GLOBAL AND REGIONAL FACTORS CONTROLLING CHANGES OF COASTLINES IN SOUTHERN IBERIA (SPAIN) DURING THE HOLOCENE

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Abstract — The interaction between global (glacio-eustatic sea-level rise) and regional factors (oceanographic and tectonic) has controlled the evolution of coastline during the Holocene in Southern Iberia.

At ca. 10,000 ^{14}C years BP a deceleration of relative sea-level rise took place both in the Atlantic and Mediterranean littorals, with a maximum transgression at 6450 ^{14}C years BP. In subsiding areas (present tidal flats) estuaries illustrate a clear marine influence recorded both in sediments and the fauna while in uplifting areas prograding spit–bar systems developed. Two phases of major progradation are distinguished in these systems: the first one between 6450 and 3000 ^{14}C years BP, with a sedimentary gap at ca. 4000 ^{14}C years BP; and the second one from 2750 ^{14}C years BP up to present, with an intervening gap between 1200 and 1050 ^{14}C years BP. These progradation phases develop during stillstands followed by relative sea-level fall, while the sedimentary gaps represent relative high sea level. In the Mediterranean areas, with a higher uplift rate, marine terraces almost coeval to those gaps occur.

The most pronounced modifications in littoral dynamics occurred at between 3000 and 2750 ^{14}C years BP represented by changes in the direction of longshore drift and prevailing winds and in the predominance of progradation over aggradation processes.

At ca. 1000 ^{14}C years BP the estuaries record a greater fluvial than marine influence, and at 500 years ago an extraordinary increase in coastal progradation took place in all littoral zones. The European Medieval Warm period is characterized, at least during its initial phase, by low pressure climate conditions, while during the Little Ice Age anticyclonic conditions gave rise to a strong coastal progradation.

INTRODUCTION

Global factors, such as the general glacio-eustatic sea-level rise that took place from the Last Glacial Maximum until 6450^{14}C years BP, together with regional factors, such as tectonic or oceanographic ones, control the Holocene evolution of the coastline in the Iberian coast (Zazo *et al.*, 1996a). Here, the coasts of the Southern Iberian Peninsula, the main regional factors are: the tectonic framework (boundary between the European and African plates) with numerous active faults (Fig. 1) during the Late Pleistocene and Holocene that affected the coastline that produced areas of either uplifting or subsiding trends (Zazo *et al.*, 1994). Moreover, the area suffers the effects of the interchange of Atlantic and Mediterranean waters through the Gibraltar Strait, the present input of which bears seasonal variations, being greater in summer under anticyclonic conditions.

Detailed mapping, sedimentological analysis, archaeological and historical studies, and radiocarbon datings (Tables 1 and 2) carried out mainly in spit–bar systems, suggested the existence of two major phases of coastal progradation: the older one lasted from 6450–3000 ^{14}C years BP with a sedimentary gap or period of reduced sedimentation around ca. 4000 ^{14}C years BP; the younger one extends from 2750 ^{14}C years BP to Present, with an intervening gap in sedimentation between 1200 and 1050 ^{14}C years BP. Zazo *et al.* (1994) and Lario *et al.* (1995) have interpreted that the phases of progradation occur during periods of stillstand to gentle sea-level fall (minor lowstands), and are also related to increased entrance of 'Superficial Atlantic Waters' in the Mediterranean under anticyclonic conditions.

