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Evidence for Holocene sea level and climate change from Almenara marsh (western Mediterranean)

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Abstract

In the Almenara marsh (western Mediterranean), four cores were analyzed to establish the relationship between the marsh record of the Almenara marshlands and the environmental factors responsible for its evolution during the Holocene. One hundred and eighty-six samples were collected for sedimentologic and paleontological study: 63 for biomarker analysis; 5 for amino acid racemization (AAR) dating; and 5 for ^{14}C dating. Litho and biofacies analyses identified distinct paleoenvironments, with the presence of a marsh environment alternating with inputs of alluvial material and marine sediments. Biomarkers indicated the constant presence of terrestrial (herbaceous) plants, together with a variable development of aquatic macrophytes. During the Holocene transgression, the Almenara marsh was occupied by oligohaline marsh facies with an oscillating water level and peat formation, which was established at the bottom of the record at 7570 cal yr BP and persisted until 3100 ± 780 yr (AAR). Maximum surface flooding occurred at 5480 cal yr BP, registered 450m from the current coastline. At least three peat beds (dated with ^{14}C dating and AAR) correlated with Bond (episode 5900 cal yr BP) and Wanner (episodes 4800–4500 and 3300–3500 cal yr BP) cycles and thus correspond to a regional model that affected the Northern Hemisphere.

Keywords: Marsh; Holocene; Western Mediterranean; Micropaleontology; Organic geochemistry; ^{14}C dating; Amino acid racemization (AAR)

INTRODUCTION

Research in a variety of environments indicates that the position of the sea level after the eustatic maximum depends on regional and local factors. Small sea-level variations and cyclic climatic variability (warm/cold and humid/arid) are characteristic of the upper Holocene (Dabrio et al., 2000; Boski et al., 2008). These small variations can be determined in periods of thousands of years and, in this case, are associated with the contribution from the North Atlantic linked to deglaciation from inland areas and changes in surface seawater temperature (Bond et al., 1997, 2001; Cacho et al., 2001; Goy et al., 2003; Wanner et al., 2011). From 3000 cal yr BP, these sea-level variations can be established for periods of hundreds of years (Zazo, 2006; Zazo et al., 2008) and are related to changes in atmospheric pressure linked to variations in the North Atlantic Oscillation (NAO) and cycles of solar activity. In addition, in pollinic studies in a series of inland lakes, lagoon, and caves from 5000 cal yr BP, several phases of alternating dry/wet periods that characterized the regional climate during the upper Holocene (Fumanal and Dupré, 1986; Dupré et al., 1988; Burjachs and Julià, 1994; Yll et al., 1994; Badal García and Roiron, 1995; Carrión and Van Geel, 1999; Carrión et al., 1999, 2010) and the presence of the seasonal climate increased the availability of sediment and favored the formation of these systems (Ferrer and Blázquez, 1999).

The detailed study of the sedimentary filling of coastal lagoons and marshes allows us to gain a reliable idea of the climatic and eustatic changes during the Quaternary. A paleoenvironmental model of marsh development has recently emerged from several studies on the Mediterranean coast of Spain: Peñíscola (Usera et al., 2006), Torreblanca (Collado and Robles, 1983; Segura et al., 1997), La Safor (Viñals, 1996), Moraira (Viñals and Fumanal, 1995), Albufereta (Blázquez and Ferrer, 2003; Ferrer et al., 2005; Ferrer and Blázquez, 2012), and Albufera of Valencia (Sanjaume and Carmona, 1995; Ruiz and Carmona, 2005; Carmona and Ruiz, 2011; Marco-Barba et al., 2013; Carmona et al., 2016). Long-term coastal records in the upper Pleistocene register of

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the Pego-Oliva wetland are scarce; previous studies (Dupré et al., 1988; Mateu, 1989; Viñals et al., 1989; Viñals, 1996) obtained their results from six borehole cores and 90 stratigraphic profiles. Torres et al. (2014) identified Marine Oxygen Isotope Stage (MIS) 15-1, through amino acid racemization (AAR), litho- and biofacies and biomarkers with a record covering approximately 650 ka, and subsidence rates in which no important hiatuses occurred. In the Xàbia basin, Fumanal et al. (1993) drilled five boreholes of an average depth of 30 m, which recorded sediments from the Middle Pleistocene. In the Elche basin, numerous boreholes up to 30 m deep have been drilled and studied in detail (Blázquez, 2005). Thanks to the microfossil content of the samples and their suitability for sedimentologic and magnetic study, our group was able to reconstruct the paleoenvironmental evolution of the Elche lagoon area (southeast Spain) during the Quaternary (Blázquez and Usera, 2010).

These earlier studies, based on sedimentary, geomorphological, palynological, micropaleontological, and chronostratigraphic studies, indicate that the present-day transition systems in the eastern peninsula formed as a result of still-stand Holocene transgression (MIS 1). Pirazzoli (2005) proposed that the relative sea-level maximum was reached around 6000 cal yr BP in the Mediterranean area; however, the approximate date of the Holocene maximum flood is widely agreed to be 7000 cal yr BP. From that time onward, spits and bars appeared in estuaries and river mouths and migrated to the mainland (Goy et al., 1996; Zazo et al., 1999; Dabrio et al., 2000). This occurred after a first episode of fluvial deposits (gravels), between 13,000 and 8000 cal yr BP, which infilled the erosive surface formed during the eustatic minimum (Amorosi and Milli, 2001; Boyer et al., 2005). When the rate of sea-level rise slowed between 7000 and 6000 cal yr BP, spit systems, barriers, and deltas were formed (Carmona and Ruiz, 2008; Amorosi et al., 2009), especially between 4000 cal yr BP and 3000 cal yr BP (Zazo, 2006). The geomorphological results are the complex associations of floodplains, littoral lakes, and deltas from the rivers that developed during this period (Bellotti et al., 2004; Amorosi et al., 2008; Carmona and Ruiz, 2011; Rossi et al., 2011). The Mediterranean deltas began to evolve between 8500 and 6500 cal yr BP (Stanley and Warne, 1994, 1997; Somoza et al., 1998; Vella et al., 2005; Anthony et al., 2014; Cearreta et al., 2016).

