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The coastal archives of the last 15 ka in the Atlantic–Mediterranean Spanish linkage area: Sea level and climate changes

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Abstract

Sea level and climate changes archived in various coastal environments during the last part of the last glacial and present interglacial periods are investigated by interpolating available geomorphology, sedimentology, palaeontology and geochronology data. The coastal response to these changes depended on the environment and geographic location. Changes of sea level during the rising, transgressive phase are well recorded in the sedimentary filling of the estuaries, whereas during the phase of highstand they are best recorded in beach–barrier environments. The postglacial rise of sea level took place in two phases: a rapid rise until 6500 cal BP, and a second phase of near stability with minor oscillations of metric magnitude. Regarding climate changes, there is no record of changing temperatures in the coastal zones of southern Spain, although there is in precipitation and wind intensity/velocity. After 7–5 cal ka BP, the general climatic trend towards aridity was punctuated by several short-lived (centennial) episodes of increased aridity that occurred with a millennial cycle, often coincident with Bond cool events and, in some cases, with decreases of sea surface temperatures. The absence of human intervention in vegetation composition until 2000 BP suggests that most environmental coastal shifts were climatically driven.

1. Introduction

The coast, link between land and sea, includes diverse geomorphologic frameworks and sedimentary environments. Marine, transitional and terrestrial landforms and deposits there efficiently archived environmental and sea level changes occurred in the last 15 ka. This time span includes the final episodes of the last glacial period and the present interglacial. These changes were driven by closely related climate and sea level fluctuations.

The termination of the last glacial period was characterised by several episodes of rapidly rising sea level known as melt water pulses. The lowering of sea level

during the Last Glacial Maximum (LGM) has been reported as much as ~130 m below its present values (Yokoyama et al., 2000) for sites remote from former ice sheets (far-field sites). The first melt water pulse occurred at 19 cal ka BP, when sea level began to rise relatively slowly at a rate of about 3.3 mm a⁻¹, until 16 cal ka BP. The melt water pulse 1A (MWP-1A) of Fairbanks (1989) and Bard et al. (1990) was characterised by increases of the rate of sea level rise that amounted up to 15 mm a⁻¹, between 16 and 12.5 cal ka BP and, again, between 11.5 and 9 cal ka BP (Lambeck et al., 2002). A short duration plateau in sea level rise may have occurred at about 12.5–11.5 cal ka BP, corresponding to the Younger Dryas (Lambeck et al., 2002). Around 7 cal ka BP the surface of the ocean was approaching the present level, but did not reach it until some time later (Lambeck et al., 2002). Since then, the

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distribution of oceanic water masses largely driven by superficial currents has come to replace the glacio-eustatic component as the main control of global sea level (Mörner, 1996). On a regional scale, the altimetric position of sea level for a given coastal tract is governed by a glacio-hydro-isostatic control, along with other possible tectonic factors.

Sea level histories in tectonic and non-tectonic Mediterranean areas (France, Sardinia, Tunisia, Italy, Greece, Turkey, Syria and Lebanon) have been investigated by Pirazzoli (2005). The obtained data are consistent with nearly stable global eustasy since 6000 BP. On the coast of southern Tunisia, evidence of mid-Holocene emergence allowed this author to construct a possible relative sea level curve for the last ~ 7000 ^{14}C a BP. According to Pirazzoli (2005): "The maximal emergence peak (about 2 m) occurred around 6000 5000 radiocarbon year BP and was probably followed by a gradual sea-level fall to the present situation at a rate of 0.4 mm a^{-1} ". The origin of this emergence is assumed to be controlled by the hydro-isostatic effect.

Mastronuzzi and Sansó (2002) investigated the environmental changes occurred on the Adriatic coast of south Apulia (Italy) during the last ~ 7000 a BP, and suggested a mid-Holocene relative high sea-stand around 6000 ^{14}C a BP, followed by a fall of sea level to a position 3–4 m lower than present at about 2160 ^{14}C a BP. Since then, the average trend is a rise of sea level up to its present elevation.

Concerning climate, there was considerable instability during the last part of the glacial period, with an abrupt cold spell (the Heinrich H1 event) between ~ 17.5 and ~ 15.5 cal ka BP, and a brief cooling episode (the Younger Dryas, or YD), between ~ 12.8 and 11.7 cal ka BP (Denton et al., 2006). These cold events occurred at the approximate limits of the Bølling-Allerød interstadial period. Whereas the Holocene epoch was commonly viewed as climatically stable compared with the climatic shifts of millennial-scale during the glacial periods (Dansgaard et al., 1993). However, recent North Atlantic ice and marine core studies revealed Holocene climate instability punctuated by repeated cool events (Bond et al., 1997) with 1500 ± 500 a periodicity. Data from a core recovered off Cape Blanco (Western Africa, latitude 20°N) suggest that the Holocene climatic cyclicity was closely followed by synchronic changes of superficial sea water (SST), thus suggesting a strong in-phase link between high- and low-latitude climate during the Holocene (de Menocal et al., 2000).

This paper analyses the record of the environmental changes that occurred along the Spanish coast in the Atlantic Mediterranean linkage area during the last 15 ka (Fig. 1). Much information comes from coastal sectors studied in previous papers (e.g., Zazo et al., 1994, 1999a, c, 2005, in press; Borja et al., 1999; Dabrio et al., 1999, 2000; Goy et al., 1996, 2003; Lario et al., 2000, 2002; Luque, 2002; Yll et al., 2003), and from Doñana-Huelva (Rodríguez-Ramírez et al., 1996, 2000; Ruiz et al., 2005; Cáceres et al., 2006). The paper also includes data from Portuguese

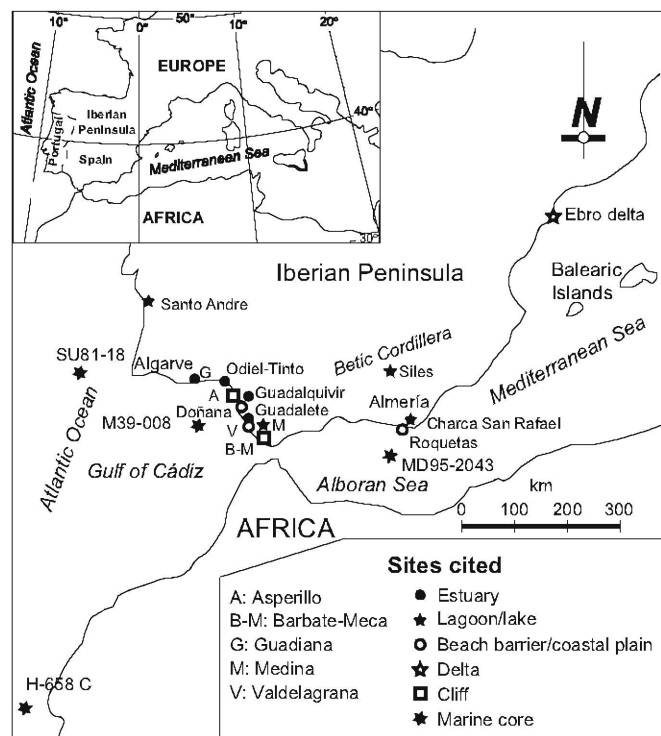


Fig. 1. Location map of the Iberian Peninsula with main on-land sections and marine drillings cited in the text: SU81-18 (Bard et al., 2000); M39-008 (Cacho et al., 2001, 2002); MD95-2043 (Cacho et al., 1999, 2001, 2002; Sánchez-Goni et al., 2002); H-658 C (de Menocal et al., 2000).

coastal estuaries (Boski et al., 2002, in press), and the Ebro delta (Somoza et al., 1998), which augment the number of environments. Marine drill core information from Gulf of Cadiz and Alboran Sea (Cacho et al., 1999, 2001, 2002; Sánchez-Goni et al., 2002) suggests a close synchronism between the rapid climate changes reported in the North Atlantic and those recorded in lower latitudes.

The aim of this paper is to identify the climatic parameter changes recorded in coastal settings, and their effects, to be able to identify the most sensitive environments to these changes. Atlantic Mediterranean coast response to climate changes taking place since the end of the last glacial to the present interglacial are suggested, compared and correlated for the first time.

2. Geological and physiographical settings

The study area is located in the structural framework of the Betic Cordillera, in the southern Iberian Peninsula (Fig. 1), and has been a tectonically unstable area during Quaternary times. The magnitude of vertical movements in coastal areas has been evaluated (Zazo et al., 1999a, 2003) based upon the present elevation of the marine terraces formed during the last interglacial (MIS 5). In the Atlantic coast, the maximum rate of elevation (0.15 mm a^{-1}) was measured in the Gibraltar Strait. This is actually the highest value measured on the Spanish littoral. In contrast, the littoral of Barbate-Meca, not far away, has remained

“relatively stable” in the last ~ 100 ka. In the Mediterranean littoral of Almeria, the maximum elevation rate (0.046 mm a^{-1}) was calculated near Roquetas. Therefore, tectonics exerts a primary control on the present morphology of the shoreline, particularly on orientation of coastlines and the lower reaches of rivers.