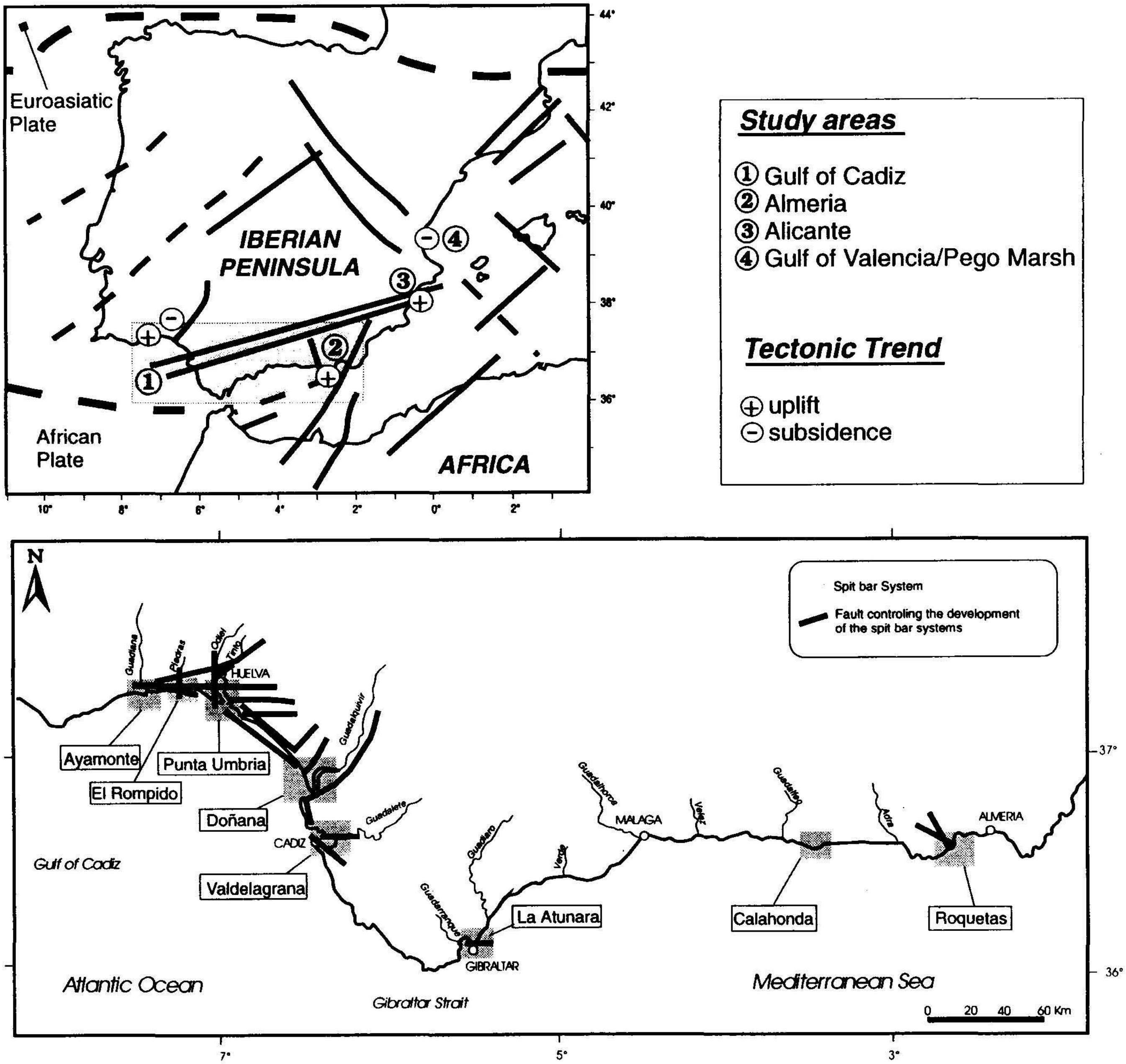

FIG. 1. Location of the study area and main fault systems affecting Late Pleistocene and Holocene coastal deposits.

More ^{14}C analysis and archaeological data, and increased availability of drill cores in the estuaries of Guadalete (Dabrio *et al.*, 1995) and Guadalquivir (Goy *et al.*, 1995) show evidence of rapid modifications to coastlines in Southern Iberia because of changes in littoral dynamics (changes in direction of prevailing winds and littoral drift) both before and after the two phases of coastal progradation (Tables 1 and 2).

The aims of this paper are: (1) to analyze the changes produced in the surveyed coastline and the main factors responsible for these changes during the Holocene, based on the analysis of the exposed morphosedimentary units (spit bars, tidal flats, deltas, alluvial plains) and drill cores from Gulf of Cadiz (Atlantic) and Gulf of Valencia (Viñals, 1991; Viñals and Fumanal, 1995); (2) to place these changes in a chronological sequence based upon radiocarbon dating (using uncorrected radiocarbon ages), archaeological, and historical data; and (3) to compare the changes with the classic climate changes described in Northern Europe.