The main objective of the present study was to characterize the paleoenvironmental changes in the Almenara marsh over recent millennia. This marsh is located in the southern part of the La Plana Baixa region in the province of Castellón (Fig. 1), on the Mediterranean coast of Spain. To do so, we drilled boreholes at the southern border of the marsh and carried out micropaleontological (fossil foraminifera, gastropods, ostracods, and biomarkers), sedimentologic, geochemical (carbonate and organic matter), and chronostratigraphic (AAR and ^{14}C) analyses. We intend to propose a model of evolution of the coastal areas during the Holocene that is able to complement and complete earlier models.

Geochemical studies of the Almenara marsh were carried out by Lopez-Buendía (1995) and Lopez-Buendía et al. (1999). Analyzing the peat record, these authors made a proposal for its evolution during the Holocene, based on stratigraphic analysis at depths of less than 5 m. They proposed the formation of a marsh in 6000–5500 cal yr BP, located behind a barrier island associated with the Holocene transgression, in accordance with the common regional coastal marsh model suggested by previous authors (Pérez Cueva, 1977; Dupré et al., 1988; Rosselló, 1993; Sanjaume et al., 1996; Segura et al., 1997). From the results of the geochemical analysis and ^{14}C dating, the authors proposed two sea-level maxima around 3000 cal yr BP and 1700 cal yr BP.

Later, other authors (Mediato and Santisteban, 2006; Mediato et al., 2011a, 2011b) performing geochemical studies of cores and ^{14}C dating proposed that the evolution of this sector was closely related to sea-level oscillations. Recently, Mediato (2016) presented a series of well-supported conclusions about the evolution of the coastal sector between Sagunto and Benicassim on the basis of the marshland records of Almenara, Nules, and Benicassim; stratigraphic sections; and optically stimulated luminescence dating. The correlation of the marshland record (^{14}C dating) with buried deposits allowed us to propose a date for the maximum Holocene flood of 7000 cal yr BP, with oscillations in marsh water level in response to sea-level changes linked to regional factors. These changes (phases) have a cyclicity of 1500–1800 yr. However, the tectonic context needs to be studied in more detail to obtain more reliable data and to be able to determine whether these phenomena are related to eustatic movements.

STUDY AREA

Geologically speaking, the study area is determined by craggy sandstone-made reliefs of Iberian direction from the Espadán mountain range. From a structural point of view, it infills a graben of the Upper Oligocene-Miocene age linked to the crisscrossing of orthogonal faults of Iberian orientation (northwest–southeast) with others running northeast–southwest, which produce a tectonic subsidence (Fontboté et al., 1990) that is also observed in the continental shelf (Rey and Fumanal, 1996). This depression is limited by faults parallel to the coastline that were filled during the Pliocene and Pleistocene with alluvial fan sediments (Pérez Cueva, 1979) grading to the coastal environment through barrier island marsh systems.

Pérez Cueva (1977, 1985) carried out geomorphological studies of the coastal plains of Castellón. This author proposes the formation of the plain from two sequences of alluvial fan development, one dating from the middle Pleistocene and the other from the late Pleistocene. At the alluvial fan toes, marshes developed as a result of the Holocene transgression. Recently, Mediato (2016) distinguished between two facies of the Pleistocene coastal plain: one of an alluvial fan toe with predominance of fluvial processes and another linked to small alluvial fans connecting with the edges of the basin.