The area is located in the subtropical high-pressure belt and experiences the influence of the Azores anticyclone, a long-lasting high-pressure cell in the NE Atlantic, particularly felt during the dry summer months. The climate in the Gulf of Cadiz area is of the Mediterranean-Atlantic type, with mean annual rainfall around 550 mm a^{-1} , mostly concentrated in winter months. Mean temperatures range between 16 and 19°C , with a thermal amplitude of 10 16°C . Prevailing winds blow from SW. This fact, added to the orientation of the coast, generates an active west to east littoral drift which is mainly responsible of the growth of spits (beach and barrier systems) that close partially estuaries.

The climate along the Alboran coast is markedly seasonal Mediterranean, with cool winters (average temperature 13°C in January) and hot (average temperature 24°C in July), dry summers. The scarce rainfall (average 200 300 mm) is of cyclonic origin and related to prominent contrasts of temperatures between land and sea.

Prevailing winds in the study area blow from the west and east (the so-called *Ponientes* and *Levantes*, respectively) and usually persist for several days. The warm, moist westerly winds are particularly intense in autumn and winter. They induce major storms associated with low pressure over the Mediterranean.

The average tidal range is about 2 m in the Gulf of Cadiz but decreases to a few centimetres in the Mediterranean. The non-tidal coast was very sensitive to oscillations of sea level, even at very small scale (decimetre-scale), that seem to be largely related to local influences of the interchange of water-masses through the Strait of Gibraltar under eustatic and climatic forcing.

3. Material and methods

Geomorphological maps of marine, terrestrial and transitional morpho-sedimentary units, erosional surfaces, and neotectonic features were prepared for every selected study area using $1:32,000$, $1:18,000$ and $1:5000$ scale air photographs and field surveys. Before sampling, facies analysis of sedimentary units was used to identify shallow marine, beach, lagoon, and terrestrial (alluvial fan and aeolian dunes) coastal facies. Estuaries, river mouths and lagoons were cored by means of long (max. 65 m) drill holes using rotation rig and shorter (4 5 m) hand-operated coring devices.

The paleontological macro (molluscs) and micro (foraminifers and ostracods) faunal and pollen content have been analysed in cores from estuaries, lagoons, coastal cliffs and river mouths in the Mediterranean.

Magnetic susceptibility, mineralogy, geochemistry and grain size analyses were applied in coastal cliffs and some drill cores from estuaries. Paleosol micromorphology was also studied.

Isotopic ratios of the stable isotopes of carbon ($^{13}\text{C}/^{12}\text{C}$) and oxygen ($^{18}\text{O}/^{16}\text{O}$) were determined in samples of the foraminifer *Ammonia*, the best represented in estuaries.

Radiocarbon data available from previous authors are used (Rodriguez-Ramirez et al., 1996; Zazo et al., 1999b, 2005; Dabrio et al., 2000; Lario et al., 2002; Goy et al., 2003). Usually, sediments were dated by accelerator mass spectrometry (AMS) and conventional radiocarbon techniques applied on mollusc shells: *Glycymeris glycymeris* in beach and barrier systems, the available molluscs and wood fragments in estuaries, and charcoal in aeolian dunes. In the Atlantic area, the local reservoir effect has been calculated as $440 \pm 85 \text{ a}$ (Dabrio et al., 2000). The value is significantly similar to the 400 500 a calculated for areas of the North Atlantic affected by the Gulf Stream by Harkness (1983), Stuiver et al. (1986), Bard (1988), Southon et al. (1990). In the Mediterranean samples, Goy et al. (2003) used the value proposed by Sanlaville et al. (1997) of 400 years for the reservoir effect in the Mediterranean, very close to the 402 -year figure given by Stuiver and Braziunas (1993), which is currently incorporated in the calibration software used. Calibration of radiocarbon ages was performed using the CALIB Program and its revised version (Stuiver and Reimer, 1993; Stuiver et al., 1998).

Optically stimulated luminescence (OSL) dating was applied to marine, fluvial/alluvial and aeolian deposits rich in quartz in the cliff sections. Other isotopic such as ^{14}C and U-Th were also used in combination with OSL: radiocarbon in the Asperillo Cliff (Zazo et al., 1999b, 2005) and U-Th in the Barbate sector (Zazo et al., 1999a). In the later (Zazo et al., in press), sub-millimetric quartz grains were used to estimate the radiation dose. For each sample, this equivalent dose (ED) was measured on several aliquots (between 12 and 48 , Table 1) with a single-aliquot regenerative (SAR) dose protocol (Murray and Wintle, 2000). In all cases, the mean ED was calculated by averaging all the individual values, except where some of them were statistically different from the mean (e.g., BB03-3). In some cases, archaeological and historical archives were used to refine the obtained ages.

4. Results

4.1. Cliff coasts

Cliffs along the coasts of the Gulf of Cadiz (Huelva and Cadiz Provinces, Fig. 1) allow the observation of Pleistocene and Holocene deposits (Fig. 2a and b) that are good archives of coastal environments. The Asperillo cliff (Fig. 3) extends some 35 km in a NW SE direction, parallel to the elongation of the El Abalarío dome (Zazo et al., 2005), between the resorts of Mazagón and Matalascañas

Table 1

Radioisotopic contents of the sediment samples measured in the laboratory by gamma spectrometry using a Ge detector, and annual dose rates, equivalent doses, and OSL age estimates for Barbate samples

Sample reference	Radioisotopic contents			K (%)			Th (ppm)			U (ppm)			Environmental dose rates ($\mu\text{Gy a}^{-1}$)		Annual dose rate		Equivalent dose		n	SAR protocol	OSL age	
	±		±	±		±	±		±	±		±	±	±	±	±	±	Ka			±	
	U (ppm)	±	Th (ppm)	±	K (%)	±	Gamma	Cosmic	$\mu\text{Gy a}^{-1}$	±	Gy	±										
BB00EL1	0.63	0.03	0.88	0.05	0.28	0.01	141	170	613	25	0.5	0.1	24	220° \pm 10' 160° \pm 0'	0.77	0.1						
BB03-10	0.44	0.02	0.96	0.05	0.80	0.01	208	160	848	22	5.6	0.3	24	250° \pm 10' 160° \pm 0'	6.7	0.6						
BB03-9	0.41	0.02	0.93	0.03	0.70	0.01	20	160	792	22	5.3	0.2	24	250° \pm 10' 160° \pm 0'	6.7	0.6						
BB03-7B	0.47	0.02	1.15	0.05	0.30	0.01	221	160	651	25	3.4	0.2	24	220° \pm 10' 160° \pm 0'	5.2	0.5						
BB03-7A	0.42	0.02	1.01	0.03	0.27	0.01	176	160	578	19	5.0	0.2	24	250° \pm 10' 160° \pm 0'	8.7	0.7						
BB03-6	0.41	0.02	0.65	0.03	0.22	0.01	165	160	526	19	3.0	0.2	24	250° \pm 10' 160° \pm 0'	5.7	0.6						
BB03-5	0.41	0.02	1.35	0.05	0.52	0.01	181	160	666	19	8.6	0.5	24	250° \pm 10' 160° \pm 0'	12.9	1.2						
BB03-4	0.41	0.02	1.28	0.03	0.31	0.01	165	50	487	18	50	2	48	250° \pm 10' 160° \pm 0'	102	10						
BB03-3	0.43	0.02	1.50	0.08	0.71	0.02	273	50	860	30	96	8	24	250° \pm 10' 160° \pm 0'	112	14						
BB03-2	0.49	0.03	0.56	0.04	0.34	0.01	215	50	558	12	63	2	24	240° \pm 10' 160° \pm 0'	113	10						
BB03-1	0.60	0.03	1.33	0.05	0.69	0.01	215	50	804	24	87	6	24	250° \pm 10' 160° \pm 0'	108	12						

n, number of aliquots measured using the SAR protocol which allows comparing the natural OSL signal to signals regenerated with artificial doses. Uncertainties for the annual dose rate and equivalent dose are based on statistic errors only, whereas for the OSL ages they combine both statistic and systematic errors (modified after Zazo et al., in press).

(Huelva province). The average elevation is 18–20 m. The cliff is being carved into weakly cemented sandstones that form the most recent part of the sedimentary fill of the western Neogene Guadalquivir basin. It records the interaction of sedimentation on a coastal plain and coeval upwarping. The coastal evolution of this coastal tract has been analysed by Zazo et al. (1999b, 2005), who presented a detail chronology based on radiocarbon and OSL dating.