CHANGES OF COASTLINES CA. 10,000 ^{14}C YEARS BP

Figure 2 shows the main changes observed in coastal morphology of Southern Iberian Peninsula taking into account the variable geodynamic behaviour both in tidal range (mesotidal in Atlantic and microtidal in Mediterranean) and the tectonic trend (uplift/subsidence). Data from morphosedimentary units exposed on land or drowned (estuaries, tidal flats, alluvial plains, peat

TABLE 1. ^{14}C Ages of coastal deposits from south and southeast Spain

Sample	Locality	Laboratory	^{14}C years BP	Material	Unit	Reference
PG-12	La Atunara	UQM	2675±110	shell	beach	Lario *et al.*, 1995
PG-13	La Atunara	UQM	3200±110	shell	beach	Lario *et al.*, 1995
PG-14	La Atunara	UQM	3140±120	shell	beach	Lario *et al.*, 1995
PEGO	Alicante	R-2013	6130±100	shell	beach	Viñals and Fumanal, 1995
CH-1	Calahonda	LGQ-1025	1520±170	shell	spit bar	Lario *et al.*, 1995
CH-2	Calahonda	LGQ-1026	2720±180	shell	spit bar	Lario *et al.*, 1995
CH-3	Calahonda	LGQ-1027	800±190	shell	spit bar	Lario *et al.*, 1995
CH-4	Calahonda	LGQ-1028	720±190	shell	spit bar	Lario *et al.*, 1995
R-8	Roquetas	UQM	6450±100	shell	spit bar	Goy *et al.*, 1986
R-7	Roquetas	UQM	3600±100	shell	spit bar	Goy *et al.*, 1986
R-10	Roquetas	UQM	2150±400	shell	spit bar	Goy *et al.*, 1986
R-2	Roquetas	UQM	1870±35	shell	spit bar	Goy *et al.*, 1986
F-24	La Atunara	IRPA-1159	1210±35	shell	spit bar	
H-2	El Rompido	R-2179	1460±50	shell	spit bar	Zazo *et al.*, 1994
H-3	El Rompido	R-2180	1875±50	shell	spit bar	Zazo *et al.*, 1994
H-4	El Rompido	R-2207	1440±50	shell	spit bar	Zazo *et al.*, 1994
H-5	El Rompido	R-2203	2605±50	shell	spit bar	Zazo *et al.*, 1994
D-2	Doñana	R-2187	1790±50	shell	spit bar	Zazo *et al.*, 1994
D-7	Doñana	R-2206	2185±50	shell	spit bar	Zazo *et al.*, 1994
D-9	Doñana	R-2185	1860±50	shell	spit bar	Zazo *et al.*, 1994
D-11	Doñana	R-2210	2010±50	shell	spit bar	Zazo *et al.*, 1994
D-14	Doñana	R-2204	1490±50	shell	spit bar	Zazo *et al.*, 1994
D-15	Doñana	UtC-4185	2340±60	shell	spit bar	
D-16	Doñana	UtC-4188	1650±50	shell	spit bar	
D-17	Doñana	R-2188	1850±50	shell	spit bar	Zazo *et al.*, 1994
D-18	Doñana	UtC-4192	1370±60	shell	spit bar	
C-3	Valdelagrana	R-2182	2320±50	shell	spit bar	Zazo *et al.*, 1994
C-4	Valdelagrana	R-2208	3145±50	shell	spit bar	Zazo *et al.*, 1994
C-5	Valdelagrana	R-2181	2270±50	shell	spit bar	Zazo *et al.*, 1994
C-6	Valdelagrana	R-2186	2120±50	shell	spit bar	Zazo *et al.*, 1994

deposits, spit bars, marine terraces, and aeolian dunes) have been incorporated because they are useful for dating (Tables 1 and 2) and because their variable development allows interpretation of many major changes of coastal processes, climate and sea level.

Letters and symbols, in Fig. 2, indicate some processes of coastal dynamics (changes in littoral drift, or wind directions, fauna, and trends of relative sea level) that have been recorded and dated with a certain degree of confidence in the morphosedimentary units. Approximate present elevations of some morphosedimentary units (datum: Present Mean Sea Level, MSL) are indicated.

