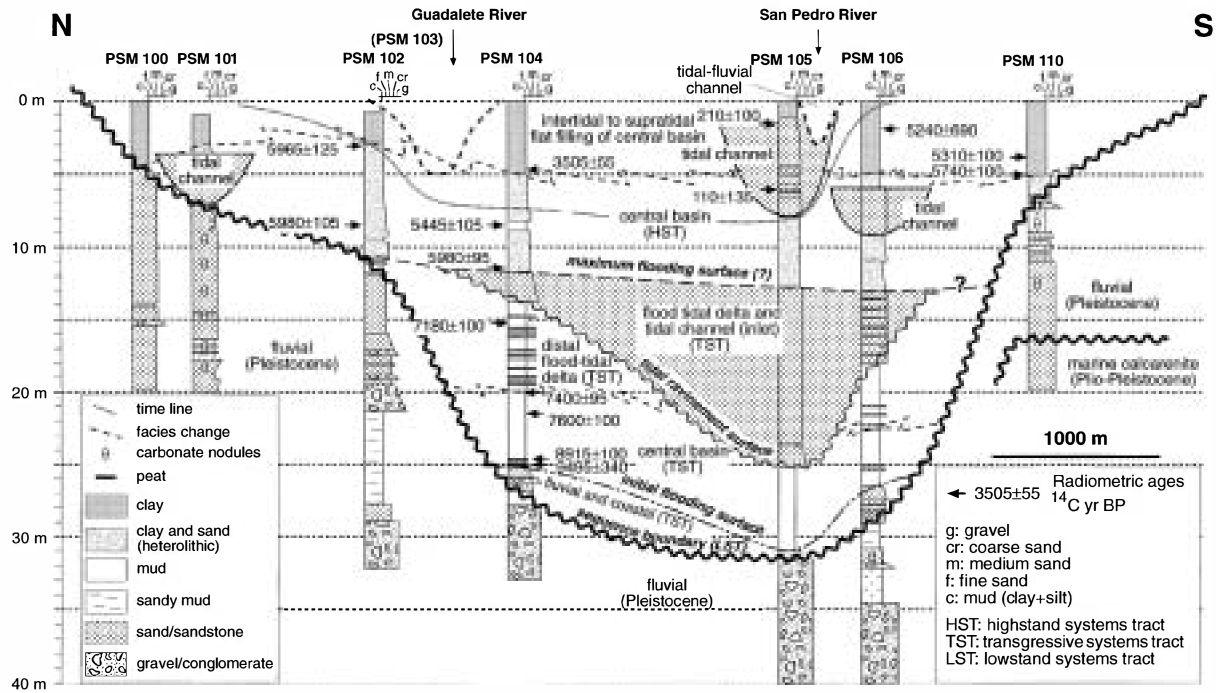

Figure 3. North-south cross section of the estuarine facies in the Guadalete incised-valley fill. Location in Figure 2.

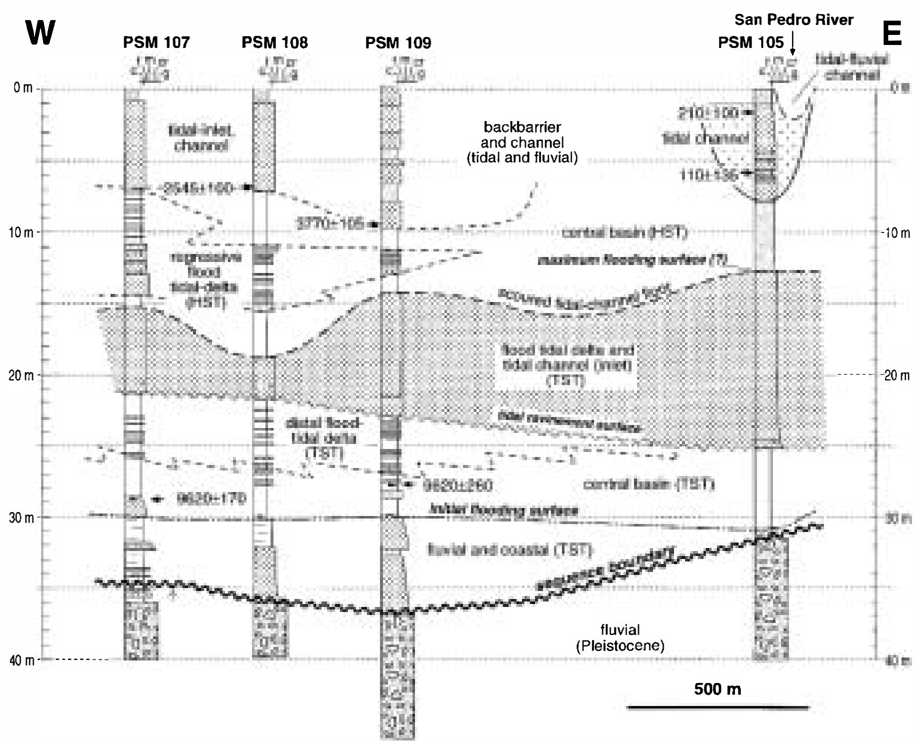

Figure 4. East-west cross section of the estuarine facies in the Guadalete incised-valley fill. Same legend as Figure 3. Location in Figure 2.

effect has been calculated as -440 ± 85 ^{14}C yr BP by means of two accelerator mass spectrometry (AMS) ablation probes carried out on organic material and on a shell collected in the same layer of the lower reaches of the Guadalquivir river (samples P13/1 and P13/2, Table 1, Figure 1). We have corrected the radiocarbon ages of all samples of marine shells cited in this paper to get a more precise correlation with data from non-marine realms.

Palaeontological studies included taphonomy (fragmentation, abrasion, bioerosion, and bioencrustation), palaeoecology of macrofauna and microfauna, and analysis of pollen and diatoms. Studies of the vertical variation of fossil content within the cores have been very rewarding, as indicated later. In contrast, the study of diatoms did not yield consistent results.

Stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) were studied with mass spectrometry in more than 40 samples. Each sample consisted of four well-preserved shells of the benthic foraminifer *Ammonia* sp. without internal fill. Since the variation of the ice volume accumulated at high latitudes has been very low during the last 9000 yr, these isotopic parameters have changed very little during Holocene times. Thus, we assume that temporal isotopic changes recorded in the area are related to local factors, in particular, the isotopic compositions of estuarine waters that are controlled by salinity and temperature.

The Guadalete estuary and Valdelagrana spit

The bay of Guadalete underwent tectonic subsidence during the Quaternary. Movements along the Puerto de Santa María and Cádiz faults favoured the positioning of the Guadalete river valley, opening to the west (Figures 1, 2). River incision took place during the Last Glacial period. During the postglacial rise of sea level, the seaward reaches of the valley were inundated and acted as a wave-dominated estuary separated from the sea by the complex Valdelagrana spit. Correlation of 11 drill cores in the estuary, and 32 drill logs in the Valdelagrana spit allows to identify and trace sedimentary units, and to reconstruct the sequence stratigraphy both across and along the axis of the valley fill (Figures 3, 4).

Lithostratigraphy and environmental interpretation

Pre-estuarine fluvial sediments. Underlying the Holocene estuarine deposits is a lithosome of fluvial sediments (Figure 3). It consists of a fining-upwards pile of well-rounded polygenetic conglomerates, sandstones with interbedded layers of matrix-supported pebbles, and mudstones. Dominant colours are yellow and greenish, with vertically elongated leached zones interpreted as root casts. Carbonate nodules, locally elongated vertically, and having botryoidal shapes are also frequent. We interpret this succession as deposited by a braided river, with more or less swampy flood plains.

The age of this lithosome is unknown because we could find no material suitable for dating. Radiometric dating of a similar sequence of rocks in the Odiel-Tinto estuary yielded ages ranging between 25 000 and 30 000 ^{14}C yr BP (Table 1). Accordingly, we infer a Late Pleistocene age. Therefore, we assume that the fluvial lithosome is the lowstand systems tract (LST) of the last fourth-order eustatic cycle of Vail et al. (1977).

The Guadalete river cut an incised valley into the fluvial deposits, prior to the postglacial (Late Pleistocene-Holocene) sea level rise. This erosion is related to the maximum of the Last Glacial period when sea level dropped 120 m, as recorded in the Gulf of Cádiz continental shelf (Somoza et al. 1994).