The exposed sedimentary sequence records the last ~120 ka. In ascending stratigraphic order, there are paleosols, fluvial deposits (coastal swampy flood plain), beach deposits (shoreface to foreshore facies aged MIS 5 (marine isotopic stage) 5, and aeolian deposits (Fig. 2a). Three large aeolian units separated by large, more continuous surfaces which are associated with erosion that truncates a previous surface with plant colonisation and pedogenesis during stabilisation and more humid periods. Aeolian Unit AU1 formed during the last part of MIS 5. Aeolian Unit AU2 is the thickest and, toward the upper part, includes layers rich in organic matter and incised paleovalleys. OSL and radiocarbon data suggest that this unit accumulated between oxygen isotopic stage (OIS) 4 and the early OIS 2 under paleowinds blowing from W and SW. The surface separating AU2 and AU3 is the most widespread erosional surface. Radiocarbon ages of discontinuous organic layers below and above the surface are ~21 cal ka BP and 17,520–14,110 cal a BP (2σ), respectively. OSL ages around 16 cal ka BP (Fig. 2a) fit well in this range (Zazo et al., 2005).

Aeolian unit AU3 (Fig. 2a) forms the uppermost part of the cliff and includes most of the discontinuous layers rich in organic matter found in the stratigraphic section, with ages between 16 ka BP and 13,650–12,710 cal a BP (2σ). The uppermost aeolian deposits in AU3 probably represent the earliest Holocene. More recent mapping surveys allowed differentiating four subunits of transverse dunes traceable 5–6 km inland, with changing prevailing-wind directions. From land to sea, i.e., in ascending stratigraphic order, the accumulation of sand took place under winds from W (subunit 1), SW (subunit 2), W (subunit 3), and again SW in subunit 4 that is the youngest one and tops the exposed section of the cliff.

The increased abundance of organic-rich layers suggest that, at least the uppermost part of Unit AU3 accumulated under a moist climate during the Bølling-Allerød interstadial. Pollen data (Zazo et al., 1999b) suggest that the vegetation remained almost unchanged during the sedimentation of the upper part of Unit AU2 (~21 ka BP) and Unit AU3. Pollen assemblages in both units show similar compositions: mainly shrubs associated with *Pinus* and scattered occurrences of thermophilous trees (*Alnus*, *Betula*, *Carpinus*, *Quercus*, etc.).

Unit AU3 is separated from the semi-mobile and mobile aeolian dunes (AU4–AU7) by an erosional surface that partly levelled the topographic irregularities of the cliff (Fig. 4a), and an overlying crust-like horizon (Fig. 4b). Mineralogical analyses reveal the occurrence of goethite

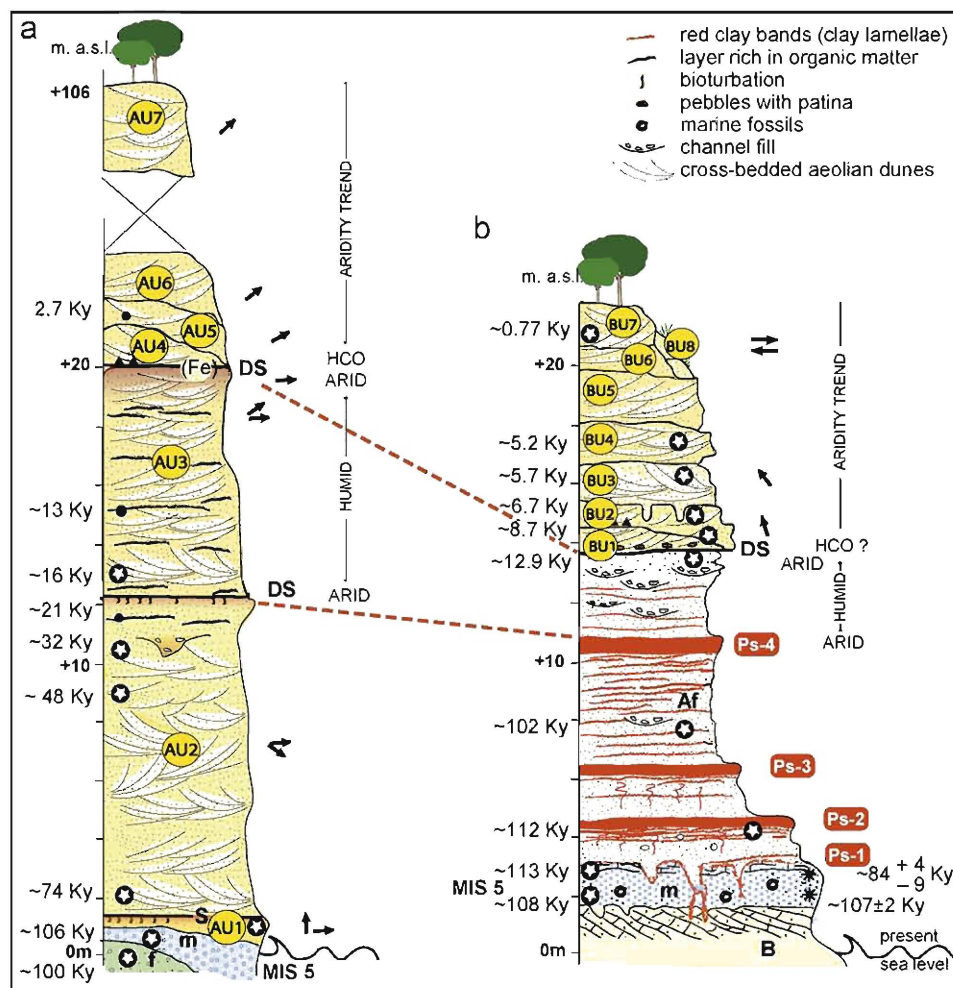


Fig. 2. Correlation of composite type sections in Asperillo (a) and Barbate (b) cliffs (Gulf of Cadiz). Morpho-sedimentary units archive climate changes occurred during the last 15 ka. B, Messinian basement; f, fluvial; m, marine; U1–U8, aeolian units; DS, deflation surface; HCO, Holocene Climatic Optimum; Ps, paleosols; S, surface separating aeolian units; ☆, OSL ages; ●, Radiocarbon ages; ★, U-Th ages; ▲, lithic workshops (late Neolithic–Chalcolithic, ~5000 cal a BP); →, prevailing wind directions. Elevations in metres above mean annual high tide level (m a.s.l.). Modified after: (a) Zazo et al. (1999b, 2005) and (b) Zazo et al. (in press).



Fig. 3. Panorama of the 18–20m high Asperillo Cliff, and erosional surface in the contact of aeolian units AU2 and AU3. Note: abundant organic-rich layers in AU3.

(10–25%) as the only iron oxide. This layer suggests relatively continuous rainfall able to support herbaceous substrata with abundant shallow roots that supplied organic matter to the soil profile (Zazo et al., 2005). Late Neolithic–Chalcolithic lithic workshops dated in the area between 6 and 4 ka BP (Martín de la Cruz et al., 2000) rest on the surface and appear associated to the aeolian unit AU4.

Radiocarbon and OSL ages suggest that Unit AU3 accumulated during the Last Deglaciation. The surface of deflation that levelled AU3 is of latest Pleistocene or Early Holocene age, whereas the age of the iron-rich, crust-like horizon, at present partly degraded, must correspond to the Holocene Climatic Optimum. Late Pleistocene Holocene pollen data from south-west coast of Portugal report a climatic amelioration between $\sim 10,020 \pm 50$ and 5380 ± 50 ^{14}C a BP (Santos et al., 2003).

The assemblage of semi-mobile and mobile aeolian dunes reaches locally up to 80 m in thickness, such in the

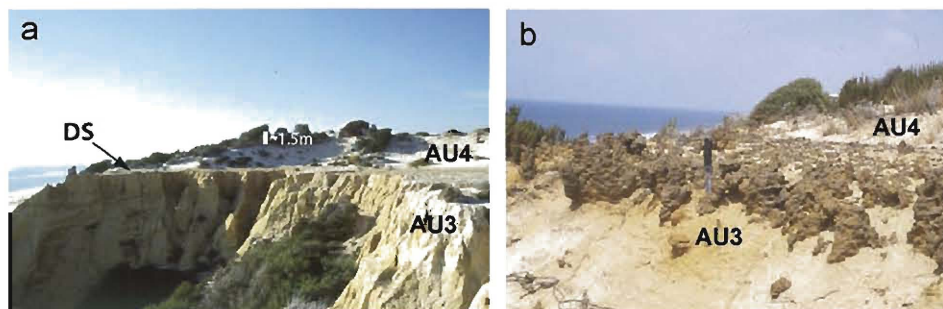


Fig. 4. Upper part of the Asperillo Cliff to show: (a) the deflation surface (DS) (scale: the bar at the plants is ~ 1.5 m) and (b) the iron-crust horizon (knife for scale: 18 cm long).



Fig. 5. Panorama of 16 m high Barbate-Meca cliffs (B, Messinian basement; m, marine unit; Af, alluvial fans; Ps1–Ps4, red paleosols; D, aeolian dunes).