Drill cores from the Mediterranean area, particularly in the alluvial plain of Valencia Gulf (Viñals, 1991; Viñals and Fumanal, 1995), and in tidal flats of the Gulf of Cadiz (Dabrio *et al.*, 1995; Goy *et al.*, 1995; Zazo *et al.*, 1996b) indicate that the 'global' glacio-eustatic relative rise of sea level prior to ca. 10,000 ^{14}C years BP experienced a deceleration that favoured the start of development of peat layers that occur interbedded in lagoonal deposits (Mediterranean coast) or on intertidal flat sediments (Atlantic coast) (Fig. 3). A series of prograding bodies occurring in the shelf at about 50–60 m water depth are interpreted as stillstand deposits (Hernández-Molina *et al.*, 1994).

EVOLUTION OF THE COASTLINE BETWEEN CA. 10,000 AND 6450 ^{14}C YEARS BP

Atlantic Littoral

Wind patterns recorded in the systems of coastal dunes forming the present Asperillo cliff (northwest of the Guadalquivir estuary, Huelva coast), an area with an uplift trend, show a change in the direction of prevailing winds (Borja and Díaz del Olmo, 1995) between two dune deposits separated by a layer rich in organic matter dated (Tables 1 and 2) as ca. 10,000 ^{14}C years BP (Zazo *et al.*, 1996a). Wind directions changed from SW to W (palaeocurrents pointing towards the NE and E respectively).

Cores drilled in tidal flats of the Gulf of Cadiz (Fig. 3) record the rise of sea level as estuarine clay that directly overlay peat layers. Upward increase in sand content and faunal content indicate partial filling of the estuary and development of tidal flats.

Analysis of microfauna (Fig. 4) reveals a noticeable increase of Miliolids and fragments of Echinoderms and a decrease of *Haynesina germanica* and *Elphidium excavatum* in sediments deposited between 8000 and 7000 ^{14}C years BP. We think that the change is related to more-open marine conditions in the estuaries during this time.

TABLE 1. *cont'd*

Sample	Locality	Laboratory	^{14}C yearsBP	Material	Unit	Reference
PU95-1	Punta Umbría	GX-20907	3315±70	shell	spit bar	
PU95-2	Punta Umbría	GX-20908	3555±75	shell	spit bar	
PU95-3	Punta Umbría	GX-20909	1900±70	shell	spit bar	
IC95-1	Ayamonte (I.Canela)	GX-20899	835±65	shell	spit bar	
IC95-3	Ayamonte (I.Canela)	GX-20900	3130±70	shell	spit bar	
AG-1	Alicante	SAN-CEDEX	5190±300	shell	marine terrace	Gozalvez, 1985
AG-2	Alicante	SAN-CEDEX	3640±330	shell	marine terrace	Gozalvez, 1985
AG-4	Alicante	SAN-CEDEX	5540±170	shell	marine terrace	Gozalvez, 1985
F-17	S.Roque-La Atunara	UtC-4189[1]	2760±50	shell	marine terrace	
PEGO-1	Alicante	UBAR-77	10,120±460	organic mud	marsh	Viñals and Fumanal, 1995
PEGO-3	Alicante	UBAR-78	8300±90	organic mud	marsh[2]	Viñals, 1991
PEGO-5	Alicante	UBAR-43	7120±90	organic mud	marsh[2]	Viñals, 1991
LP-13	Guadalquivir	UtC-4026[1]	2490±60	twigs	estuary[2]	
LP-13	Guadalquivir	UtC-4031[1]	2930±60	shell	estuary[2]	
PSM104/C0	Guadalete	GX-20913[1]	3505±55	organic muds	estuary[2]	
PSM104/C3	Guadalete	GX-20914[1]	5885±60	shell	estuary[2]	
PSM104/C5	Guadalete	GX-20925[1]	6420±45	shell	estuary[2]	
PSM104/C9	Guadalete	GX-20916[1]	7620±55	shell	estuary[2]	
PSM104/C11	Guadalete	GX-20917[1]	7840±45	shell	estuary[2]	
PSM104/C15	Guadalete	GX-20918[1]	8040±55	shell	estuary[2]	
PSM104/C20	Guadalete	GX-20919	8915±100	peat	estuary[2]	Dabrio *et al.*, 1995
PSM104/C21	Guadalete	GX-20920	9495±340	peat	estuary[2]	Dabrio *et al.*, 1995
A-7	El Asperillo	LGQ-759	10,500±50	peaty sand	dune slack	Zazo *et al.*, 1996a
A-7B	El Asperillo	LGQ-897	11,240±220	peaty sand	dune slack	Zazo *et al.*, 1996a