The morphology of the erosional surface across the relatively narrow fluvial valley was reconstructed in cross sections using core data (Figures 3, 4). It is interesting to note that the deepest part of the incision tends to occur towards the south-east of the axis of the present estuary. During the ensuing transgression a part of the valley was flooded and transformed into the Guadalete estuary. Thus, the erosional surface is a type-1 sequence boundary (as used in Van Wagoner et al. 1988).

Estuarine deposition took place during the transgressive and the highstand phases of the fourth-order eustatic cycle. Five facies can be distinguished:

Transgressive fluvial and marine facies. The first evidence of marine conditions found above the sequence boundary is a layer of grey sands with fragments of Scaphopoda and Balanidae. Locally it occurs associated with nonfossiliferous yellow gravel and sand, very much like the previously described fluvial deposits. It is capped by grey-greenish mudstones with abundant plant debris that form discrete peat layers of centimetre thickness. Radiometric dating of such peat layers indicates an Early Holocene age (samples PSM104/C20: 8915 ± 100, and PSM104/C21: 9495 ± 340 ^{14}C yr BP, Table 1).

We interpret the alternating marine and fluviatile deposits to belong to the transgressive systems tract (TST). They record a changing limit of terrestrial and coastal environments during the fluctuating rise of sea level in Late Pleistocene and Early Holocene times. They accumulated in the topographically lowest parts of the incised valley which were the first to be reached by the advancing seas. Therefore, these rocks can be considered as a rudimentary bay-head delta, partly reworked during the ensuing transgression. The sequence boundary and the transgressive surface (Van Wagoner et al. 1988) are represented by the same erosional surface.

The upper limit of the transgressive fluviatile and marine unit is a channel-shaped erosional surface that we interpret as the initial flooding surface (sensu Allen & Posamentier 1993, 1994). Probably, the morphology of the surface was inherited in part from the former fluvial channel.

Grey mudstone facies (transgressive central-basin deposits). The lower, deepest part of the estuary fill, between 25 and 21.7 m depth in core PSM 104, consists of well-sorted grey to greenish mudstone (medium grain size 0.004 to 0.002 mm) with scattered shells, very often complete. No internal sedimentary structure was observed with the naked eye. However, laboratory evidence reveals changes in stable isotope and faunal contents for the upper part of the section (Figure 5). In particular, percentages of the benthic foraminifera *Haynesina germanica* and *Elphidium excavatum* decrease upwards.

The fossil content in the lower half (25 to 23.4 m) of the interval sampled shows low diversity. It consists of fragments of Cardiidae and Rissoidae, and abundant plant debris. Low values in $\delta PDB^{18}O$ and $\delta PDB^{13}C$ indicate a relatively low salinity and/or warm water. These values tend to increase upwards, with several oscillations.

The faunal diversity of the upper half (23.4 to 21.7 m) is higher, albeit low. There are miliolids and echinoderms and abundant *Bittium reticulatum*, *Cardium* sp. and rissoids; however, *Haynesina germanica* and *Elphidium excavatum* decrease. This fauna indicates a more marine environment.

Mudstone and shell layers facies (transgressive distal backbarrier). This facies consists of silty clay, with fine silts (grain size 0.015625 mm) dominating towards the top. Interbedded layers, typically 2 to 20 mm thick, of medium to poorly sorted, fine and medium sands, and shell accumulations (coquinas), occur irregularly spaced at intervals in the order of tens of centimetres. The species diversity is high, with many remains of *Ostrea* sp. and *Bittium reticulatum*, other gastropods, bryozoans, scaphopods, and crustaceans. Traces of bioerosion by Clyonidae spongids are abundant. High percentages of miliolids and echinoderm fragments, coupled with heavier values of stable isotopes are clear indicators of open marine waters (Figure 5, interval 20.5 to 13.8 m).

We interpret the interbedded coarse-grained layers as a distal fringe of washover and flood-tidal-delta deposits on the landward side of the estuarine barrier (Figures 3, 4). Backbarrier deposits prograded into the central basin of the estuary during the transgression, interfingering with the mudstone facies ca. 7400 to 7180 ^{14}C yr BP. A large part of the mudstone and shell layers facies was removed by erosion at the bottom of the main estuarine channel or tidal inlet between ca. 7000 and 6000 ^{14}C yr BP. We consider the resulting erosional surface as a tidal ravinement surface (Allen 1991, Allen & Posamentier 1993) similar to those described in other estuaries (Dalrymple et al. 1992, 1994, Zaitlin et al. 1994).

Sand facies (flood-tidal delta and tidal channel or inlet). This sand unit is the largest; it can be traced easily in longitudinal profiles of the estuary, but does not extend very much across it (Figures 3, 4). This is a clear indication of a channel fill or channel-related origin. Unfortunately, drilling techniques did not preserve the original sedimentary structures.

This facies consists of medium light-grey sand grading upwards to fine sand. Millimetre to centimetre-thick layers of silt and silty clay occur interbedded within the sand. A 5-cm-thick mud layer near the base was traced in various cores (Figure 4, depth: 20.7 m in PSM 108, 21.6 m in PSM 109, 24.8 in PSM 105). The fossil content of the sand facies consists of complete single shells and fragments of *Cardium* sp., and of bioclasts of bivalves and gastropods.

We interpret the sand facies as deposited in the proximal backbarrier, most probably in flood-tidal deltas, where communities of benthic molluscs settled. However, we could not recognise sedimentary structures to prove this. The concurrence of tides, of seasonal changes in river input, and of storm overwash, deposited the sand layers. The intervening mudstone layers settled from suspension during quiet episodes.

The curve of stable isotopes in core interval 13.8 to 12.5 m in PSM 104 records a decrease which can be interpreted as a reduction of salinity (Figure 5). It may record the last stages of the transgression and the co-

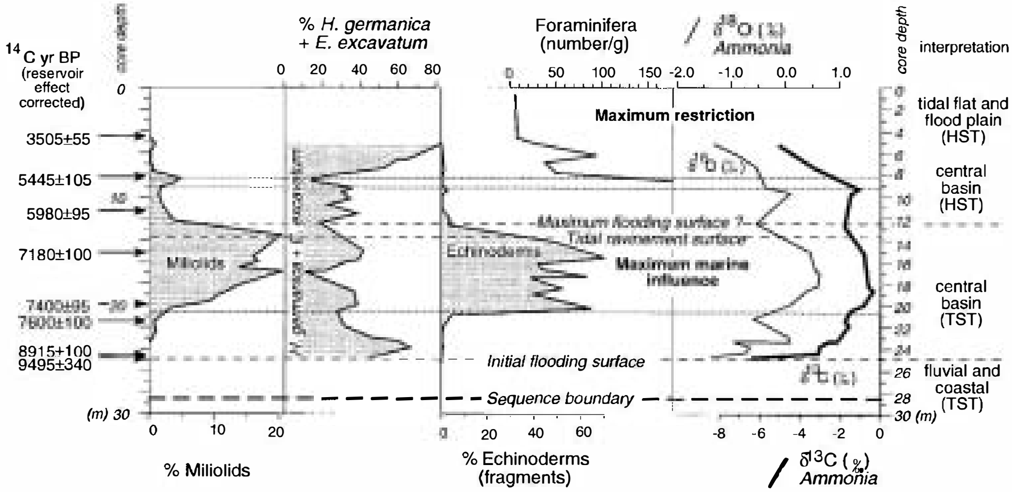

Figure 5. Fossil content and stable isotope (δPDB^{18}O and δPDB^{13}C) curves of core PSM 104 in the Guadalete estuary. See Figure 3 for lithology. The percentages of miliolids and those of *Haynesina germanica* and *Elphidium excavatum* represent their relative abundances in the assemblages of benthic foraminifera. The percentage of echinoderms is the relative abundance of echinoderm fragments in relation to total biogenic particles (bioclasts). Foraminifera (number/g) is the number of benthic foraminifera per gram of dry sediment. This number exceeds 170 from 8.5 m down to 25 m.

eval increase of the fluvial contribution of fresh water to the estuarine basin.

The top of this sand body is rather flat in a section across the valley, but is clearly erosional in an axial section (Figures 3, 4). We have tentatively placed the maximum flooding surface at the flat uneroded top of the sand body. The erosional surface visible in the axial section is interpreted as the bottom of the tidal inlet that was left behind, and buried once the barrier began prograding seawards during the early highstand.