Asperillo bench mark, with elevation 106 m. The three youngest aeolian units (AU4, AU5, AU6 and AU7) accumulated under prevailing SW winds around 5 cal ka BP.

Pollen data from an organic layer aged 2920–2350 cala BP (2σ) of the aeolian Unit AU5 (the U5 of Zazo et al., 2005) indicate that the assemblages do not significantly differ from those of Pleistocene (Zazo et al., 1999c), except for the lack of *Cistaceae* and *Artemisia*, and the abundance of *Erica* and *Cistus* that records the degradation of the natural vegetation during the late Holocene.

In the littoral of Cadiz, the E–W oriented, 11 km long Barbate-Meca cliff exposes a sedimentary sequence of Quaternary deposits that rests unconformably on Late Miocene biocalcarenes and silts (Fig. 5). The Quaternary sequence has been studied recently (Zazo et al., in press) supported by chronologic data derived from U–Th and OSL dating (Table 1). Most sections consist of a beach (bottom), alluvial and aeolian (top) deposits (Fig. 2b), but the best section crops out near the village of Barbate (Fig. 5). Here, it includes a basal marine unit with a transgressive maximum ~ 3.5 m a.s.l. (above sea level) that is covered unconformably by reddish sandy deposits with thin gravel interbeds (lags and channel-shaped bodies) that become more abundant towards the top. This unit has been interpreted as alluvial-fan deposits with sheet-flood facies.

The occurrence of four red paleosols in the alluvial deposits indicates reduced supply of sediment to the alluvial fan and suggests repeated periods of increased aridity, during which the formation and recrystallisation of hematites favouring the dehydration of iron oxides, produced rubefaction.

Table 1 gives the OSL age-estimates calculated by making the ratio of the mean ED to the annual dose rate. According to OSL and U–Th data (Zazo et al., 1999a), the basal marine sediments are of last interglacial age (MIS 5), and the alluvial-fan sequence was deposited between $\sim 112 \pm 14$ and $\sim 12 \pm 1.2$ ka (OSL ages), but there are only three available dates from the alluvial sequence (Fig. 2b). Toward the top of the sequence, more abundant, wide channels record a more humid period that, considering also the OSL age, assign it to the Bølling-Allerød interstadial. Usually, the top of the alluvial sequence is a sharp (Fig. 6), erosional surface overlain by scattered, fine-grained gravel, covered by aeolian dunes moved by winds from the E and W. The superficially cemented aeolian deposits began to accumulate between 8.6 ± 0.6 and 5.7 ± 0.5 ka (OSL ages), as deduced from sections where both the surface and the gravel lag have been observed. From these data it is inferred that the erosional surface topping the alluvial deposits corresponds to a period of increased wind action and intense deflation that impeded the accumulation of sand. Such strong aeolian erosion exposed pebbles to



Fig. 6. Deflation surface (DS) separating alluvial fan (Af) with conglomeratic channel-fill (Ch) and dune (BU1) deposits in Barbate cliff. White-pink notebook (circle) in the lower-left side is 16.5 cm long.

rainwater and favoured the formation of iron and manganese patinas on exposed pebbles. This may suggest a period of relatively higher rainfall following the period of high wind strength (velocity) and erosion. Since then, aeolian systems (BU1 BU8) began accumulating in the area, and the activity of the coastal alluvial fan was interrupted, at least in this coastal tract. The aeolian deposits consist of five dune systems accumulated from wind that blew successively from the south, southeast, southwest, and for the more recent, from west and east. Poorly developed greyish palaeosols indicating somewhat more humid periods punctuate the general arid trend.

4.2. Estuaries

The interpretation of the Late Pleistocene and Holocene coastal sedimentary evolution of the Gulf of Cadiz is based on several cores drilled in the largest estuaries (Fig. 1). The best, more continuous results were obtained in Guadalete (Goy et al., 1996; Dabrio et al., 1999, 2000) and Odiel-Tinto (Dabrio et al., 1999, 2000) estuaries. In the Guadalquivir estuary, the biggest of all, results are still fragmentary (Zazo et al., 1999c), and reconstructions of the fossil infill of the paleo-valley are most difficult at present

owing to the lack of dated cores and complex tectonic activity. In the Portuguese coast, evolution of the coastline and fill of paleo-valleys during the last 13,000 cal a BP has been deduced using results from the Guadiana and other estuaries along the Algarve coast (Boski et al., 2002, in press).

In all cases, the sedimentary record begins with fluvial conglomeratic deposits. The paleo-rivers incised fluvial deposits. The erosional surface represents a sequence boundary and the flooding surface of the postglacial eustatic rise, overlain by the valley fill deposits of the transgressive and highstand phases (Dabrio et al., 2000).

The first transgressive deposits are fluvial to marine facies deposited between 13,000 and 10,000 cal a BP at 49 m b.s.l. (below present sea level), and 30 m b.s.l., respectively. In southern Portugal, the Younger Dryas deposits are still included in the fluvio-marine facies, suggesting a remarkably stable sediment accretion during this time-span (Boski et al., in press).

Cores drilled close to the estuary mouth record fully marine sedimentation coeval with a rapid rise in sea level between ~9000 and 6500 cal a BP. From this time onward, the rate of sea-level rise decreased and effective sandy barriers started prograding at ~5000 cal a BP, enclosing in the process some of the estuaries which turned into restricted brackish to fresh-water lagoon environments. In the non-closed estuaries, the sedimentary trend changed from vertical (accretion) to lateral (progradation), as the basin was progressively being replenished and the shallower facies became dominant in the reduced accommodation space. The neat result was the prevalence of coastal progradation upon vertical accretion which, at ~2400 cal a BP, triggered accelerated expansion of tidal flats and rapid growth of the sandy barriers (Dabrio et al., 2000).

The filling of estuaries in the coast of the Gulf of Cadiz (Fig. 7) follows a similar pattern. Rates of sea level rise vary from the first phase of transgression between 10,000 and 6500 cal a BP, with rates around 5.7 mm a^{-1} and rates of sedimentation about 5 mm a^{-1} , to a second during the highstand (6500 cal a BP to present) with rates of sea level rise of 2.5 mm a^{-1} and rates of sedimentation about 1.5 mm a^{-1} (Dabrio et al., 2000; Lario et al., 2002). There are also two phases in the Portuguese coast: between 13,000 and 7500 cal a BP the rate of sea level rise was 7 mm a^{-1} , but it decreased to 0.9 mm a^{-1} between 7500 cal a BP and the present, coinciding with the rate of accumulation of organic matter (Boski et al., in press).

4.3. Ramblas (ephemeral rivers)

The most complete sedimentary sequence in the Spanish Alboran coasts (Fig. 1) is the drill core recovered in the present swampy La Charca-San Rafael (Roquetas, Almería) that records the last 20,000 a (Pantaleón-Cano et al., 1996; Yll et al., 2003). The study of sedimentology and ostracods allowed Luque (2002) to separate phases of infill and paleoenvironmental changes in the area. The oldest

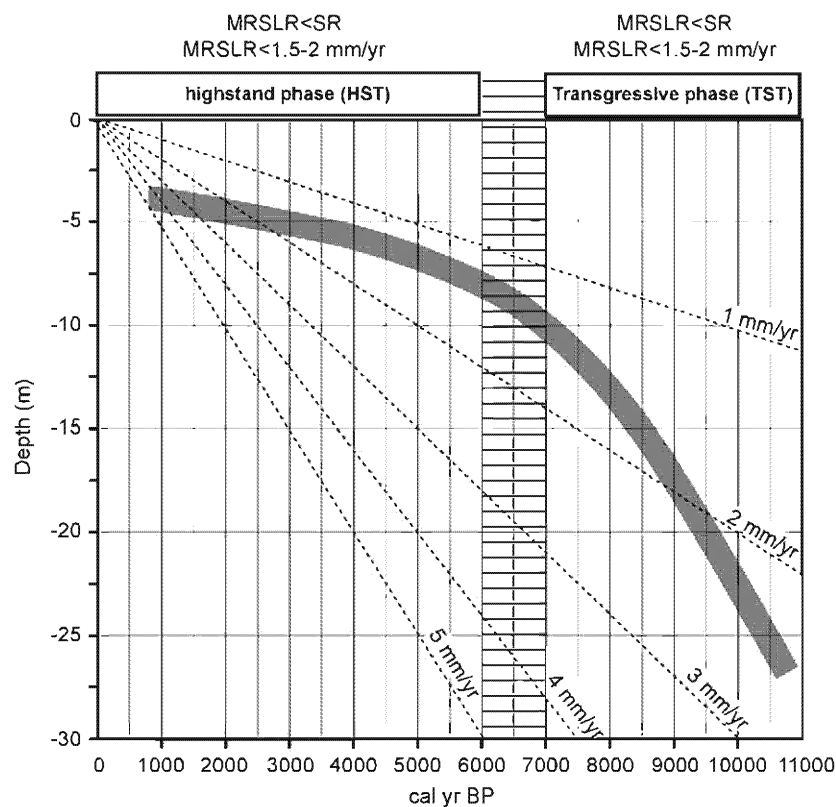


Fig. 7. Sedimentation rates (SR) and trends deduced from Spanish Holocene estuarine sequences; MRSLR, mean relative sea level rise (after Lario et al., 2002).

deposits (18,000–8000 cal a BP) located between 19 and 14.5 m b.s.l., are alluvial fan facies. Then the area changed to a lagoon with short, sporadic connections with the open sea until ~6000 cal a BP recorded in deposits located around 8 m b.s.l., when it changed to a brackish lagoon. Around 5000 cal a BP (at 6 m b.s.l.) a barrier island separated the lagoon from the open sea, and it turned into a shallow, fresh-water lake which persisted until ca. 3000 cal a BP (recorded at 4 m b.s.l.) when it dried out. Around 1000 cal a BP, the environment was occupied by an unstable shallow pond, inundated during winter storms.