(1) AMS; (2) core Laboratories: UQM - GEOTOP, Université du Québèc à Montreal, H3C 3P8 Montréal, Canada; R - Dip. Fisica, Centro di Studio per la Geochimica Aplicata, Universitá 'La Sapienza', Roma, Italy; LGQ - Lab. de Géologie du Quaternaire, CNRS, Luminy, 13288 Marseille, France; IRPA - Institute Royal du Patrimonie Artistique, 1040 Bruxelles, Belgium; UtC - R.J. Van de Graaf Lab. 35080 TA Utrecht, The Netherlands; GX - Geochron Laboratory, Cambridge, Massachusetts, 02138 USA; SAN CEDEX - Serv. Aplic.Nucleares, Centro de Est. y Experiment. de O.P., Madrid, Sapin. UBAR - Dept. Química Analítica, Universidad de Barcelona, CETA - CEDEX, Barcelona, Spain.

Mediterranean Littoral

A layer of basal peat found in cores drilled in the Pego marsh (Viñals, 1991; Viñals and Fumanal, 1995) provides ages ranging from 10,120±460 to 7120±90 ^{14}C years BP as it was deposited progressively landwards and peat layers were drowned and covered by retreating-beach deposits. This arrangement suggests coastal onlap and the corresponding relative rise of sea level.

The Holocene maximum (Flandrian transgression) has been dated in Southern Spain at 6450 ^{14}C years BP. This is when the progradation of spit bars began (Goy *et al.*, 1986; Zazo *et al.*, 1994).

EVOLUTION OF THE COASTLINE BETWEEN CA. 6450 AND 3000 ^{14}C YEARS BP

The first spit–bar system began to grow in areas with an uplift trend, particularly on the Mediterranean coast. There, in the most complete case study (Roquetas, Almería), the first phase of progradation includes two spit bars called H1 and H2 (Zazo *et al.*, 1994; Goy *et al.*, 1995; Lario *et al.*, 1995) separated from each other by a sedimentary gap at ca. 4000 ^{14}C years BP (Fig. 2).

In places where the geomorphological context does not favour the development of spit bars and there is a higher uplift trend, there is deposition of two raised marine terraces approximately at +1 m above present mean sea level. These have been dated at 5190±300 and 5540±170, the most ancient one; and 3640±330 ^{14}C years BP, the youngest one, in the Alicante coast (Gozalvez, 1985).

In subsiding areas (Gulf of Valencia) drill cores record marine beach deposits dated as 6130±100 ^{14}C years BP, overlaying lagoon deposits (Viñals and Fumanal, 1995). These are placed below present MSL.

In the Atlantic area, filling of open estuaries began at this time and aggradation clearly surpassed coastal progradation (Figs 2 and 3). Palaeontological (Fig. 4) and sedimentological data indicate that the marine influence in all the surveyed estuaries was less.

Regarding the relative changes of sea level, we interpret that spit–bar systems began to grow immediately after the maximum glacio-eustatic rise of sea level (ca. 6450 ^{14}C years BP). Progradation of spits was favoured by stillstand or gentle lowstand conditions, whereas the gap separating spit bars H1 and H2 (ca. 4000 ^{14}C years BP) should indicate a positive oscillation (rise) of sea level with gentle transgression inside the general regressive trend of the first phase of progradation.