Heterolithic facies of the highstand systems tract (HST). The upper parts of the cores consist of finely interlayered grey mudstone and light-grey, parallel-laminated fine sand. An overall fining upwards grain-size trend is usually recognised, and locally repeated several times vertically. In some cores, metre-thick layers of fine sand occur interbedded.

Fossils, particularly gastropods and *Cardium* sp., are usually abundant; locally, wood fragments also occur. The diagrams of fossil content show a reduction of miliolids and the absence of echinoderm fragments (core PSM 104, Figure 5, interval 10 to 5 m). Percentages of the benthic foraminifers *H. germanica* and *E. excavatum* living in the restricted tidal-flat environments increase upwards. The δ^{18}O and δ^{13}C curves constructed from data of *Ammonia* spp. both record a decrease towards the top. The inflexions of both curves at 9 m are close to higher percentages of miliolids and lower contents of *H. germanica* and *E. excavatum* at 8 m, and may perhaps be related to a minor rise of sea level at ca. 5445 $\pm$ 105 ^{14}C yr BP (Figures 3, 5, Table 1).

The heterolithic, clay and sand facies are interpreted as vertically accreted sand flats fed mainly by fluvially derived sediment. Study of cores did not reveal a cyclic pattern similar to those described for tidally-influenced settings.

The sand bodies included in the heterolithic facies at ca. 7.5 to 3.5 m in core PSM 101, and ca. 9 to 6.5 m in core PSM 106 (Figure 3), consist of fine grey sand with interbedded thin layers of mud. They have a scarce fossil content that is concentrated mostly in their upper parts. This fauna is similar to that of the sand units described in the other estuarine facies. These bodies are interpreted as meandering tidal channels of the lower intertidal flat.

A particularly thick sand body occurs between 8 and 2 m in PSM 105. Its lower half exhibits a fining upwards sequence recorded in the increasing number of fine-grained intercalations. The fossil content includes *Cardium* sp., very often fragmented, and plant remains. This facies very much resembles a tidal flat. In contrast, the upper half consists of fine sand with scattered mollusc shells and bioclasts. This is interpreted as repeated incision and filling of a meandering tidal channel which produced a multi-storey sand body. According to radiometric dating it is younger than 500 ^{14}C yr BP (Figure 3 , Table 1).

The topmost part of the heterolithic facies consists of burrowed brown clay. The upwards increasing occurrence of small lenticular gypsum crystals, and the scarcity of fossils indicate environmental restriction. The absence of *A. beccarii* prevented isotope analysis. The clay facies are interpreted to have been deposited in high intertidal to supratidal flats inside the estuary with daily subaerial exposure.

Palaeogeographical interpretation and discussion (Figure 6)

The described succession of facies forming the incised-valley fill of the Guadalete river closely matches the vertical sequence found in many wave-dominated estuaries (Dalrymple et al. 1992, 1994, Roy 1994, Zaitlin et al. 1994). The LST is represented by an erosional surface cut by the river during the lowstand (Figures 3, 4). It is a type-1 sequence boundary (Van Wagoner et al. 1988). As no fluvial deposits associated with the lowstand could be positively identified this surface coincides with the transgressive surface. The bulk of estuarine deposition inside the incised valley corresponds to the transgressive and highstand systems tracts.

The thin fluvial and marine facies in the deepest part of the incised valley were deposited during the transgression, as demonstrated by the scattered marine fossils. Thus, they are the first recognised deposits of the TST, and record the landward retreat of the fluvial-marine interface. They are separated from the overlying marine facies by an initial flooding surface.

The TST comprises central-basin mudstone facies of increasing salinity. The coarsening upwards deposits reveal the advance of the estuarine barrier and related backbarrier environments (washover fans, flood-tidal delta and tidal inlet) towards the central basin. Later incision by tidal channels in the estuary inlet was recorded as a ravinement surface that, locally, is 13 m deep (Figure 3).

The HST includes muddy (central basin), heterolithic (tidal sand flat and tidal meanders) and clay facies (central basin). It records the filling of the estuary by river-supplied sediments, and the transformation into a river-dominated flood plain, via intertidal to supratidal flats. Channel-shaped sand bodies of variable thickness represent subtidal and intertidal meandering channels. The diachronism of the vertical change from intertidal to supratidal facies, observed in cross section (Figure 3), evidences the centripetal progradation of the tidal flats (Figure 6).

The upwards increasing restriction on life conditions recorded in the transgressive and highstand systems tracts results from the vertical aggradation of sediments and the rise of the estuary floor from subtidal to inter and supratidal. The interchange of waters with the open sea is progressively reduced, magnifying the relative importance of the input of fluvial waters to the tidal flats. Assemblages of highly tolerant euryhaline benthic foraminifera shift accordingly to match the ever-changing conditions: *A. beccarii, H. germanica*, and *E. excavatum* are the most abundant taxa in the proximal, inner estuarine areas, while miliolids are only abundant in the more distal regions, towards the nearshore, where they are accompanied by echinoderms. The reduced number of taxa contrasts with the high number of individuals, owing to reduced competition and predation, and high nutrient concentration.

A major goal of our study was to relate the filling of the estuary with the accumulation of the estuarine barriers, in the context of the regional phases of progradation H_1 to H_4. Detailed mapping of morpho-sedimentary units in the estuarine barrier and radiometric dating of samples collected there allow to recognise deposits of spit systems H_2 to H_4 (Figure 2, Table 1). The oldest date in the emergent part of the estuarine barrier is 2705 ± 100 ^{14}C yr BP, i.e. H_2.

We have found no subaerial H_1 deposits in the Valdelagrana area so far. However, their existence is supported by the fact that a large part of the estuary filling, and the change from inter- to supratidal took place between 6000 and 5000 yr BP (Figures 3, 4, 6). The subaerial part of the H_1 barrier has probably been removed by erosion. Unfortunately, we could not sample deep enough in Valdelagrana and we ignore in how far the barrier has been preserved in the subsurface.

It is interesting to point out that subaerial H_1 deposits have neither been found in the other estuaries of the Gulf of Cádiz, regardless of their wave-or tide-dominated dynamic regime. This is the case even in estuary mouths with well-developed spit systems.

We suggest thatthis absence of the subaerial part of H_1 is due to a combination of factors. H1 was deposited immediately after the maximum flooding, when a large part of the river input was retained inside the bay-head delta and did not reach the estuarine barrier. This probably means that the estuarine barrier was not particularly large, and that most of it was eroded before, or even during the time of H_1 deposition by tidal-inlet shift. Further evidence for this is that the preserved