The pollen record covers the last 20,000 a (Pantaleón-Cano et al., 1996; Yll et al., 2003). Between 18,000 and 15,000 cal a BP, the pollen component is constituted mainly by deciduous and evergreen *Quercus* and *Pinus* that reflect a relatively warm and humid landscape dominated by the thermophilous component. Between 15,000 and 7000 cal a BP, the pollen assemblages record a decrease of the arboreal pollen and an increase of the steppe component. The Holocene Climatic Optimum extended between 7000 and 5000 cal a BP, and is registered as a marked reduction of the steppe component in relation to the dominant shrub component and arboreal pollen. A most radical change in the landscape at 5000 cal a BP marked the beginning of semi-arid conditions and the definitive installation of steppe communities.

No direct human influences in the change of vegetation have been found before 2000 cal a BP (Yll et al., 2003),

probably because rapid regeneration of natural landscapes and the vegetation nature (sclerophyllous maquis) exceeded the impact of human activities established in the area.

4.4. Beach-barrier systems

These prograding morpho-sedimentary units occur in the Atlantic coast as estuarine barriers in river mouths, and in the Mediterranean coast as former barrier islands separating former lagoon systems from the sea. They are the emergent part of the Holocene highstand which, in the Atlantic Mediterranean linkage area began, ca. 6500–7000 cal a BP (Goy et al., 1986; Zazo et al., 1994; Dabrio et al., 2000).

The most complete beach barrier system is the Holocene coastal plain of Roquetas, exposed in the uplifting coasts of Almería province (Figs. 1 and 8a and b). Careful morpho-sedimentary analysis based on geomorphologic mapping and numerous radiocarbon dates allowed Goy et al. (2003) to reconstruct the evolution of the coastline and to deduce regional climatic and sea level trends during the Middle and Late Holocene.

Ridges that record beach progradation are formed by coarse sand to fine gravel with up to 15% bioclasts. Ridges occur as couplets separated by a narrow intervening depression or swale (Fig. 8). Adjacent couplets are separated by slightly wider swales, and pairs of couplets are separated by still wider swales. A remarkable feature is

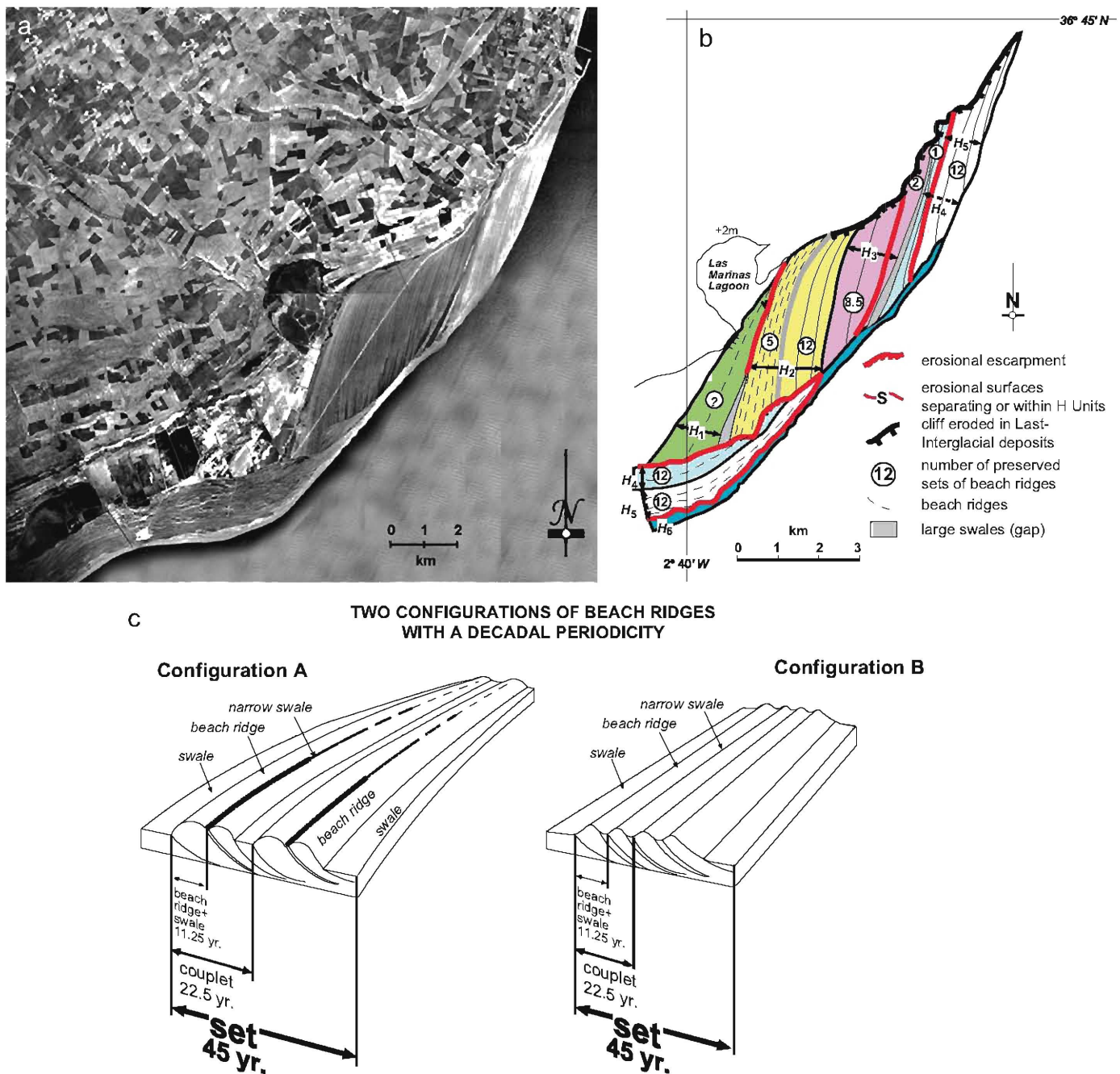


Fig. 8. (a) Aerial photograph of Roquetas coastal plain and beach-barrier systems, (b) map of prograding units H₁–H₆ (Fig. 9) and (c) beach ridge configurations (modified after Goy et al., 2003).

that the swale found every fourth beach ridges is noticeably wider, resulting in obvious patterns or configurations of ridges that are referred to as sets. Some sets have high, wide, clearly distinguishable, beach ridges, and wide swales; in contrast, other sets exhibit smaller-scaled ridges and swales. These configurations are called A and B (Fig. 8c).

Changes in set configuration, occurrences of particularly wide swales (or gaps) or erosional surfaces truncating the systems of beach ridges, and changes in the orientation of ridges and swales led Goy et al. (2003) to identify six

prograding units or groups of sets (H-units) that began prograding, ca. 7400 cal a BP (Figs. 8 and 9).

Considering the age of H-units and the number of beach ridge sets in each unit, the former authors suggested deposition times of 11.25 years for single ridge and swale units, 22.5 years for couplets, and 45 years for a set of beach ridges (Fig. 8c). A millennial periodicity (1400–1200 a) is recorded during the first three prograding units, and a subharmonic periodicity (~700 years) is observed during the most recent units (Fig. 9).