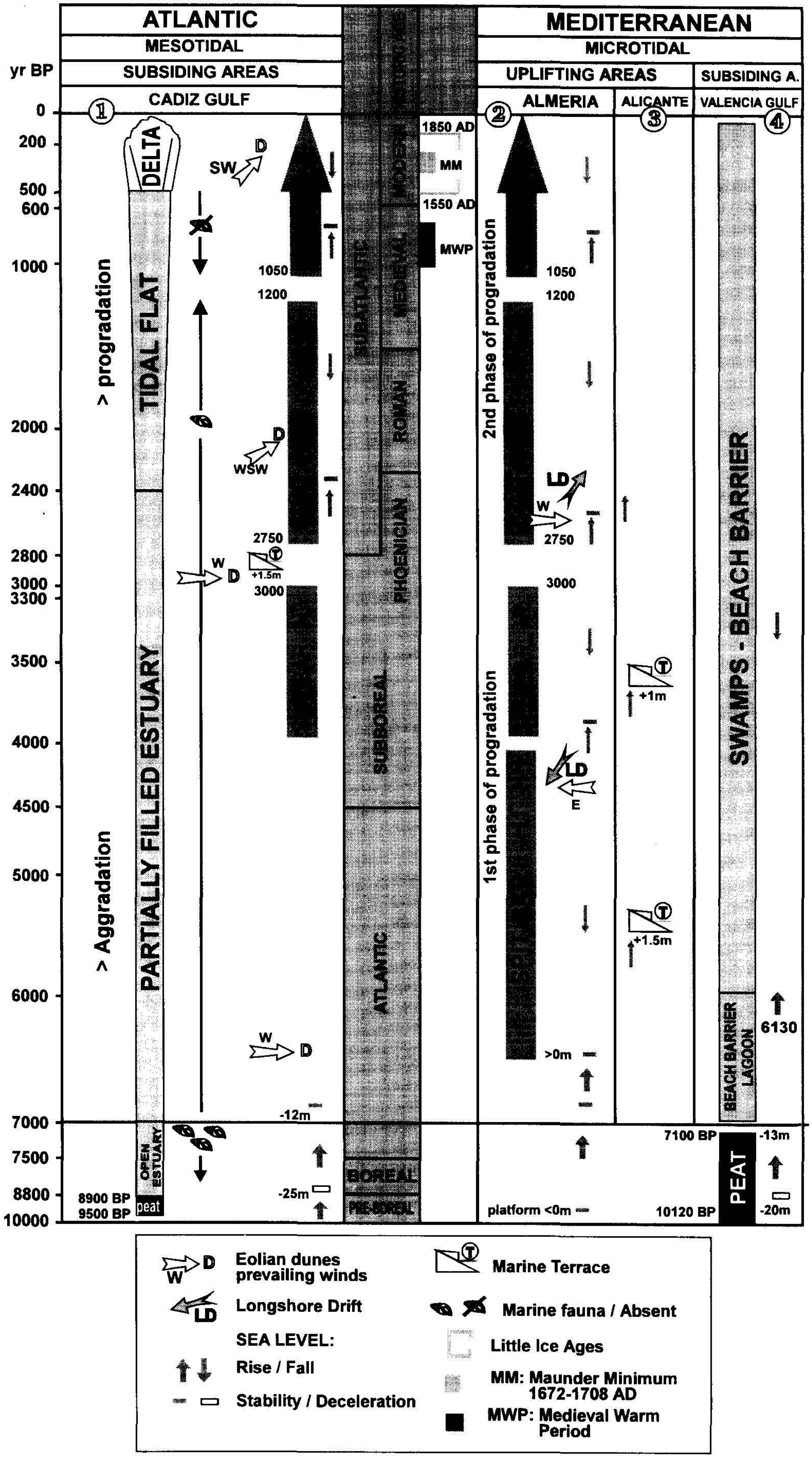

FIG. 2. Evolution of the shoreline during the Holocene in the Atlantic and Mediterranean littorals of Southern Spain in variable tectonic and tidal range settings (modified after Zazo *et al.*, 1996b).