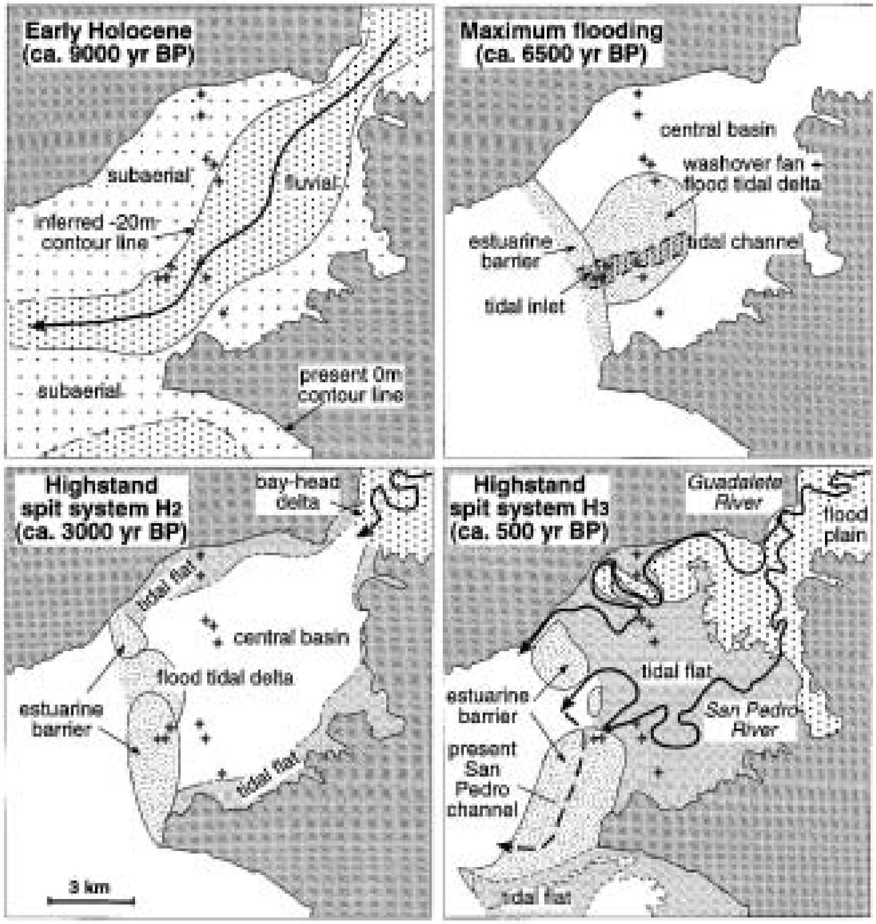

Figure 6. Schematic maps showing the changing palaeogeography of the Guadalete incised valley (the limit between 'exposed' and 'fluvial' represents an inferred contour line 20 m below present MSL). Constructed with data from drill cores and maps by INTECSA (Internacional de Ingeniería y Estudios Técnicos S.A.), and maps of an anonymous author (1740–1750), Barnola (1743), Rodolphe (1750), Coello (1842–1858), Tofiño de San Miguel (1789), and Rambaud (1996).

subaerial part of H_2 is also very modest and consists largely of a last-generation tidal inlet and ebb delta that occur 2 km west of site PSM 110 (Figure 2). This seems to indicate that the only parts of the estuarine barrier spared from erosion during H_1 and H_2 were close to the margins of the estuary-mouth, far enough from the tidal inlets that continuously cannibalised the barrier (Figure 6). The best preserved vestiges of the H_1 and H_2 estuarine barriers lie probably in the clastic wedge interpreted as a regressive flood-tidal delta, and found 8 to 15 m below MSL (Figure 4). The absence of morpho-sedimentary units of H_1 age can be interpreted as a proof that MSL during the Flandrian transgression was approximately the same as at present. Otherwise, coastal barriers left behind during the ensuing slight fall of sea level would have had a better chance to be preserved as stranded sandy crests.

Morpho-sedimentary analysis of spits and tidal inlets indicates that there were two main estuarine channels, roughly coincident with the present Guadalete and San Pedro rivers, as late as the 18th century (Figures 2, 6). These channels supplied sand to the coastal areas as demonstrated by radiometric ages of shells from the channel fill (cores PSM 108 and 109). The spits did not completely close the bay.

The relative importance of the northern Guadalete distributary as a supplier of sand to the coastal zone increased after public works in 1730 AD. The renewed input of sand to the northern extremity of the H_4 estuarine barrier favoured the rapid growth of a spit, largely the present Valdelagrana spit, towards the south (Rambaud 1996), sheltering, in the pro-

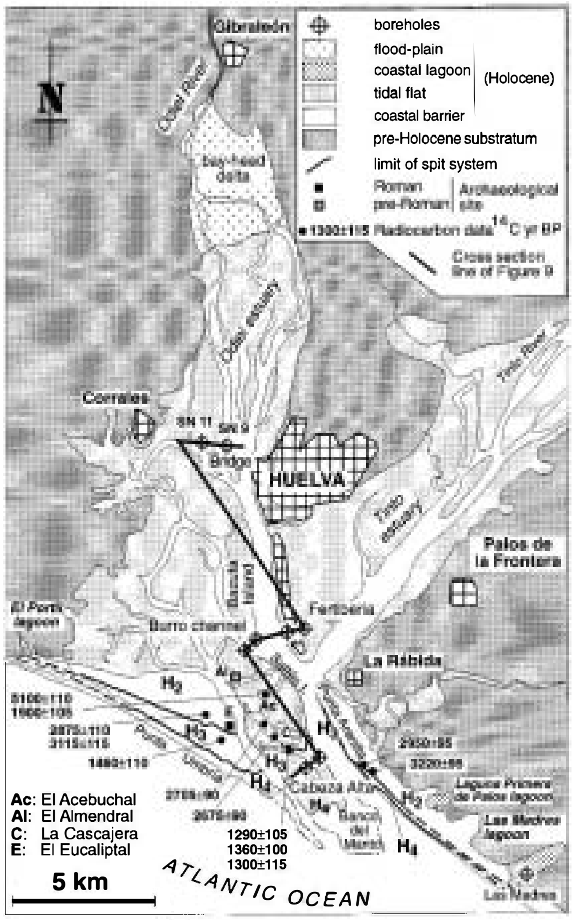

Figure 7. Odiel-Tinto estuary and estuarine barrier formed by the spit systems of Punta Arenilla and Punta Umbría, and the complex Saltés Island. Heavy lines separate spit units H_2 to H_4. Drill sites are the bridge between Huelva and Corrales (SN-9 and SN-11), Fertiberia factory (F-6, F-7 and F-14), and Saltés Island at Burro Channel (BC-11 to BC-17) and Cabeza Alta (CA-20 and CA-21). Note that several holes were drilled in some sites.

cess, the mouth of the axial channel. A set of three washover fans dissecting the spit existing at ca. 1750 AD (Figure 2) may be the result of the 1755 Lisbon earthquake.

Erosion by the residual, meandering axial distributary of the Guadalete river destroyed a part of the H_3 estuarine barrier. Eventually the abandoned and almost filled channel became the residual meandering tidal channel, known as the San Pedro river, which is no longer fed by the main river, but ends aimlessly in the intricate supratidal flats (Figure 2).

Odiel-Tinto estuary and Punta Umbría spit

The confluence of the Odiel and Tinto rivers at Huelva town forms a complex bifurcate estuary (Figure 7). Both branches are funnel-shaped. The Odiel-Tinto estuary is of the mixed, tide-and wave-dominated type and, at present, it is largely filled by supratidal flats (marismas). Active tidal flats occur, nowadays, only south of Saltés Island (Borrego 1992). The Odiel river has deposited a bay-head delta at the northern extremity of its estuary, near the village of Gibraleón. Nowadays, the estuary is partly enclosed by the spit systems of Punta Arenilla which grows to the northwest, and Punta Umbría which progrades in the opposite direction.

To study the evolution of sedimentary infill we used two continuous drill cores (SN 9 and 11) in the tidal flats of the inner, more enclosed estuary, and 30 logs of reconnaissance drills at Saltés Island and the Fertiberia factory near the junction of the rivers.

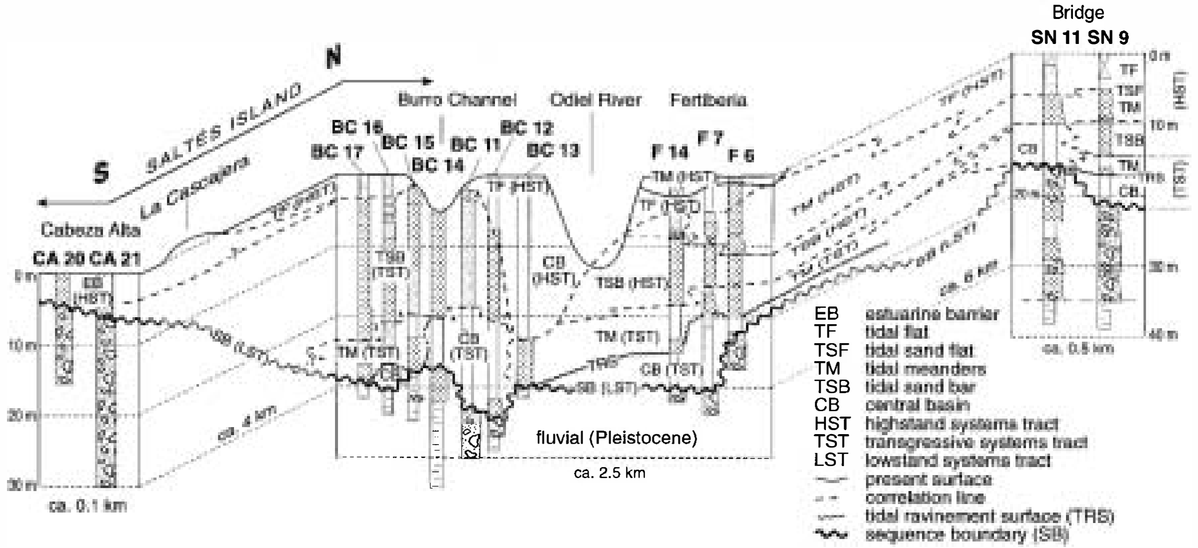

Figure 9. Generalised longitudinal section of the Odiel-Tinto estuary with sequence stratigraphy of the incised-valley fill. Note that the section comprises three sets of drillings that trend roughly at right angles to the valley axis (Figure 7). Legend in Figure 3.