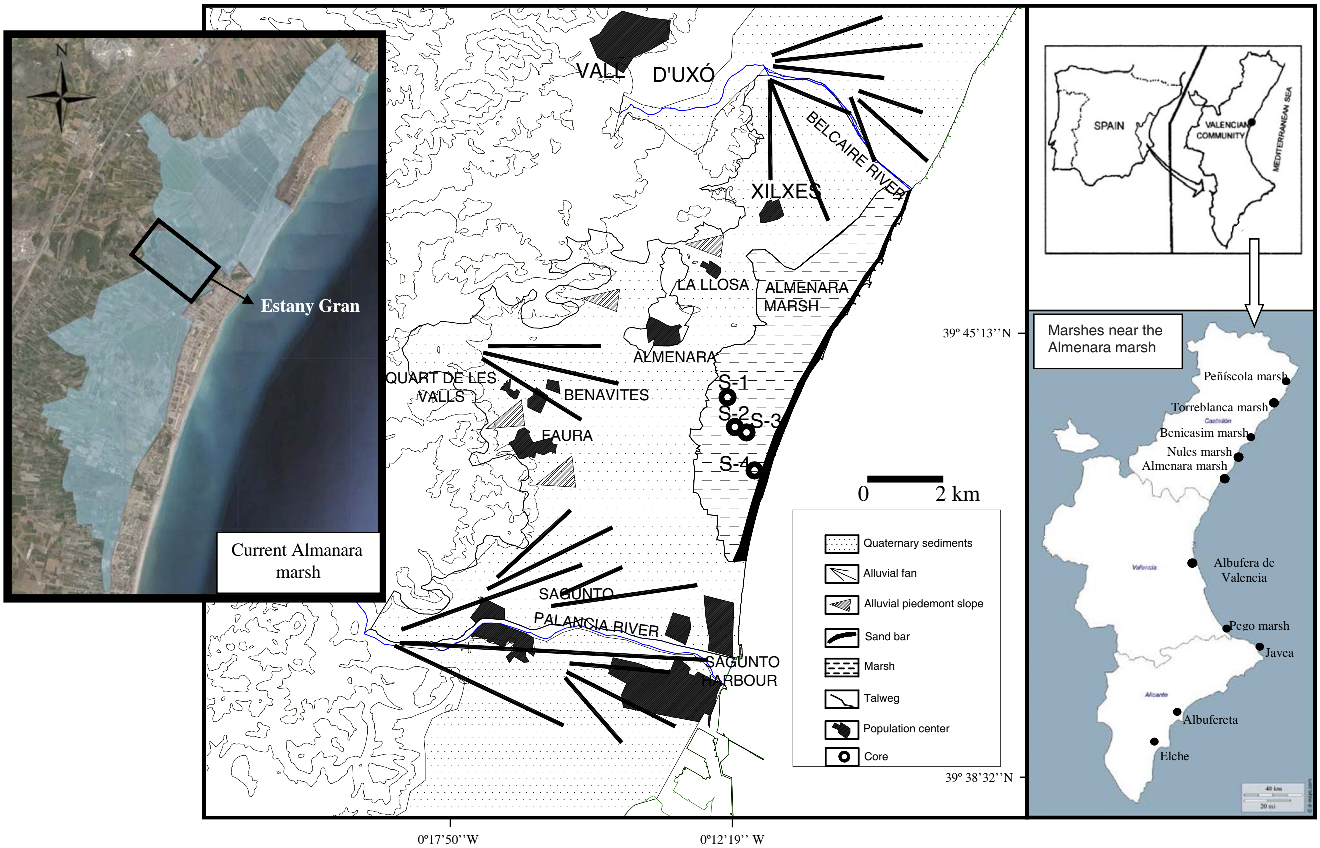

Figure 1. (color online) Location of the study area, geomorphological scheme, and situation of the mechanical cores. Altitude is reported in meters above mean sea level.

In a general Quaternary context, the main geomorphological elements are (Fig. 1) as follows:

(a) Two main rivers: the Palancia River in the north and the Belcaire River in the south. These rivers are the origin of the alluvial deposits that limit the wet area today.

The Palancia River has its catchment in the Toro mountain at the southern end of the Javalambre mountain range. It is about 85 km in length, and its catchment basin covers 911 km^2. It moves within a syncline where Triassic and Miocene materials outcrop, between the anticlines of Espadán and Calderona. The upper basin is characterized by steep slopes, so the flow of the Palancia and its tributaries is deeply incised. When the slope diminishes, the river builds an alluvial fan. According to Segura et al. (1995) several morphogenetic phases starting in Lower–Middle Pleistocene can be established. The alluvial fan apex is located on the fault at the inland boundary of the coastal plain. The riverbed is braided, with shallow, wide channels. Toward the coast near the mouth, the river splits. Sometimes the Palancia River overflows southward, infilling ancient channels at the south of the main channel. However, the detailed topographical analysis carried out by Aranegui Gascó et al. (2005) suggests that in the northernmost point of the study area another (smaller) paleobed developed, which would explain some of the overflows of the Palancia into the Almenara marsh.

The Belcaire River is a short ephemeral flow (approximately 22 km) that starts north of the town of Vall d'Uxó. Its catchment area is 97 km^2. It has a high slope that favors continuous overflow at lower elevations. Near the coast, the river builds an alluvial fan, which limits the Almenara marsh to the north, separating it from the Nules marsh.

(b) A system of alluvial fans and glacis of discrete development, connecting hillsides and plains that constitute the inner boundary of the marsh. Their absence in some areas enlarges the wetland area.

(c) According to the regional model, the sandbar-marsh system that makes up the area today was formed after the stabilization of the sea level during MIS 1 (Pirazzoli, 2005). The Estany Gran, located in the center of the marsh, has an average depth of about 7 m. Next to the current levee, the pebbly beach evolved in several ways. According to Pascual (1991), erosive processes were observed in the coastal sector of Xilxes between 1967 and 1986, which represented a retreat of up to 40 m and led to the construction of breakwaters to protect the buildings on the seafront. Conversely, the La Llosa beach remains stable, while in the town of Almenara a progradational trend is recorded (10–20 m between 1967 and 1986), and near the city of Sagunto the beach is eroded (up to 30 m). Pablo et al. (2014) recorded a shoreline retreat of 174 m between 1956 and 2012 in this coastal sector.

The Almenara marsh is water fed from (1) contributions from the surrounding mountain ranges, (2) Belcaire River and Palancia River overflows, (3) springs (*ullals*) reflecting a

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high water table, (4) saltwater intrusions during storms (rollover), and (5) the irrigation systems (ditches, wells, and pumps) associated with intensive agriculture.

Since ancient times, there have been constant attempts at desiccation in this and other coastal wetlands in order to adapt them for agricultural use. Indeed, these efforts continue today.

MATERIALS AND METHODS

From the geomorphological study, paired aerial photos (scale 1:25,000) from 1991 were interpreted, in order to identify the main forms of the marsh (Fig. 1). We analyzed the topographic information at a scale of 1:10,000 (and in some areas 1:2000) and orthophotos from 2000 (scale 1:5000) and 2009 (scale 1:1000) for the coastal zone. Fieldwork allowed us to compare and contrast the major sedimentary and stratigraphic characteristics of the formations. The initial results enabled us to define the best location for coring through trenches.