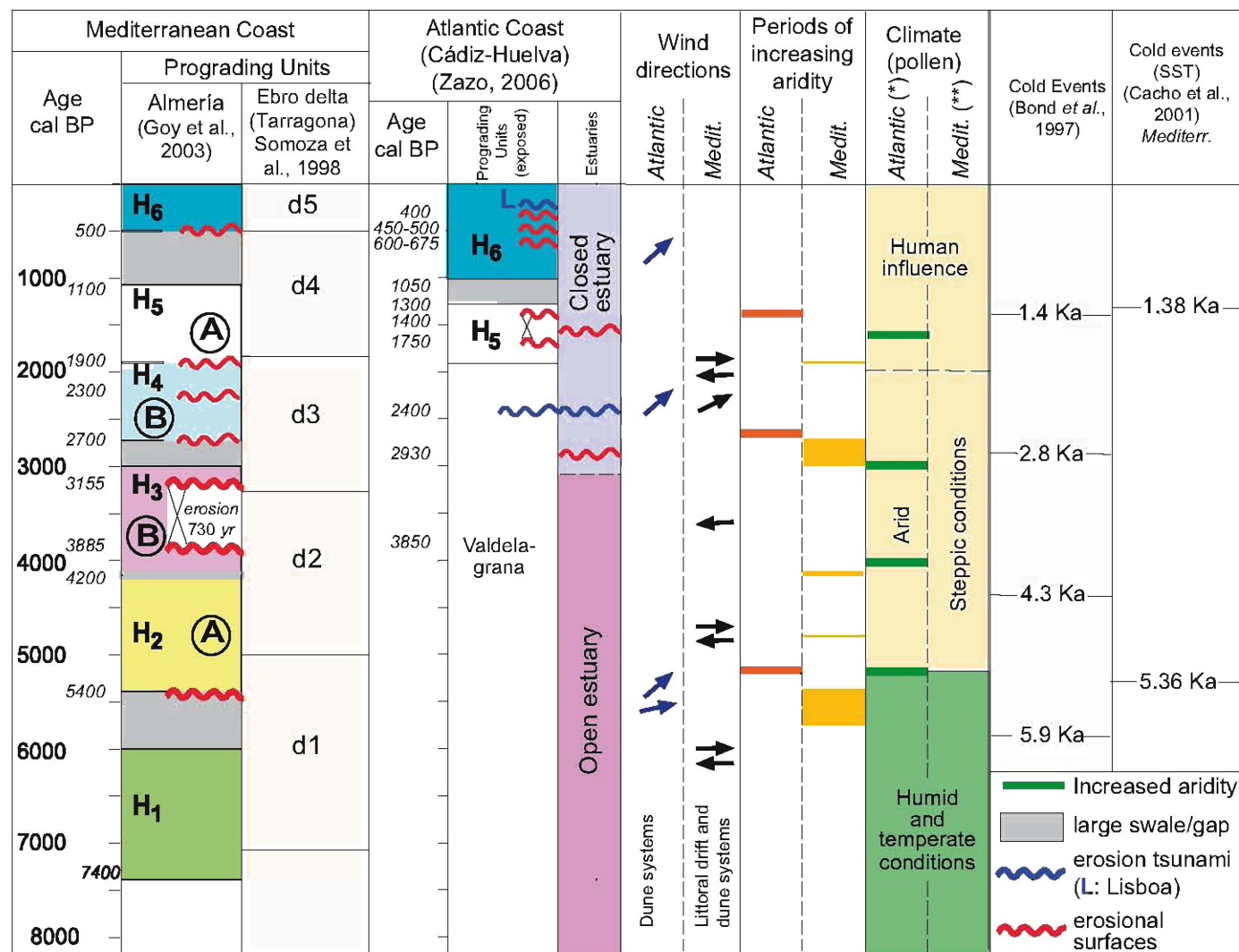


Fig. 9. Chronostratigraphy of prograding beach (H) and delta (d) units and correlation with periods of increased aridity (deduced from changes of set generation and configurations), and climate deduced from pollen in Atlantic (Santos et al., 2003) and Mediterranean (Pantaleón-Cano et al., 1996; Yll et al., 2003). A and B relate to beach ridge configuration of Fig. 8c (Zazo, 2006).

In the Gulf of Cadiz, the first data on chronology and periodicities in beach barrier systems were suggested by Zazo et al. (1994). Later, radiocarbon ages obtained in other prograding systems of the area (Lario et al., 1995; Goy et al., 1996; Rodríguez-Ramírez et al., 1996; Dabrio et al., 1999) were tuned with archaeological and historical data (Borja et al., 1999), and synchronised with the evolution history of estuarine fills (Dabrio et al., 2000).

The oldest ages obtained in the exposed beach barrier systems of the Gulf of Cadiz come from the Valdelagrana spit that closes the Guadalete estuary. A site of Bronze Age (1850–1650 BC) found in the inner part of the system proves that it was already growing around 3500 cala BP (Gómez-Ponce et al., 1997). Indirect data obtained in other nearby coastal lagoons suggest that the progradation of Atlantic beach barrier systems began ca. 6500 cala BP, as in Punta Arenillas spit bar in Odiel-Tinto estuary. Interpretation of beach ridges in aerial photography and

the correspondence with field data is usually problematic because the relatively fine grain size (medium-fine sand, up to 10% of bioclasts) favours aeolian activity that accumulates sand in foredune fields that mask a significant part of the outcrops. This makes morpho-sedimentary analyses very difficult. However, there are sites where the prograding H-units are well preserved, as in the emergent part of the Doñana estuarine beach barrier in Huelva (Fig. 10a and b). The initial phases of progradation can be deduced from data of drill cores recovered in the adjacent Guadalquivir marshlands: one of these revealed that the Doñana spit partly enclosed a coastal brackish lagoon between more than 5500 and 5400 cala BP (Ruiz et al., 2005).

The prograding systems exposed in Doñana (Fig. 10a and b) includes part of H₅, as age of the oldest exposed beach ridges is 1800 cala BP, and H₆ (*sensu* Goy et al., 2003). Analysis of beach ridges morphology, age, and distribution reveals that sets of four beach ridges, similar to

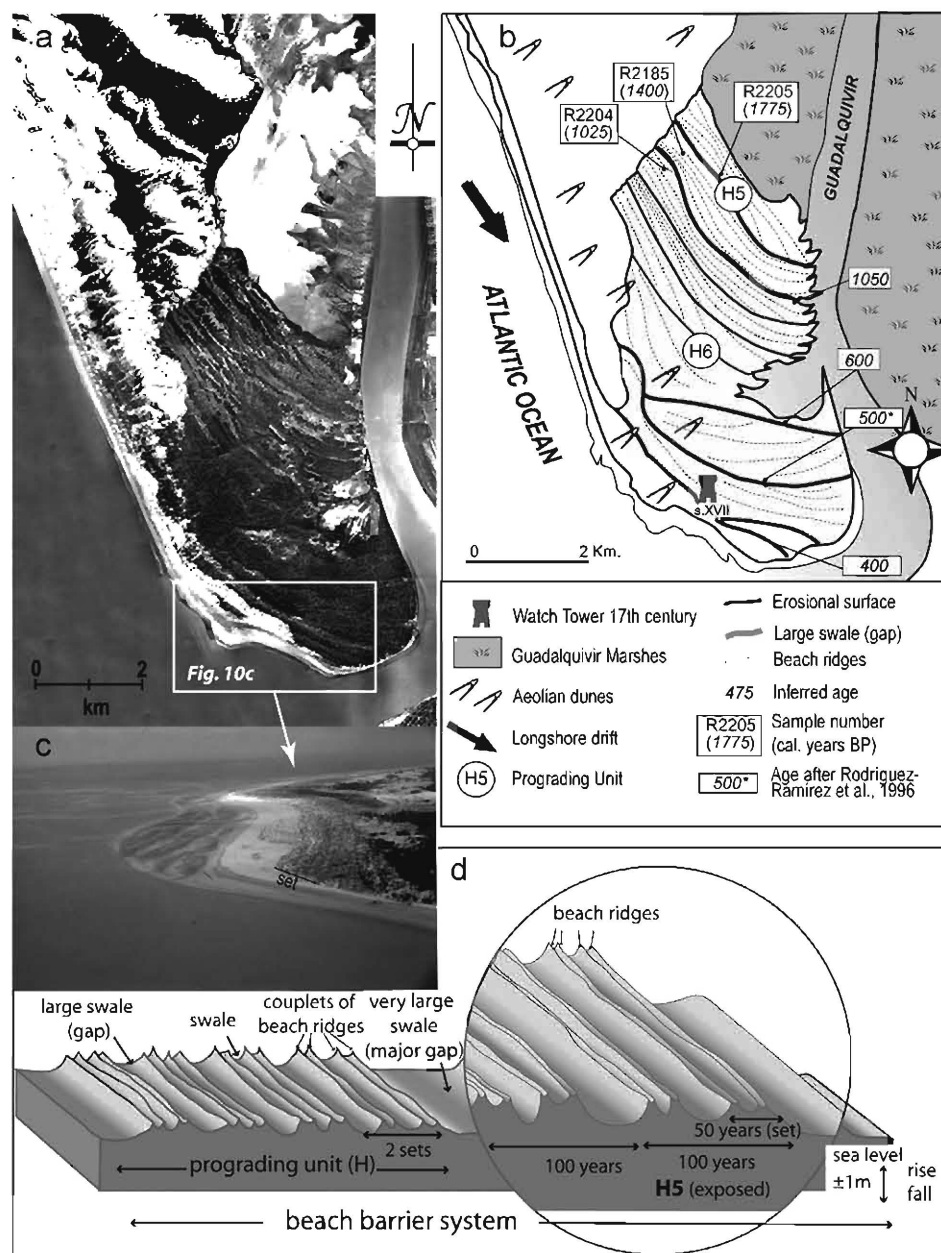


Fig. 10. (a) Aerial photograph of the southern part of Doñana spit and beach-barrier systems at the Guadalquivir river mouth, with box indicating area pictured in the oblique photograph. (b) Map of prograding units H₅ and H₆ (Fig. 9). (c) Sets of beach ridges in the southernmost extremity of the spit, at the Guadalquivir river mouth (oblique aerial photograph). (d) Terminology of sets of beach ridges and periodicity deduced for their generation in Doñana.

those in Roquetas, can be separated, although they are less conspicuous owing probably to the smaller grain size that magnifies wind action. Sets are formed by two beach ridges separated by a swale. However, closer observation reveals that each beach ridge is actually formed by two low crests, which lay close-by (Fig. 10d); therefore, they are easy to miss.