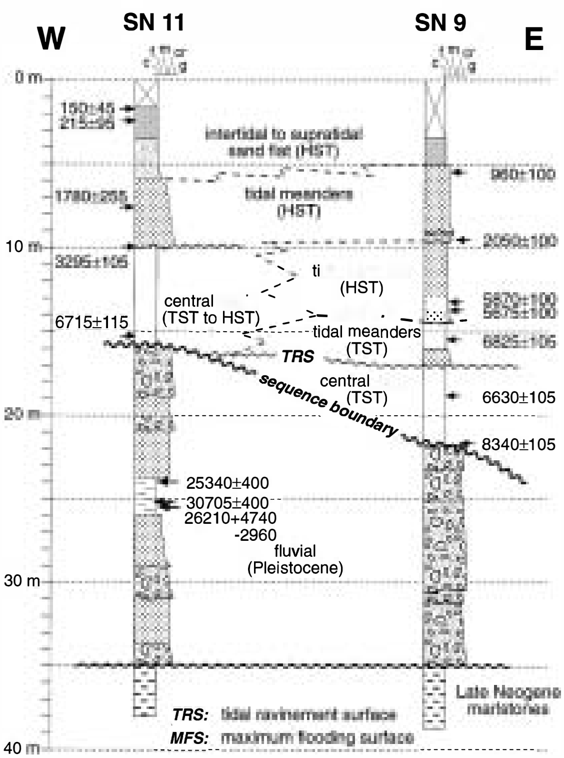

Figure 8. Lithological logs of drill cores, radiocarbon ages, and sequence stratigraphy of the western branch (Odiel) of the Odiel-Tinto estuary. Location in Figure 7. Legend in Figure 3.

Lithostratigraphy and environmental interpretation

The pre-Holocene substratum consists of Late Neogene marlstones that are followed upwards by an erosional surface, and then, yellow gravel with predominantly quartzite pebbles up to 0.10 m in diameter, yellow siliciclastic sand, and grey-greenish sandy mudstone arranged in fining-upwards sequences (Figure 8). Reddish colours with vertical discoloured patches indicate plant roots and subaerial conditions. We interpret the rocks above the erosional surface as deposits of braided or sinuous rivers, and correlate them with the pre-estuarine lithosome in the Guadalete estuary.

Wood fragments in the mudstone interval were used for AMS radiometric dating. Samples collected in the middle part of the interval were dated as ca. 25 000 to 30 000 ^{14}C yr BP (Table 1, Figure 8). We were unable to date samples from the upper part of the unit.

River erosion in the Late Pleistocene cut an incised valley, generating a type-1 sequence boundary. A part of the incised valley was flooded during the postglacial rise of sea level, and transformed into a mixed tide-and-wave-dominated estuary that has been largely filled with transgressive and highstand deposits during Holocene times. As in the Guadalete estuary, the Late Pleistocene and Holocene deposits form an incomplete fourth-order depositional sequence.

The estuary fill includes five facies that are briefly described below.

Mud facies of the central basin (TST and HST) consist of grey mudstone with scattered wood fragments. Abundant remains of *Donax trunculus* and *Cardium* sp., and also of possible *Gastrana* sp., are restricted to a few layers. Comparison of the radiometric ages yielded by the lowermost fossils sampled in the central estuarine deposits just above the erosional sequence boundary, indicates that sedimentation began much earlier in the topographically lower parts of the incised valley than in more elevated areas (sample SN 9/1, ca. 8340 ± 105 ^{14}C yr BP, and sample SN 11/5, ca. 6715 ± 115 ^{14}C yr BP, located 6 m higher; Figure 8). As shells in the last sample have linked valves, we infer coastal onlap during the Holocene sea-level rise that culminated in the Holocene maximum flooding at ca. 6500 ^{14}C yr BP.

Tidal meanders sand facies (TST and HST) consist of layers of sand, one to several metres thick, which fine upwards and change into grey mudstone (Figures 8, 9). Above the erosional base of the channel-fill, coarser grain sizes and the larger mechanically accumulated shells of *Cardium* occur, with some *Gryphaea* (including two-valved specimens), other ostreids, and gastropods. Large *Cardium* are common in the upper parts of the sandy intervals, and co-occur with *Chamelea*, rissoids, and wood fragments. Radiometric ages suggest reworking and mixing of shells in the channels.

Tidal sand bar facies (TST and HST) consist of fine grey sand with *Ostrea*, *Cardium*, *Solen*, *Chamelea*, *Dentalium*, and nassariids. Layers of *Ostrea* occur towards the top. Radiocarbon dating indicates reworking of fossils because older dates occur above younger ones (e.g. Figure 8). We interpret these facies as shoals in the estuarine channel.

Intertidal to supratidal sandflat facies (HST) form the topmost part of the tidal sand flats and the associated tidal meanders (Figure 9). They exhibit a fining-upwards trend and the sediment becomes grey to brownish clay, often crossed by plant roots. These facies were deposited when the crest of the sand bar approached the present MSL and became inter to supratidal.

The prograding facies of the estuarine barrier (HST) comprise yellowish sands with abundant shells of molluscs. A large part of these facies is exposed subaerially in the spits and on Saltés Island (Figures 7, 9). The beach ridges carry a cover of aeolian deposits.

The evolution of the estuarine barrier during the HST has been studied by several authors, mostly from a morphological point of view. Suárez Bores (1971) used isotopic measurements to date the subaerial parts of the El Almendral (3200 yr BP) and La Cascajera (2700 yr BP) spits, both on Saltés Island. Goy et al. (1996) added more radiometric measurements of samples collected on the Punta Umbría spit, and related them to the progradation phases H_2 to H_4. Archaeological data have been used by Almagro et al. (1975) who cited pre-Roman remains in the El Almendral spit, and by Amo (1976) who described Roman remains in El Eucaliptal near Punta Umbría (Figure 7).

Palaeogeographical interpretation and discussion (Figure 10)

Despite the irregular distribution of the borehole sites, the correlation of drill cores allows a reconstruction of the Odiel-Tinto estuarine valley filling in sequence-stratigraphic terms (Figure 9). The erosional type-1 sequence boundary lies ca. 5 to 35 m below present MSL and it is patently irregular, particularly in sections which are more or less transverse to the estuary axis. The unexpected topographically elevated relief made up of Pleistocene deposits under the present Saltés Island probably conditioned the accumulation of sand bars at the bay mouth, forming a shoal as early as the transgressive maximum. The grain-size distribution suggests an offlapping pattern and a landward progradation of the bars into the muddy central basin.

The history of the Las Madres peat bog, located close to the entrance of the Odiel-Tinto estuary, is interesting. During the lowstand, fluvial incision deepened the valley of Las Madres which was later inundated during the post-glacial sea-level rise, forming an open-marine embayment (Figure 10). Shortly after the maximum sea-level rise, the small bay was isolated from the sea by a beach barrier and transformed into a lagoon ca. 5480 ± 60 ^{14}C yr BP (Table 1). The very existence of prograding beach ridges at the south-eastern side of the bay mouth, in the area where the initial Punta Arenilla spit was attached to the shore, is a strong indication of the early development of spits at, or near the entrance to the estuary during the H_1 phase.