Four zones were located in the south of the marsh (Table 1). Drilling was performed, and a 15 cm diameter core was obtained. After the stratigraphic study, samples were taken systematically every 10 cm. The 186 samples underwent sedimentologic, paleontological (foraminifera, gastropod, and ostracod identification), and chronological study. The sedimentologic study focused on granulometric analysis and the ratios of organic matter and calcium carbonate, and it was carried out at the Geomorphology Laboratory of the Department of Geography (University of Valencia) and the Geological Laboratory of the Catholic University of Valencia. For the micropaleontological study, the samples were dried, weighed, dispersed in some cases (unit I) with the help of sodium hydroxide, and washed through a 0.063 mm mesh. They were then floated in dense liquids (trichloroethylene) to facilitate the recovery of the shells of microfossils (gastropods, charophytes, ostracods, foraminifera, etc.). Tests were carried out using a binocular stereomicroscope.

Other bioindicators were determined to analyze the origin of organic matter: alkanes, the ACL (average chain length) index, and the P_{aq} index (aquatic proxy). Alkanes were calculated in order to distinguish the upper vegetation. The index was calculated by P_{aq} $(C_{23} + C_{25})/(C_{23} + C_{25} + C_{29} + C_{31})$ (Ficken et al., 2000) and was used to evaluate the contribution of organic matter derived from macrophytes. The TAR_{HC} index (terrigenous/aquatic) was calculated by the expression $(C_{31} + C_{29} + C_{27})/(C_{15} + C_{17} + C_{19})$ (Silliman et al., 1996) and compares the contributions of terrestrial vegetation and algae.

For the chronological study, six bulk organic sediment samples were ^{14}C dated using accelerator mass spectrometry (Beta Analytic, Florida, USA). The databases used were IntCal04 (Talma and Vogel, 1993) and IntCal13 (Reimer et al., 2013). Also, the chronology was established through AAR in five samples, using the age calculation algorithms obtained in central and southern Spain ostracods by Ortiz et al. (2015), performed in the Biomolecular Stratigraphy Laboratory (Politechnical University of Madrid). Analytical samples of each bed contained only single monospecific *Candona angulata* or *Heterocypris salina* valves.

RESULTS

Sedimentary units and paleoenvironmental interpretation

S-1 core

Sedimentologic and micropaleontological analyses were carried out in 29 samples from the S-1 core (Fig. 1, Table 1). The analyses allowed identification of four sedimentary units. Three radiometric dates provide a partial chronology for the upper part of the sequence (Tables 2 and 3). The application of two different methods of numerical dating represents a risk because of the use of different scales and calibration methods; despite this, the results are quite compatible. The sedimentologic and micropaleontological results of the sedimentary units are shown in Supplementary Table 1, and a paleoenvironmental interpretation is presented in Figure 2.

The bottom of the S-1 core (between −3.5 m and 2.10 m, unit I; Fig. 2) comprises a carbonate-rich sediment, with rhizotubules, organic matter, and fragments of shells from freshwater and oligohaline organisms such as gastropods and charophytes. The presence of ferruginous concretions in the sediment and their thickness and other characteristics indicate a massive precipitation of carbonates in a subaerial environment. In this core, this unit is older than 7460 cal yr BP. Unit II, which begins at −2.10 m, appears as dark silt and clay, with poorly preserved charophyte remains. The increasing amount of organic matter (plant remains), the decline in the presence of carbonates, and signs of hydromorphy denote an oscillating water table and emersion processes that distinguish this unit from the one beneath it. In unit III, the water depth seems to have progressively stabilized, resulting in a marsh environment with cycles of rising and falling water levels. Subunits IIIa and IIIc consist of peat, with a fauna typical of freshwater and oligohaline environments with wide ranges of temperature and salinity. At the top of subunits IIIb and IIId, silts and clays with poor organic matter content appear, with a small sandy fraction made of biogenic remains: oogonia of charophytes and articulated ostracods suggest a greater depth. This intermittent marsh environment develops at this point in the Almenara marshlands between 7460 cal yr BP and 3100 ± 780 yr (AAR).

Finally, a more stable freshwater marsh environment seems to consolidate at the top (unit IV), from 3100 ± 780 yr (AAR). Silts and clays persist, and ostracods of oligohaline water appear articulated, as well as freshwater and oligohaline water gastropods and restricted benthic foraminifera (*Ammonia tepida* Cushman).

In short, an intermittent oligohaline or freshwater marsh is recorded after 7460 cal yr BP, lying on a carbonate surface, reaching stability from 3100 ± 780 yr (AAR) and remaining stable until recent times.

Table 1. Location of the cores. m amsl, meters above mean sea level.

Core	Geographic coordinates (datum: WGS84)	Altitude (m amsl)	Depth (m)	Distance from the coast (m)	Number of samples
S-1	39°44′26″N, 0°11′53″W	0.30	3.5	1600	29
S-2	39°44′05″N, 0°11′53″W	0.90	3	1200	26
S-3	39°44′04″N, 0°11′50″W	0.14	4	1160	42
S-4	39°43′38″N, 0°11′29″W	0.62	9.8	450	88

S-2 core

Twenty-six samples from the S-2 core (Fig. 1, Table 1) were analyzed, and four sedimentary units were defined. The sedimentologic and micropaleontological results of the sedimentary units are shown in Supplementary Table 2, and a paleoenvironmental interpretation is presented in Figure 3.

As in S-1, the bottom of S-2 (unit I) comprises a carbonate-rich sediment, followed by unit II (–2.6 m): a palustrine environment also with a high carbonate content (rhizotubules), some oogonia of charophytes, and plant remains. As in S-1, an oligohaline or freshwater marsh environment appears progressively, recording cyclical fluctuations in water level. The IIIa, IIIc, IIIe, and IIIg subunits are peat deposits (in IIIc, up to 95%), whose fauna is typical of freshwater or oligohaline environments. Several species of ostracods and gastropods—*Radix balthica* (Linné), *Bytinia tentaculata* (Linné), and so forth—are identified, many of which appear articulated. The peat is highly enriched with higher plant remains (herbaceous or tree). These environments indicate a shallower water depth at this point of the basin. At the top of the core (subunits IIIb, IIId, and IIIf), silts and clays are recorded with low organic matter content; the sand fraction is composed of biogenic remains such as thalus and oogonia of charophytes, gastropods, oligohaline species, and oligohaline and freshwater ostracods articulated. Charophytes may account for 95% of the sediment (sample 16, at the top IIIb level). Finally, unit IV represents the greatest stability of the water body at this point of the basin, with lenticular gypsum, pyrite, carbonate precipitations, and iron oxide concretions.