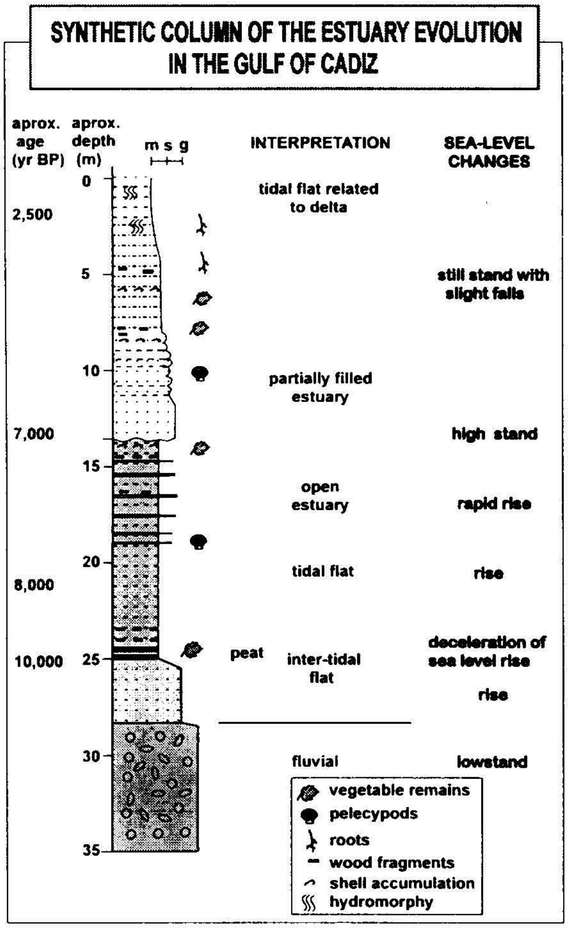

FIG. 3. Synthetic section of the evolution of the estuaries of the Gulf of Cadiz (Atlantic littoral) deduced from drill-core data (modified after Dabrio *et al.*, 1995).

Between 3000 and 2750 ^{14}C years BP a larger positive oscillation (rise) of sea level formed the gap that separates the two major phases of progradation (Fig. 2).

A seismic progradational unit made up by two minor subunits found in the Spanish Mediterranean continental shelf off Almeria (Hernández-Molina *et al.*, 1995) is interpreted as the record of two minor sea-level falls in the last 6500 years and correlated with the two prograding phases of the coast.

EVOLUTION OF THE COASTLINE BETWEEN CA. 2750 ^{14}C YEARS BP AND PRESENT

In the second, younger phase, processes of coastal progradation prevailed over aggradation in this region, independently of the tectonically-induced rate, and of subsidence of the area. As a result, the deposition of large systems of emerged spit bars in both the Mediterranean and Atlantic (Ayamonte, El Rompido, Punta Umbria, Doñana, Valdelagrana) coastlines reduced the connection of the Guadiana, Tinto-Odiel, Guadalquivir, and Guadalete (Gulf of Cadiz) estuaries with the open sea and they turned progressively into lagoons until they reached their present-day stage dominated by tidal flats and marsh.

Between 3000 and 2750 BP, a major change in the direction of prevailing winds in Almería (from Westerly to Easterly, palaeocurrents N90°E and 270°E respectively) caused reversing of littoral drift (Goy *et al.*, 1986) that is recorded in the systems of spit bars (H3 and H4) deposited during the second phase of progradation.

A change in prevailing winds is also recorded in the Atlantic coast along the Asperillo cliff outcrop (located between Huelva and Doñana). Aeolian-dune deposits yielding Roman remains were deposited under prevailing winds blowing from WSW. These overlay deposits of former aeolian-dune systems, accumulated by winds blowing from the west, which are covered by a palaeosoil incorporating neolithic–calcolithic artefacts (Borja and Díaz del Olmo, 1995). The younger systems of dunes step over the beach barrier deposits of spit bars accumulated during the second phase of progradation in Doñana (Huelva). There is evidence of a sudden marine fauna impoverishment and diversity drop ca. 1000 ^{14}C years BP in cores drilled in the Guadalquivir marshland. Grain size