The occurrence of marine shells well inside the Odiel-Tinto estuary beyond the topographic constriction formed by pre-Holocene deposits proves that open estuarine conditions existed at least until ca. 3295 ± 105 ^{14}C yr BP. Strong tidal influence in the funnel-shaped estuary did not favour the development of estuarine barriers and spits until relatively

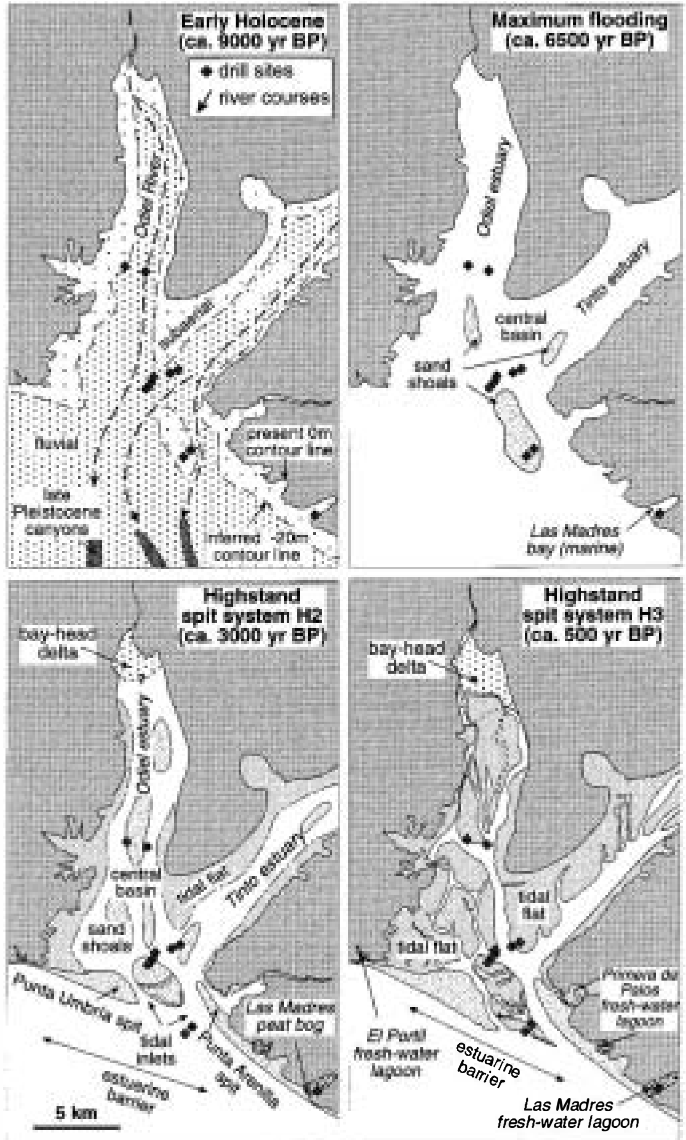

Figure 10. Schematic maps showing the changing palaeogeography of the Odiel-Tinto incised valley. The limit between 'exposed' and 'fluvial' represents an inferred contour line 20 m below present MSL. Constructed with data from drill cores and data from Cimentaciones Especiales S.A., GEOCISA (Geotecnia y Cimientos S.A.), and Laboratorio de Análisis Industriales VORSEVI S.A.

late stages. This, together with the reduced sediment supply shortly after the maximum transgression may explain the lack of subaerial remains of H_1. Shells of H_1 age occur in cores and at the surface, but they are reworked and incorporated into younger units (Lario 1996).

Therefore, the study of the chronology and vegetation of the Las Madres peat bog allowed Zazo et al. (1996b) to conclude that the first spit to form in the estuary was Punta Arenilla. We could not observe deposits of this spit, despite intense digging, because it is covered at present by aeolian dunes. Most probably a large part of it has been eroded recently by longshore drift.

The growth of a coastal barrier between Las Madres and the open sea transformed the valley into a peat bog under fresh-water conditions ca. 4000 ^{14}C yr BP (Zazo et al. 1996b), i.e. during the H_2 phase. The barrier closing the peat bog extends to the Punta Arenilla spit (Figure 7). Peat formation and isolation from the sea lasted until 960 ± 200 ^{14}C yr BP (Table 1), simultaneously with the development of H_2 and H_3 spit systems at the eastern side of the estuary mouth. Later, probably during the time separating H_3 and H_4, there was a temporal, but short, partial connection with the sea that inhibited peat generation.

Progradation of the Punta Arenilla and Punta Umbría spits and the emergence of small parts of Saltés Island are characteristic of the H_2 and H_3 phases. There is no proof that Punta Umbría and Saltés were connected. The asymmetrical sedimentation pattern, produced by flood-tidal currents flowing close to the eastern side of the estuary and by ebb tides running close to the western side, favours the opposite growth of the Punta Arenilla and Punta Umbría spits. The same pattern may be clearly recognised since the early stages of H_2 growth. This seems to indicate that Punta Umbría and Saltés Island were independent.

The morphology of beach ridges of Punta Umbría, Punta Arenilla, and Saltés Island has been interpreted in different ways. Figueroa & Clemente (1979) supposed that the Punta Umbría spit and Saltés Island each grew independently. In contrast, Rodríguez Vidal (1987) and Lario (1996) think that the Punta Umbría spit and Saltés Island (except Cabeza Alta) formed a single body ca. 2500 yr BP when they became separated by a tidal inlet. After studying sedimentary environments in the estuary, Borrego (1992) concluded that the spit of Punta Arenilla was deposited before the emergence of the spits on Saltés Island, which emergence took place more or less simultaneously with the beginning of the deposition of the Punta Umbría spit.

Dabrio & Polo (1987) and Zazo et al. (1992) offered palaeogeographical reconstructions of the estuary and the spit systems but did not give a precise dating. Zazo et al. (1996b) dated the spits and related them to the progradation phases recognised in the littoral area of southern Spain, and Goy et al. (1996) and Lario (1996) added more radiometric measurements of the studied area.

Noticeable changes in coastal dynamics took place between the H_2 and H_3 phases (ca. 2550–2300 ^{14}C yr BP). The best recorded in the Gulf of Cádiz is a change in prevailing winds from W to WSW (Zazo et al. this issue). This change caused partial erosion of the estuarine barriers. After this time, spits growing to the east and southeast prevailed over spits accreting in opposite directions. We observed this in the Odiel-Tinto and Guadalete estuaries, and also in the other estuaries in the Gulf of Cádiz (Guadalquivir, Piedras, and Guadiana, Figure 1).

The dominance of *Cardium* in the upper 10 m of cores SN 9 and 11 indicates restricted environmental conditions inside the Odiel-Tinto estuary. We relate this to increased sheltering by the Punta Umbría spit as it grew towards the south-east. This is supported by radiometric ages of shell accumulations in the spit (Figure 7, Table 1).

Concluding remarks

The incised-valley fills along the Gulf of Cádiz record a fourth-order depositional sequence, still incomplete. The lower limit is a type-1 boundary surface produced by river incision during the lowstand of the Last Glacial period ca. 18 000 ^{14}C yr BP.

The absence of lowstand fluvial deposits, and the modest development of fluvial-to-marine deposits acting as a transgressive, rudimentary bay-head delta, indicate high rates of sea level rise between 14 000 and 10 500 ^{14}C yr BP (cf. Zazo et al. this issue). A part of the incised valley of the Guadalete river evolved into a wave-dominated estuary, whereas the estuarine parts of the Odiel and Tinto rivers became dominated by tides and waves. At present, both estuaries are largely filled with sediments deposited during the TST and HST phases of the eustatic cycle.

The maximum advance of barriers into the estuarine basins occurred between ca. 7000 and 6000 ^{14}C yr BP. The ages of deposits overlying the inferred maximum flooding surface probably narrow this gap to ca. 6500 to 6000 ^{14}C yr BP. There is no evidence of sea level rising appreciably above the present MSL during this Flandrian transgression. However, a small positive sea-level oscillation may have occurred ca. 5500 ^{14}C yr BP, as suggested by isotopic values in the Guadalete estuary.

A large part of the estuary fills is of H_1 age (ca. 6554–4400 ^{14}C yr BP). In contrast, no subaerial parts of the H_1 estuarine barriers are known. In the Odiel-Tinto estuary, the dominance of tides did not favour spit development. In the Guadalete estuary, the absence of estuarine barriers results from the concurrence of reduced input of fluvial sands to the bay mouth, and of erosion by laterally shifting tidal inlets. Indirect evidence from the Las Madres peat bog indicates that H_1 deposits did accumulate. The only remains of H_1 estuarine barriers are found at the bases of the sequences close to the thalwegs of the studied incised valleys. It is most unlikely that H_1 deposits will ever be found in the emergent parts of spit barrier complexes.