S-3 core

Sedimentologic and micropaleontological analyses of 42 samples in the S-3 core (Fig. 1, Table 1) were performed, and four sedimentary units were defined. Five radiometric datings provided a partial chronology for the upper part of the sequence (Tables 2 and 3). The sedimentologic and micropaleontological results of the sedimentary units are shown in Supplementary Table 3, and a paleoenvironmental interpretation of the units is shown in Figure 4.

The bottom of the core (unit I) consists of a carbonate-rich sediment, equivalent to those found in S-1 and S-2. However, it also contains a few calcium carbonate shell–made organisms, indicating that the deposit may have accumulated as a result of a particularly strong drying process in the earlier marsh environment. Toward –3.10 m, a palustrine deposit consisting of silt, clay, rhizotubules, and restricted environment organisms is found, as well as the brackish-water foraminifera *A. tepida* and *Criboelphidium excavatum* (Terquem); freshwater ostracods *Darwinula stevensoni* (Brady and Robertson), *Heterocypris* sp., *Paralimnocythere psammophila* (Flössner), *Candona* sp., and *Bradleycypris obliqua* (Brady); and freshwater gastropods and bivalves. From the taphonomic point of view, these organisms are poorly preserved and are matrix infilled, suggesting that they are indigenous. Toward –2.9 m, the oscillating oligohaline or freshwater marsh mentioned in S-1 and S-2 appears, with a thickness of 2 m. Four peat beds (IIIa, IIIc, IIIe, and IIIg) are observed, alternating with lighter-colored sediments (IIIb, IIId, and IIIf) as a result of the recovery of the water level. The faunal content at IIId indicates greater flow stability than at IIIb, as

Table 2. Absolute dating: ^{14}C (Beta Analytic, Florida, USA). Material dated: organic sediment. Pretreatment: acid washes.

Core	Sample	Depth (m)	Laboratory	Conventional radiocarbon age (^{14}C yr BP)	Measured radiocarbon age	2-Sigma range database IntCal04 (cal yr BP)	Beta Cal 3.20 database IntCal13 (cal yr BP)
S1	11	1.65	Beta-288411	6470 ± 50	6500 ± 50 yr	7460–7280 (95.4%)	7400–7325 (52.7%) 7430–7409 (15.5%)
S3	7	0.95	Beta-288410	4280 ± 40	4310 ± 40 yr	4880–4820 (95.4%)	4966–4815 (90.1%) 4754–4711 (5.3%)
S3	29	2.8	Beta-288412	6610 ± 40	6630 ± 40 ^{14}C yr	7570–7430 (95.4%)	7518–7463 (46.3%) 7563–7536 (21.9%)
S4	19	1.4	Beta-288413	4680 ± 40	4580 ± 40 ^{14}C yr	5480–5310 (80.1%) 5580–5530 (10.3%)	5417–5343 (44.19%) 5467–5442 (15.2%) 5337–5323 (8.1%)
S4	24	1.9	Beta-288414	5970 ± 40	6010 ± 40 ^{14}C yr	6900–6720 (95.4%)	6807–6745 (40.1%) 6856–6812 (28.1%)

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Table 3. Absolute dating: amino acid racemization (AAR; Biomolecular Stratigraphy Laboratory of the Polytechnical University of Madrid). Method: AAR. D/L Asp, D-aspartic acid.

Core	Sample	Depth (m)	Material dated	Laboratory	D/L Asp	Age (yr)
S1	5	1.1	*Candona angulata*	LEB-12511-12513	0.155 ± 0.009	3100 ± 780
S1	10	1.6	*Candona angulata*	LEB-12522-12523	0.192 ± 0.004	7400 ± 400
S3	14	1.5	*Heterocypris salina*	LEB-12533-12534	0.179 ± 0.002	5600 ± 250
S3	16	1.7	*Candona angulata*	LEB-12535-12536	0.180 ± 0.003	5700 ± 200
S3	18	1.9	*Heterocypris salina*	LEB-12539-12540	0.181 ± 0.002	5800 ± 200

attested by the abundance of autochthonous ostracods (articulated) and charophytes. Ostracod species indicate a freshwater environment, and even though they appear throughout the record, their abundance varies: in the top subunit, IIIf, *D. stevensoni* and *Candona* sp. predominate. In any case, all the species indicate the presence of permanent waters. The species recovered at unit IV tolerate a higher salinity range (up to 5‰). This paleoenvironmental event (unit III) developed at 7570 cal yr BP (similar to S-1) and persisted at least until 4820 cal yr BP. Unit IV, at the top of the record, indicates a more stable marsh regime until desiccation and the formation of the present-day soil (samples 1 and 2). Peat gradually disappears at level IV, between samples 4 and 3.

Subunit IIIf of S-3 and subunit IIId of S-2 present similar facies, as does unit IV in both cores.

S-4 core

In S-4 (Fig. 1, Table 1), 89 samples were analyzed, and seven sedimentary units identified. Two radiometric dates provide a partial chronology for the upper part of the sequence (Table 2). The sedimentologic and micropaleontological results of the sedimentary units are shown in Supplementary Table 4, and a paleoenvironmental interpretation is shown in Figure 5.