As in Roquetas, a decadal periodicity is also assumed for the deposition of a single beach ridge and the associated swale (Fig. 10c and d). Rodríguez-Ramírez et al. (2000) proposed the same periodicity, together with a shorter (3–7 a) one, for the beach ridges and swales deposited at the

modern, southern extremity of the Doñana spit between 1961 and 1996.

5. Discussion: the coast as archive of sea level and climate changes

In the Spanish continental shelf of the Gulf of Cadiz, the transgressive systems tract contains four seismic units interpreted as short episodes of reduced sea level rise or stillstands, probably coupled with increased sediment supply to the shelf at water depths of 110, 65, 70, 55, 40 and 30 m b.s.l. (Lobo et al., 2001). Lacking age control,

these authors rely upon data from other authors for their chronology. Ages assigned to these units are the beginning of the Deglaciation (probably ~ 15 cal ka BP), and the successive short-lived cool episodes Older Dryas (also recognised in the Alboran Sea by Nebout et al., 1999), Younger Dryas and Holocene Cool Event at ~ 8.2 cal ka BP, the latter two also recognised in the Alboran Sea (Hernández-Molina et al., 1994).

On the coast, the sedimentary record associated with sea level rise of the post-glacial transgression can be only deduced from estuarine fill. The first evidence of sedimentation is a fluvio-marine unit that fills an erosional incision cut in Pleistocene fluvial conglomerates, and penetrated by drill cores located close to the shore. The oldest data for this unit is 13 cal ka BP in silts (49 m b.s.l.) of the Portuguese estuaries (Boski et al., in press) and 10.5 cal ka BP (2σ) in a peat layer (25–30 m b.s.l.) that overlays older grey muddy sands with remains of Scaphopoda and Balanidae in Spanish estuaries (Dabrio et al., 2000). In the Algarve coast, there is sedimentary continuity and gradual transition to more marine facies, with maximum marine influence around 10 cal ka BP. Sedimentary continuity indicates that the impact of the cool Younger Dryas episode on coastal paleoenvironments was negligible or nil (Boski et al., in press), unlike to the 20 m fall of sea level suggested by shelf data (Rodrigues et al., 1991; Dias et al., 2000).

Teixeira et al. (2005) used a series of fixed sea level index points inferred from radiocarbon dates of biological indicators collected in lagoon and estuarine sediments to construct a curve of relative mean sea level for the last 9000 cal a BP in the Algarve coast (Fig. 11). The curve shows a fast rise between 9000 and 7000 cal ka BP, a period of deceleration between 7000 and 5000 cal a BP, and a stable trend after 5000 cal a BP.

These data match those obtained from the estuarine fills of the Atlantic coasts of southern Portugal and Spain. In

all cases, the rise in sea level took place in two phases (Dabrio et al., 1999, 2000; Boski et al., 2002, in press): a rapid rise (average 5.7 mm a^{-1}) between 13,000 and 6500 cal a BP, followed by deceleration (average 2.6 mm a^{-1}). These phases are also noted in the rates of sedimentation measured in estuaries, where the processes of vertical aggradation gave way to those of progradation, particularly since 2400 cal a BP. More open marine conditions occurred at ~ 8000 cal a BP (Goy et al., 1996). Consequently, the coastal archives do not record the stillstands or sea level falls during the cool Younger Dryas episode and Holocene Bond event at ~ 8.2 cal ka BP seemingly recognisable in the shelf.

Relative changes of sea level during the Holocene highstand can be recognised in beach barrier systems. The H-units began prograding during rises of sea level after episodes of lower relative sea level that coincide with the large swales or gaps separating the various H-units (Goy et al., 2003). The meaning of these prograding units for relative changes of sea level is similar to that of the prograding d-units reported from the Ebro delta (Fig. 9) by Somoza et al. (1998). They began prograding immediately after a relatively high sea level and remained prograding during the ensuing fall or stillstands. In any case, oscillations over the last 7.4 cal ka BP do not oscillate more than 1 m. A general trend of sea level fall has been recorded over the last 5 cal ka BP, probably due to hydro-isostatic effect.

Concerning the climate changes, a large part of the information available has been derived from the study of marine drillings (Fig. 1). The reconstruction of SSTs in the Portuguese margin (e.g., Bard et al., 2000; Pailler and Bard, 2002), the Alboran Sea (Cacho et al., 1999) and the Mid-Atlantic at the same latitude (Chapman and Shackleton, 1998), recorded LGM winter temperatures that are only $\sim 5^\circ\text{C}$ less than modern SSTs, i.e., similar to mild periods (Bard et al., 2000). Study of the Spanish continental margin by Cacho et al. (1999, 2001, 2002) revealed the occurrence of ice-rafted debris (IRD) during Heinrich events in the Gulf of Cadiz and polar waters in the Alboran Sea, with a decrease of SST around $1\text{--}2^\circ\text{C}$. SSTs descended some 4°C during the Younger Dryas. In contrast, SSTs rose during the Bølling-Allerød interstadial around 7°C in the Gulf of Cadiz and 9°C in the Alboran Sea (Cacho et al., 2002). The mild Holocene climate was punctuated by a series of short cooling events ($1\text{--}2^\circ\text{C}$), most of which can be correlated with the cold Bond events. A periodicity of 730 ± 40 a (or its harmonic) occurs between these events (Cacho et al., 2001). In the Alboran Sea, such events took place at 11.01, 10.27, 8.24, 5.36, and 1.38 cal ka BP, whereas only those at 10 and 7.98 cal ka BP have been recognised in the Gulf of Cadiz.

Pollen records coupled with lake levels have been used by Magny et al. (2003) as a hydrological signal. During the 8.2 cal ka BP cold event in Europe (Magny et al., 2003), there is evidence that north-latitudes between ca. 50° and 43° underwent wetter conditions in response to the cooling,

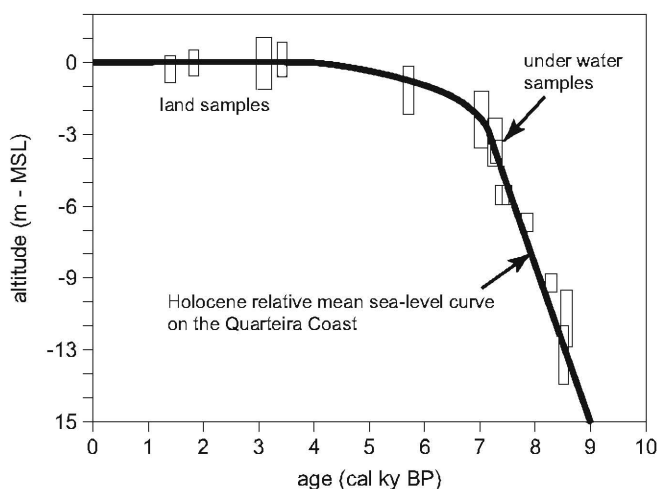


Fig. 11. Curve of relative mean sea level for the last 9000 cal a BP in the Algarve coast. Each error box represents one sample (Teixeira et al., 2005).

whereas northern and southern Europe were marked by drier climate. The latitudinal amplitude of this middle zone could have been larger during phases of climate cooling weaker than the 8 cal ka BP event. In southern Spain, this event has been recorded as lake level oscillation such as Lake Siles-Jaen (Carrión, 2002) and Laguna de Medina level drops (Reed et al., 2001), close to the coast of Cadiz (Fig. 1). In the latter, a desiccation phase recorded at about 8000 cal a BP was followed by maximum lake levels at ca. 7000 cal a BP.