During the H_2 phase (ca. 4200–2550 ^{14}C yr BP), most of the estuarine sedimentation was concentrated in tidal meanders (Odiel-Tinto estuary) and intertidal to supratidal flats (Guadalete estuary) of the axial zones. Restrictions on life conditions increased during this phase. Estuarine barriers grew noticeably, although continued shifting of tidal inlets destroyed a large part of the subaerial barrier in the Guadalete estuary. Rapid coastal accretion separated the Las Madres lagoon from the sea and transformed it into a peat bog under relatively arid conditions. Aridity must have enhanced soil degradation and erosion, and thus increased the amount of sand available for the littoral drift that allowed spit growth in opposite directions. The aridity increased from ca. 3000 ^{14}C yr BP onwards (cf. Zazo et al. this issue).

Between the H_2 and H_3 phases (ca. 2550–2300 ^{14}C yr BP) a change in prevailing winds from W to WSW strongly affected the estuarine barriers causing partial erosion and spits growing mainly to the east and south-east.

During the H_3 phase (ca. 2300–800 ^{14}C yr BP), the estuarine deposits in the mixed, tide-and-wave-dominated Odiel-Tinto estuary are largely tidal meanders and tidal sand flats. Rapid growth occurred at the Punta Umbría spit and Saltés Island in contrast to more modest rates in Punta Arenilla. This is partly a result of the mutually avoiding pathways followed by flood and ebb tides: east and west respectively. This pattern is still active at present. In the Guadalete estuary, rapid seaward progradation accumulated a wide estuarine barrier mostly fed by the axial distributary channel. Tidal flats were covered by flood-plain deposits starting at the innermost parts. As the accommodation space in the largely filled estuaries had been greatly reduced by this time, most of the sediment by-passed them and was delivered to the coast. Arid conditions and increasing agriculture and mining (e.g. in the catchment area of the Tinto river) magnified the relative importance of fluvial transport and the effects of longshore drift. By the end of the phase, the peat bog of Las Madres ceased to exist after a short-lived connection with the sea.

The H_4 phase (ca. 500 ^{14}C yr BP to the present) records further advance of bay-head deltas and flood plains over large areas of the estuaries, particularly in Guadalete. The residual estuarine basins act as by-pass tracts for fluvial transport and large volumes of sand have been supplied to the longshore drift, enhancing the longitudinal growth of spits. Wind directions shifted to the south-west. Human activity triggered rapid modifications of the shoreline such as in the Valdelagrana spit complex. Three large washovers, breaching one of the older spits may be the result of the 1755 Lisbon earthquake.

As the climatic influence on coastal changes is a major issue of our research, some attention must be paid to the Little Ice Age (ca. 1550–1850 AD). Several arguments favour an influence of this climatic deterioration on the recorded coastal changes but it is difficult to separate this from man-induced phenomena. Rates of estuary filling in SW Spain increased considerably in the last 500 yr (H_4), with coastal progradation amounting to up to 1.8 m/yr. Progradation was prominent during the 16th, 17th, and especially the 18th century (Lario et al. 1995). Analysing the frequency of major floods of the Guadalquivir river since the 15th century, a noticeable increase is observed since 1550, and especially after 1600 (Menanteau 1979). A period of less frequent floods lasting from 1650 to about 1750 partly coincides with the Maunder Minimum (1672–1708). However, the largest flood ever occurred in 1709, just at the end of this minimum. There is presently a direct relationship between catastrophic floods caused by heavy rains concentrated in a few hours and the occurrence of atmospheric 'cold drops' during spring and early autumn, when the meteorological dynamic regimes of the Mediterranean Sea and the Atlantic Ocean interfere with each other (Zazo et al. 1994). In addition, it must be stressed that, as a whole, dune generation in SW Spain increased in the last 200 yr, that is to say largely after the Little Ice Age (Zazo et al. this issue). Therefore, a climatic control on these floods and the related increase in the filling of estuaries, and on the generation of aeolian dunes seems probable. However, a variety of other, man-induced processes also played a role in triggering, or at least magnifying, these phenomena. They include changing cultivation methods and the abandonment of cultivated land; in addition intensive mining required fire-wood to melt minerals, and led to deforestation and increased runoff and damage during floods (Lario et al. 1995). Increased rates of coastal progradation suggest a stable or slightly falling mean sea level during the Little Ice Age (Zazo et al. 1994) but, as pointed out above, there are other factors to be considered.

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References

Allen, G. 1991 Sedimentary processes and facies in the Gironde estuary: A recent model of mesotidal estuarine systems. In: Smith, D.G., G.E. Reinson, B.A. Zaitlin & R.A. Rahmani (eds) Clastic Tidal Sedimentology. Canadian Soc. Petrol. Geol. Mem. 16: 29–39

Allen, G.P. & H.W. Posamentier 1993 Sequence stratigraphy and facies model of an incised valley fill: the Gironde estuary, France – J. Sedim. Petrology 63: 378–391

Allen, G.P. & H.W. Posamentier 1994 Transgressive facies and sequence architecture in mixed tide-and wave-dominated incised valleys: example from the Gironde estuary, France. In: Dalrymple, R.W., R. Boyd & B.A. Zaitlin (eds) Incised-valley Systems: Origin and Sedimentary Sequences. Soc. Econ. Paleontol. Mineral. Spec. Publ. 51: 225–240

Almagro, M., M. del Amo, A. Beltrán, A. Blanco, C. Cerdán, M. Fernández-Miranda, J.P. Garrido, G. Leisner, P. Leisner, J. Luzón & E.M. Orta 1975 Huelva. Prehistoria y Antigüedad. Editorial Nacional, Madrid, 320 pp

Amo, M. del 1976 Restos materiales de la población romana de Onuba. Huelva Arqueológica, II. Publicaciones del Museo de Huelva e Instituto Onubense Padre Marchena. Ediciones Excma. Diputación Huelva, 200 pp

Anonymous 1740–1750 Mapa del Puerto de Santa María. Número de Catálogo 941. In: Servicio Cartográfico del Ejército (ed.) Cartoteca Histórica, Índice de Atlas Universales y Mapas y Planos Históricos de España 1974. Madrid, 268 pp

Bard, E. 1988 Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: Paleoceanographic implications – Paleoceanography 3: 634–645

Barnola, J. 1743 Plano general que demuestra el estado actual de la Bahia, puerto de Cádiz y sus contornos. Museo Naval, Catalogue number 93. In: Marín Meras, L. & B. Rivera (eds) Catálogo de Cartografía histórica de España del Museo Naval de Madrid. Museo Naval-Ministerio de Defensa, Madrid 1990, 435 pp

Borrego, J. 1992 Sedimentología del Estuario del Río Odiel. Huelva. SW España. PhD Thesis. University of Sevilla, 308 pp

Borrego, J., J.A. Morales & J.G. Pendón 1993 Holocene filling of an estuarine lagoon along the mesotidal Coast of Huelva: The Piedras river mouth, southwestern Spain – J. Coastal Res. 8: 321–343

Coello, F. 1842–1858 Atlas de España y Posesiones de Ultramar. Planos de Provincia, Bahía, Contorno de Cádiz. Map 34 (1: 100,000), Madrid

Dabrio, C.J. & Polo, M.D. 1987 Holocene sea-level changes, coastal dynamics and human impacts in southern Iberian Peninsula. In: Zazo, C. (ed.) Late Quaternary Sea-level Changes in Spain. Museo Nal. Ciencias Naturales, CSIC. 10: 227–247

Dabrio, C.J., J.L. Goy, J. Lario, C. Zazo, F. Borja & A. González 1995 The Guadalete estuary during the Holocene times (Bay of Cadiz, Spain) – International Union for Quaternary Research (INQUA), Subcommission on Mediterranean and Black Sea Shorelines (MBSS) Newsletter 17: 19–22

Dalrymple, R.W., B.A. Zaitlin & R. Boyd 1992 Estuarine facies models: Conceptual basis and stratigraphic implications – J. Sedim. Petrology 62: 1130–1146

Dalrymple, R.W., R. Boyd & B.A. Zaitlin 1994 History of research, types and internal organization of incised-valley systems: introduction to the volume. In: Dalrymple, R.W., R. Boyd & B.A. Zaitlin (eds) Incised-valley Systems: Origin and Sedimentary Sequences. Soc. Econ. Paleontol. Mineral. Spec. Publ. 51: 3–10