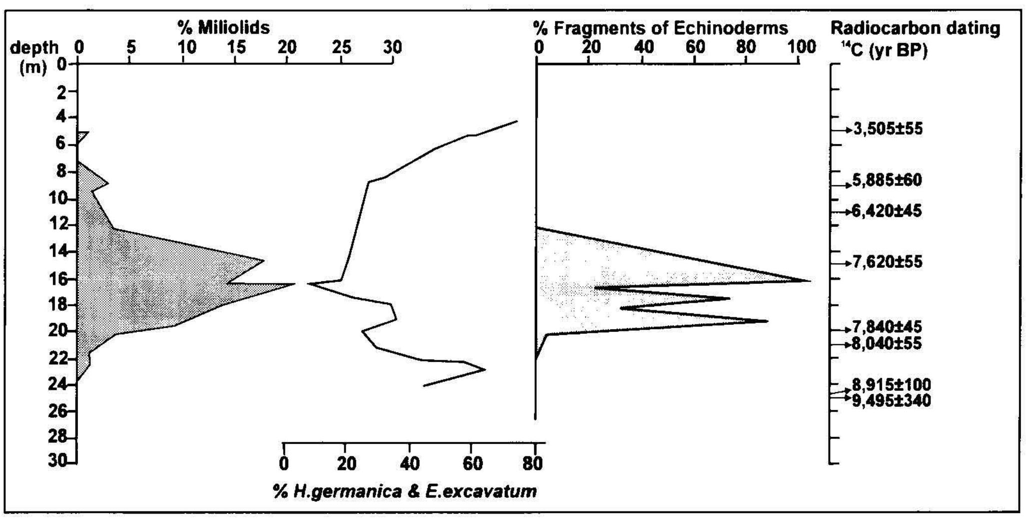

FIG. 4. Drill core PSM-104 (Guadalete marshlands, Gulf of Cadiz) with indication of percent content of some faunal taxa with paleoenvironmental significance (Miliolids, *Haynesina germanica, Elphidium excavatum*, and fragments of Echinoderms), and radiocarbon data in the core.

analysis, particularly the mean and standard deviation, in the same cores indicate that the main phase of sedimentation with strong fluvial influence occurred after 2750 ^{14}C years BP.

An extraordinary increase in progradation is detected in both the Atlantic and Mediterranean littorals ca. 500 years ago and, particularly, after the 17th century as demonstrated by the present location of watch towers built up in that time (some of them are 200 m inland in Doñana spit bar) and also by other historical data like histroical maps and flood records (Lario *et al.*, 1995).

DISCUSSION AND CONCLUSIONS

The present arrangement of Holocene morphosedimentary units (emerged or drowned marine terraces, spit bars, peat layers) found in the littoral areas of Southern Iberian Peninsula results from the control of: (a) tectonic factors that imposed the rate, sign, and magnitude of subsidence; (b) the distance to sources of sediment supply for the coastal budget (river mouths), and (c) the variable input of superficial Atlantic Waters into the Mediterranean. This is particularly evident from ca. 6500 ^{14}C years BP up to Present.

The analysis of the morphosedimentary units allowed recontruction of the sea-level history as follows:

(1) The peat layer accumulation at ca. 10,000 ^{14}C years BP suggests a deceleration of the general sea-level rise.

(2) Spit–bar systems began to accumulate immediately after the Holocene highstand (at 6450 ^{14}C years BP) during stillstands followed by gentle relative sea-level falls.

(3) The gaps of sedimentation/progradation in the spit–bar systems record relative high sea level. Nevertheless there is a light diachronism with the ages obtained in the Mediterranean raised marine terraces which also developed during relative high sea-level, moreover in the Atlantic littoral the marine terrace exposed at +1.5 m in San Roque (La Atunara) is coeval with the gap that separates the two progradation phases (Fig. 2).

(4) Regarding the climate, the input of sediment in our lattitudes increased during floods (short period, strong rain under drought conditions) with anticyclonic conditions; under these conditions (presently in summer) the input of superficial Atlantic Waters in the Mediterranean increases as well.

The initial phase of the European Medieval Warm Period coincides with an epoch of reduced progradation probably under dominantly low-pressure conditions, while the 'Little Ice Age' corresponds to epochs of anticyclonic conditions, that is warm and with strong rain in short periods that results in a high sediment supply to the coast.

Until now, we have recognized several major changes of climatic parameters, recorded in the area as changes of littoral dynamics:

(1) Between 3000 and 2750 ^{14}C years BP the direction of prevailing winds both in Atlantic and Mediterranean coasts; littoral drift in the Mediterranean coasts changed; and there was an increase of progradation processes, that prevailed upon aggradation.

(2) At ca. 1000 ^{14}C years BP the coastal palaeogeography of the Atlantic area changed: as connections of estuaries with open sea were drastically reduced, faunas experienced a sudden impoverishment recorded in drill cores as lower diversity and absence of marine faunas in estuarine deposits.

(3) At ca. 500 years ago there was an extraordinary increase of coastal progradation in all the surveyed littorals. The direction of prevailing winds changed in the Atlantic and became the same as present.

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