The bottom of the core (unit I) is interpreted as the palustrine wetland or marsh edge, where, as the presence of carbonate indicates, the saturation conditions are dominant. Rhizotubules and biogenic remains are scarce. Ferruginous concretions indicate air exposure. The carbonate content progressively decreases, becoming negligible in unit II. This unit, more than 2 m thick, consists of silt clay with two

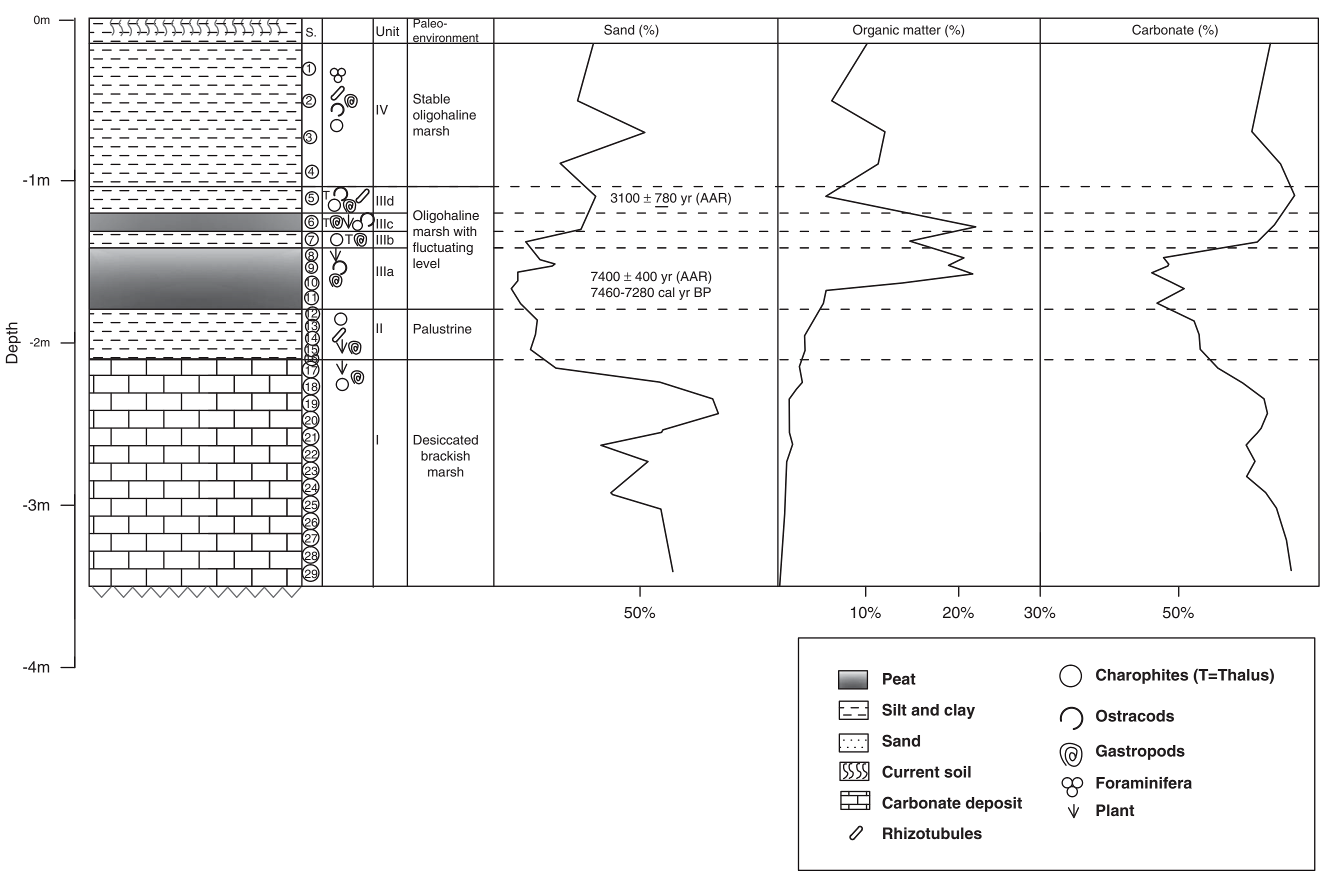

Figure 2. Stratigraphic column of the S-1 core. Textural distribution (%), % organic matter, % CO_3Ca. Palaeoenvironmental interpretation. AAR, amino acid racemization.