Figueroa, M.E. & L. Clemente 1979 Dinámica geomorfológica del Estuario de los ríos Tinto y Odiel (Huelva). Aplicación a la ordenación del territorio. IV Reunión Nacional Estudio Cuaternario, Bañolas. 2 pp

Gavala y Laborde, J. 1959 Explicación de la hoja n° 1061 (Cádiz) del mapa geológico de España a escala 1: 50.000. Apéndice: El poema 'Ora maritima' de Rufo Festo Avieno. Madrid, Servicio Publicaciones Instituto Geológico y Minero de España (IGME), Madrid, 139 pp

Goy, J.L., C. Zazo, C.J. Dabrio & C. Hillaire-Marcel 1986 Evolution des systèmes de lagoons-îles barrière du Tyrrhénien a l'actualité à Campo de Dalías (Almería, Espagne) – Editions Orstom, Paris, Coll. Travaux et Documents 197: 169–171

Goy, J.L., C. Zazo, C.J. Dabrio, J. Lario, F. Borja, F.J. Sierro & J.A. Flores 1996 Global and regional factors controlling changes of coastlines in southern Iberia (Spain) during the Holocene – Quaternary Sci. Rev. 15: 773–780

Goy, J.L., C. Zazo & J. Cuerda 1997 Evolución de los margino-litorales de la costa de Mallorca (Islas Baleares) durante el Último y Presente Interglacial. Nivel del mar Holoceno y clima – Bol. Geol. Min. 108: 455–463

Lario, J. 1996 Último y Presente Interglacial en el área de conexión Atlántico-Mediterráneo (Sur de España). Variaciones del nivel del mar, paleoclima y paleoambientes. PhD Thesis. University Complutense and CSIC, Madrid, 269 pp

Lario, J., C. Zazo, C.J. Dabrio, L. Somoza, J.L. Goy, T. Bardají & P.G. Silva 1995 Record of recent Holocene sediment input on spit bars and deltas of south Spain – J. Coastal Res., Spec. Issue 17: 241–245

Menanteau, L. 1979 Les marismes du Guadalquivir. Example de transformation d'un paysage alluvial au cours du Quaternaire récent. Thèse 3ème cycle, Université Paris Sorbonne, 154 pp

Mitchum, R.M. Jr., P.R. Vail & S. Thompson III 1977 Seismic stratigraphy and global changes of sea level. Part 2: The depositional sequence as a basic unit for stratigraphic analysis. In: Payton, C.E. (ed.) Seismic Stratigraphy. Applications to Hydrocarbon Exploration. Amer. Assoc. Petrol. Geol. Mem. 26: 53–62

Morales, J.A. 1993 Sedimentología del Estuario del Rio Guadiana. (SO España-Portugal). PhD Thesis. University of Huelva, 300 pp

Rambaud, F. 1996 Portus Gaditanus. Hipótesis de un nuevo emplazamiento – Revista Arqueología (Madrid) 187: 28–35

Rodolphe, A. 1750 Puerto de Santa Maria. Número de Catálogo 942. In: Servicio Cartográfico del Ejército (ed.) Cartoteca Histórica, Índice de Atlas Universales y Mapas y Planos Históricos de España 1974. Madrid, 268 pp

Rodríguez Vidal, J. 1987 Modelo de evolución geomorfológica de la Flecha Litoral de Punta Umbría, Huelva, España – Cuaternario y Geomorfología 1: 247–256

Roy, P.S. 1994 Holocene estuary evolution – Stratigraphic studies from southeastern Australia. In: Dalrymple, R.W., R. Boyd & B.A. Zaitlin (eds) Incised-valley Systems: Origin and Sedimentary Sequences. Soc. Econ. Paleontol. Mineral. Spec. Publ. 51: 241–263

Shouton, J.R., D.E. Nelson & J.S. Vogel 1990 A record of past ocean-atmosphere radiocarbon differences from Northeast Pacific – Paleoceanography 5: 197–206

Somoza, L., J.R. Andrés, J. Rey, F.J. Hernández-Molina, J. Rodríguez Vidal, L. Clemente, A. Rodríguez Ramírez & V. Díaz del Río 1994 Morpho-depositional evolution of the Cadiz Gulf Continental Shelf: GOLCA (Golfo de Cádiz) Project. I Simpósio Margem Continental Ibèrica Atlantica, Lisboa. Abstracts Volume, 55: 65–68

Stuiver, M., G.W. Pearson & T. Brazunias 1986 Radiocarbon age calibration of marine shells back to 9.000 yrBP – Radiocarbon 28: 980–1021

Suárez Bores, P. 1971 Determinación de la edad mediante medidas del contenido carbono-14, en muestras de conchas procedentes de los litorales de Huelva y Valencia. Gabinete de Aplicaciones Nucleares a Obras Públicas, Madrid. 13 pp

Tofiño de San Miguel, V. 1789 Plano del Puerto de Cádiz. Número de Catálogo 34. In: Servicio Cartográfico del Ejército (ed.) Cartoteca Histórica, Índice de Atlas Universales y Mapas y Planos Históricos de España 1974. Madrid, 268 pp

Vail, P.R., R.M. Mitchum & S. Thompson, III 1977 Part 4: Global cycles of Relative changes of Sea Level. In: Payton, C.E. (ed.) Seismic Stratigraphy-Applications to Hydrocarbon Exploration. Amer. Assoc. Petrol. Geol. Mem. 26: 83–97

Van Wagoner, J.C., H.W. Posamentier, R.M. Mitchum, P.R. Vail, J.F. Sarg, T.S. Loutit & J. Hardenbol 1988 An overview of the fundamentals of sequence stratigraphy and key definitions. In: Wilgus, C.K., B.S. Hastings, C.G.St.C. Kendall, H.W. Posamentier, C.A. Ross & J.C. Van Wagoner (eds) Sea-level Changes: An Integrated Approach. Soc. Econ. Paleontol. Mineral. Spec. Publ. 42: 39–45

Zaitlin, B.A., R.W. Dalrymple & R. Boyd 1994 The stratigraphic organization of incised-valley systems associated with relative sea-level change. In: Dalrymple, R.W., R. Boyd & B.A. Zaitlin (eds) Incised-valley Systems: Origin and Sedimentary Sequences. Soc. Econ. Paleontol. Mineral. Spec. Publ. 51: 45–60

Zazo, C., C.J. Dabrio & J.L. Goy 1992 The evolution of the coastal lowlands of Huelva and Cadiz (South-west Spain) during the Holocene. In: Tooley, M.J. & S. Jelgersma (eds) Impacts of Sea-level Rise on European Coastal Lowlands. The Institute of British Geographers, Blackwell Publishers, Oxford, Spec. Publ. 27: 204–217

Zazo, C., J.L. Goy, L. Somoza, C.J. Dabrio, G. Belluomini, S. Improta, J. Lario, T. Bardají & P.G. Silva 1994 Holocene sequence of sea-level fluctuations in relation to climatic trends in the Atlantic-Mediterranean linkage coast – J. Coastal Res. 10: 933–945

Zazo, C., C.J. Dabrio, J.L. Goy, T. Bardají, B. Ghaleb, J. Lario, M. Hoyos, C. Hillaire-Marcel, F.J. Sierro, J.A. Flores, P.G. Silva & F. Borja 1996a Cambios en la dinámica litoral y nivel del mar durante el Holoceno en el Sur de Iberia y Canarias Orientales – Geogaceta 20: 1679–1682

Zazo, C., A.M. Lezine, F. Borja, M. Denèfle, C.J. Dabrio, J. Lario, J. Rodríguez Vidal, J.L. Goy, T. Bardají, F. Díaz del Olmo, L. Cáceres, L. Clemente, C. Baeteman & A. Rodríguez Ramírez 1996b Holocene coastal progradation changes and peat bog development in SW Spanish coast – International Union for Quaternary Research (INQUA), Subcommission on Mediterranean and Black Sea Shorelines (MBSS) Newsletter 18: 13–17

Zazo, C., C.J. Dabrio, F. Borja, J.L. Goy, A.M. Lezine, J. Lario, M.D. Polo, M. Hoyos & J.R. Boersma (this issue) Pleistocene and Holocene aeolian facies on the Huelva coast (southern Spain): climatic and neotectonic implications