On the coast, in the present state of the art, the more reliable and continuous information can be extracted from the sedimentary sequences exposed in coastal cliffs of the Gulf of Cadiz, and from the pollen record of the swampy zone of San Rafael (Almeria) in the Mediterranean coast.

Sedimentary sequences exposed in cliff coasts (Fig. 2a and b) suggest that the Gulf of Cadiz area underwent a more humid climate during the Bølling-Allerød interstadial as witnessed by layers rich in organic matter interbedded in the aeolian dune facies of Huelva (El Asperillo) and channel-shaped bodies in the alluvial fans of Cadiz (Barbate). In the Asperillo section, the humid period is sandwiched between two more arid periods that produced deflation surfaces. The older deflation surface separating aeolian units AU2 and AU3 truncates a paleosol (Figs. 2a and 3) and developed between ~21 and ~16 cal ka BP; the younger one is of latest Pleistocene or Early Holocene age. In Barbate (Cadiz), the humid episode occurred intercalated between a non-precisely dated, red paleosol (Ps4) at the base and a deflation surface younger than ~13 to ~8 cal ka BP, cutting the top of the alluvial fan facies (Figs. 2b and 6).

Comparing the results drawn from the sedimentary sequences exposed in the cliffs and the evolution of SSTs proposed from marine drillings (Bard et al., 2000; Cacho et al., 2002), it seems clear that the LGM was not a cold period in south Iberia. In contrast, SSTs descended notably during both the Heinrich event 1 (~17.6 16 cal ka BP) and the Younger Dryas (~12 cal ka BP), and we suggest that they were probably recorded as arid periods in the coastal zones. If this is the case, the lowest deflation surface found in Asperillo (Fig. 2a), and the rubefaction of the red paleosol (Ps4, Fig. 2b) may represent the Heinrich event 1 (~17.6 16 cal ka BP), and the deflation surface topping the coastal cliffs (Fig. 2) may represent the Younger Dryas episode or a more arid period at the beginning of the Holocene.

The younger deflation surface is covered in Huelva by an iron-like crust horizon genetically related to moist and temperate climate conditions. In Cadiz, it is covered by a discontinuous lag of clasts coated by patinas of iron and manganese oxides, suggesting increased humidity. This more humid period could be assigned to the Holocene Climatic Optimum, after which aeolian dune systems accumulated in both areas, particularly since 6000 5000 cal a BP.

The scarce pollen data available for southern coastal areas of Iberia suggest that they were a refuge for some arboreal taxa during the last glaciation (Santos et al., 2003; Yll et al., 2003). Holocene vegetation landscapes of the Atlantic coasts of the Iberian Peninsula did not change remarkably. The first evidence of changes in the pollen sequences of the Atlantic Mediterranean coastal areas clearly connected to human activities are felt around 2000 cal a BP (Yll et al., 2003). In south-western Portuguese coasts (Alentejo), clear anthropogenic indicators are scarce in the pollen diagrams. Only modern *Pinus* reforestation that occurred throughout the last 300 years is recorded (Santos et al., 2003).

In contrast, vegetal cover, particularly, in the Mediterranean coast suffered a dramatic transformation at 5000 cal a BP, following the definitive establishment of the semi-desert conditions that extend to the present. However, changes with alternating humid and dry periods of secular duration have been recognised in the Atlantic south-western Portuguese coast by Santos et al. (2003) at 5.2, ca. 3.0 and 1.63 cal ka BP. These periods have been interpreted to coincide with the last four cooling Bond events.

Six major Holocene changes in vegetation have been identified by Jalut et al. (2000) in a transect covering south-east France and south-west Spain. They correspond to aridification phases that took place between 10.9 9.7 cal ka BP, 8.4 7.6 cal ka BP, 5.3 4.2 cal ka BP, 4.3 3.4 cal ka BP, and 2.8 1.7 cal ka BP.

In the present state of knowledge, the best archives of climatic changes that have occurred in the last 7000 years are beach and barrier systems. The coastline followed a pattern of periods of remarkable progradation, when H-units were formed (Fig. 9), punctuated by shorter episodes (each lasting between 600 and 272 years) of reduced progradation and formation of gaps or very wide swales. These episodes occurred with a cyclicity of 1400 3000 years. The short periods of reduced progradation are climatically influenced, and correspond to increased aridity. Some of these centennial episodes coincide with Bond cool events (Fig. 9): at ca. 1.4 cal ka BP (Atlantic), ca. 2.8 cal ka BP (Atlantic and Mediterranean) and ca. 5.9 cal ka BP (Mediterranean). However, there is less coincidence with cooling episodes of SSTs recorded in southern Iberian margin. The change in set configuration (A or B) inside the H-units records the rapid passage (a few years) to more arid conditions.

A decadal (ca. 11 years) periodicity has been deduced for the generation of a ridge and associated swale, and 50 years for the generation of a set, the most characteristic morpho-sedimentary element. This decadal time-scale has been linked to the NAO (Goy et al., 2003) or solar activity fluctuation (Zazo et al., 1994; Goy et al., 2003). Beach ridges and swales formed between 1961 and 1996 in spit bars of Huelva have been studied by Rodríguez-Ramírez et al. (2000). They concluded that the generation of ridges follows a periodicity of 3 7 years related to negative values

of the NAO index, and another around 10–12 years that can be related to periods with less sunspot activity, which produces the most conspicuous ridges.

Beach ridge systems in both coasts show evidence of intense erosion produced by storm waves generated by winds from the SW, particularly after 3270 cal ka BP (Fig. 9). In some cases, erosion has been produced by tsunamis on the Atlantic coast (Fig. 9), where there are tsunamigenic deposits associated with remarkable changes of morphology of the coastline (Dabrio et al., 1998; Lario et al., 2000; Luque, 2001), and referred historically (Galbis, 1932, 1940). Recently published reports (Ruiz et al., 2005; Cáceres et al., 2006) describe a larger number of tsunamis in the Guadalquivir estuary, with ages practically isochronous with erosions of the coastal plains in the Mediterranean that have been interpreted as caused by major changes in directions of prevailing winds and littoral drift or storms.

In synthesis, the coastal area is more sensitive to variability in precipitation than to oscillations in temperature. Direction and intensity of prevailing winds are prime factors in determining the evolution of the coast. In general, cold episodes and cool events reported in the North Atlantic region, and marine SSTs in South of Iberia are recorded in coastal regions as arid episodes (or events), marked by reduced rainfall and/or increased wind velocity and intensity. In some cases, chronological coincidence has been demonstrated, particularly during the Holocene (Fig. 9).

6. Conclusions

The coastal environments in southern Spain reacted to climate and relative sea level changes in the last 15,000 years in different ways depending on particular environments and geographical location. The responses are archived as deposits, morpho-sedimentary units and erosion of sedimentary sequences.

The global rise in sea level during the post-glacial transgressive phase is particularly well recorded in Atlantic estuaries. In contrast, small fluctuations during the high-stand phase are best recorded in beach and barrier systems. The recorded sea level rise and sedimentation rates shows two steps: a first rapid rise of sea level between ~13,000 and 7000–6500 cal a BP that resulted in rapid vertical aggradation and a second phase of deceleration dominated by lateral progradation. After the present day sea level was reached ca. 5000 cal a BP, the oscillations recorded have not exceeded 1 m.

Regarding climate, scarce pollen records suggest that the southern coastal areas of Iberia were a refuge of some arboreal taxa during the last glaciation. A most prominent change of vegetation indicative of more arid conditions was recorded around 5000 cal a BP. This change was more marked in the Mediterranean coast.

The Bølling-Allerød interstadial (~15–13 cal ka BP) coincides in the Atlantic coast with a more humid climate

that was followed by an arid period when more intense or rapidly blowing winds chiselled the deflation surface which tops the coastal cliffs of the Gulf of Cadiz. The lowest deflation surface found in Asperillo, and the rubefaction of the red paleosol (Ps4) may represent the Heinrich event 1 (~17.6–16 cal ka BP). Also, the deflation surface topping the coastal cliff may represent the Younger Dryas episode or a more arid period at the beginning of the Holocene.

Later, the Holocene Climatic Optimum corresponds to a more humid period or a climatic amelioration, particularly on the Atlantic coast. Since ca. 7000 cal a BP the record of climatic changes in the coast is better recognised in beach and barrier systems. These prograding environments record climatic changes in the general trend to aridity, and the coastline followed a pattern of periods of remarkable progradation interrupted by shorter episodes of reduced progradation. These periods of centennial duration occur with a millennial cyclicity, which frequently coincides with cool Bond events and, to a lesser extent, in the sea with decreases of the SSTs. On coastal areas, these episodes correspond to increased aridity and low relative sea levels. A decadal periodicity has been deduced for the generation of beach ridges, and interpreted as related to fluctuations of solar activity and, probably, of the NAO index variability.

Consequently, the climatic parameters likely to be recorded in the coastal archives are differences in precipitation and changes in intensity of prevailing winds, but not temperatures.

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