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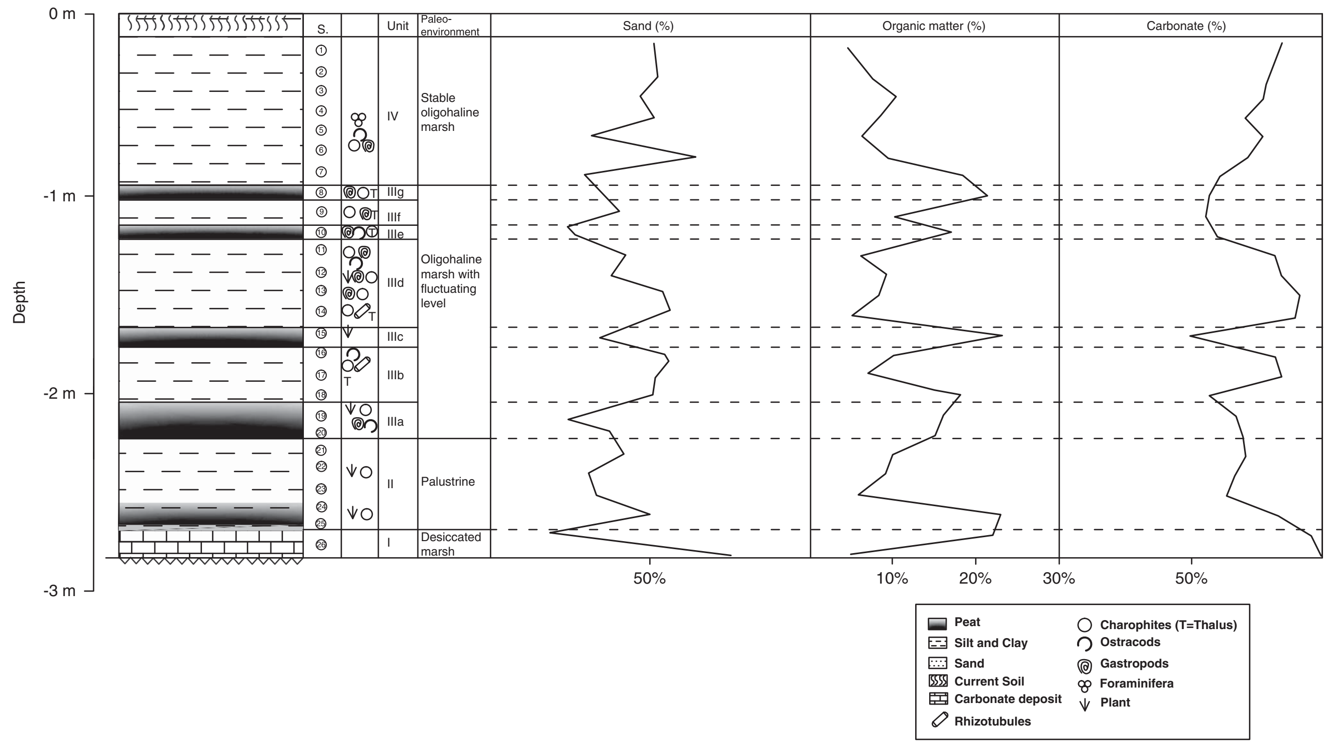

Figure 3. Stratigraphic column of the S-2 core. Textural distribution (%), % organic matter, % CO_3Ca. Palaeoenvironmental interpretation.

interbeds of sand—one comprising quartz (samples 80–78) and another at the top comprising bioclasts. The fauna includes abundant eroded bivalve shells, mainly at the top, as well as fragments of test *A. tepida* indicating oligohaline conditions. These findings are assumed to be related to the marsh-littoral interface, in backbarrier facies.

At a depth of 7.2 m is a well-sorted sand bed more than 2 m thick comprising 95% quartz, with subangular morphology, and without fossils (unit III). This event can be interpreted as part of a coastal system that emerged in backshore facies, or it may even be eolian. However, the complete absence of biogenic remains is quite surprising, and a possible fluvial contribution cannot be ruled out. Between –5 m and –2.6 m, carbonate sands (concretions and rhizotubules) and silt and clay interbeds are recorded, indicating a fluctuation of the water level with carbonate deposition during saturation episodes (unit IV). The presence of brackish-water foraminifera *A. tepida*, *C. excavatum*, and *Haynesina germanica* (Ehrenberg) confirms this. The presence of marine species tests, although scarce, indicates the vicinity of the sea and the high energy responsible for the poor conservation of the shells. Gastropods and ostracods with similar ecological requirements are preserved, showing calcium carbonate infills.

A ^{14}C dating to 6900 cal yr BP marks the beginning in this record of a freshwater or oligohaline marsh event (unit V), 1 m thick with a peat deposit at the top. Sedimentologic and faunal characteristics indicate a shallow local environment, which may be correlated with unit III of cores S-1, S-2, and S-3. A dating marks the start at 5480 cal yr BP of a deposit comprising quartz sand (unit VI), with abundant biological remains. It begins with a layer of *Posidonia oceanica* (Linné) rhizomes to –1 meter below mean sea level (m bmsl) and flattened pebbles to –0.6 m bmsl; this suggests shoreface at the bottom passing to foreshore at the top. Finally, the marsh facies (unit VII) is recovered, in spite of the marine influence deduced from the presence of marine fauna. This unit can be correlated with the top (unit IV) of S-1, S-2, and S-3.

In spite of these chronological correspondences between the peat dated in the Almenara marshland and global climatic phenomena (the Bond and Wanner cycles), these interpretations should be regarded with some caution given the ongoing debate regarding their reliability. The application of two different methods of numerical dating represents an added risk because of the use of different scales and calibration methods, although the comparison between the two provides an interesting way to control and contrast the results. Another point we should stress is that ^{14}C dating performed in sediments of geochemically open systems, like the area under study here, is problematic. Nevertheless, the relative lack of connection with the marine environment suggests that the data obtained are indeed reliable, especially the data from the cores of the interior of the marsh.

DISCUSSION

An evolutionary model

The correlation of the records from inside the marsh and near the coast allows us to propose an evolutionary model for the Holocene.

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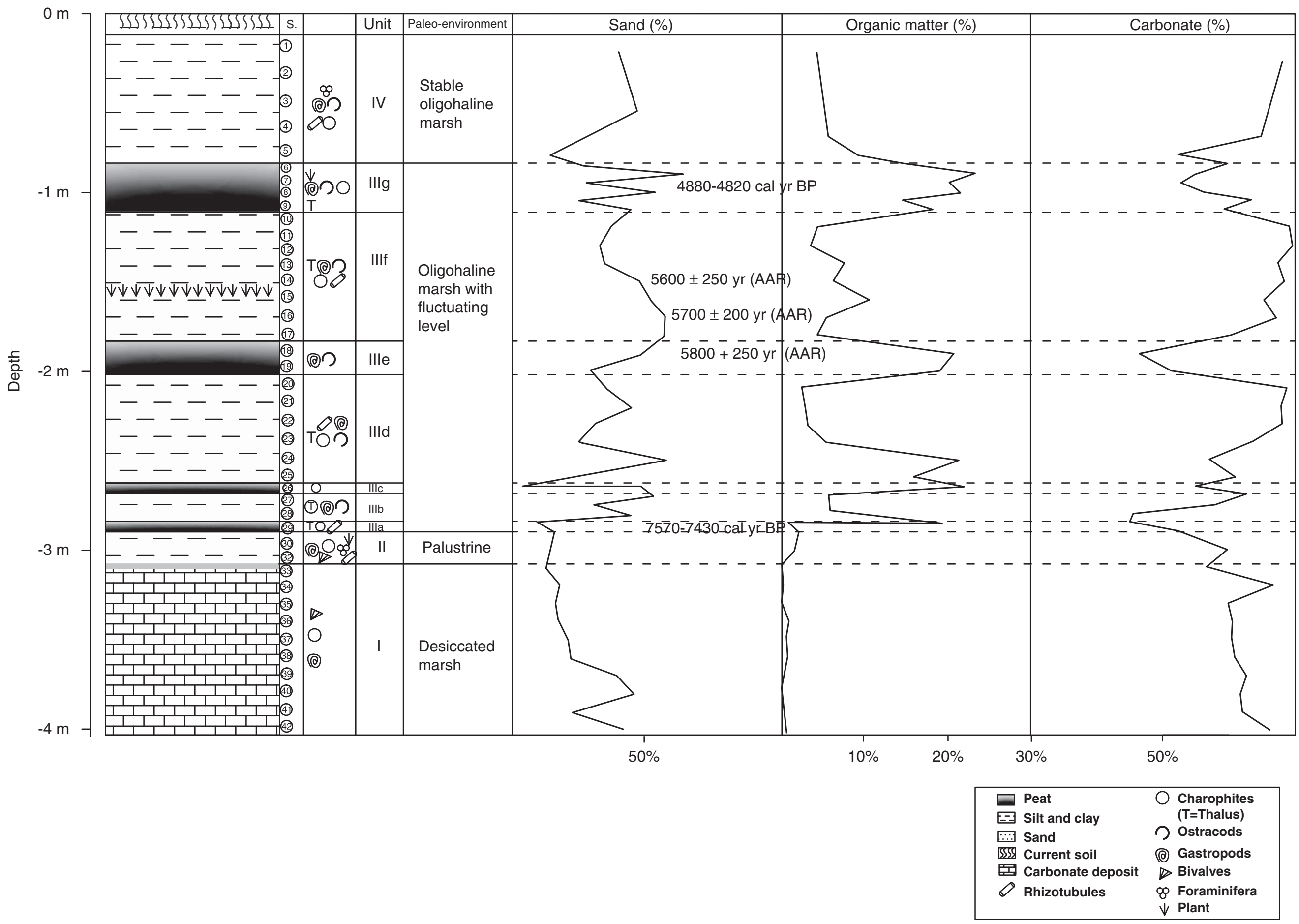

Figure 4. Stratigraphic column of the S-3 core. Textural distribution (%), % organic matter, % CO_3Ca. Palaeoenvironmental interpretation. AAR, amino acid racemization.

In the basal unit (unit I in S-1, S-2, and S-3), a carbonate deposit forms the bottom on which palustrine facies (unit II) are deposited showing the early stages of flooding that evolved into marsh facies (unit III in S-1, S-2, and S-3) (Fig. 6). The micropaleontological content of the carbonate deposit indicates the final stage of the silting of the edge of an ancient brackish marsh environment. Despite the absence of numerical dating for unit I, the archaeological occupation during the Epipaleolithic (the archaeological site Gran Estany) at the carbonate level suggests that this unit dates from at the final stage of the Epipaleolithic; this is at least 7000 yr (Gusi Jener, 1978). Pollen analysis indicates that human occupation was located in a rich ecosystem, consisting of a marsh environment surrounded by extensive vegetation, mainly comprising cork oaks covering the coastal mountains, glacis, and the alluvial fans (Gusi Jener, 1978). Pollen data from the archaeological site, borehole core information, and brackish fauna remains (unit I in S-1, S-2, and S-3) suggest that this deposit was linked to carbonate precipitation in a marshy environment in depressed areas where the carbonate-rich groundwaters rise to the ground in spite of intermittent desiccation events (Wright and Tucker, 1991; Wright and Platt, 1995). The area of carbonate deposition is separated from the sea by a barrier whose backshore (or dunes) facies are recorded in unit III of S-4, located 450 m from the present-day coastline. Therefore, this unit is the result of the basin flooding after the sea-level stabilization during MIS 1. The palustrine facies of the following unit (unit II) established themselves gradually and are recognized because of the presence of a shell-filled sediment matrix, which increases toward the top. Oligohaline species appear, indicating that a freshwater environment prevailed because of the considerable groundwater inputs. In the S-3 record, euryhaline foraminifera and data indicating a greater stability of the water body appear. At the edges of the marsh (unit II, S-1) abundant quartz sands are recorded that may be of alluvial origin.

The thickest unit (unit III, registered in S-1, S-2, and S-3) was established in the basin by 7570 cal yr BP (S-3). Facies of oligohaline or freshwater marsh are recognized, although oscillations are reflected in alternating dark, peat-rich sediments, and others showing lighter colors, rich in biogenic remains and occasionally with rhizotubules and carbonate concretions. Near the coastline (S-4), these facies correspond to a marsh (unit IV) associated with brackish-water foraminifera. The interbedding of silty clay and sands with marine foraminifera may suggest the presence of a cyclical marsh level. At the top of the record (unit V), quartz sands and marine mollusks may indicate the proximity of the sea. This marsh may have been isolated from the sea by a

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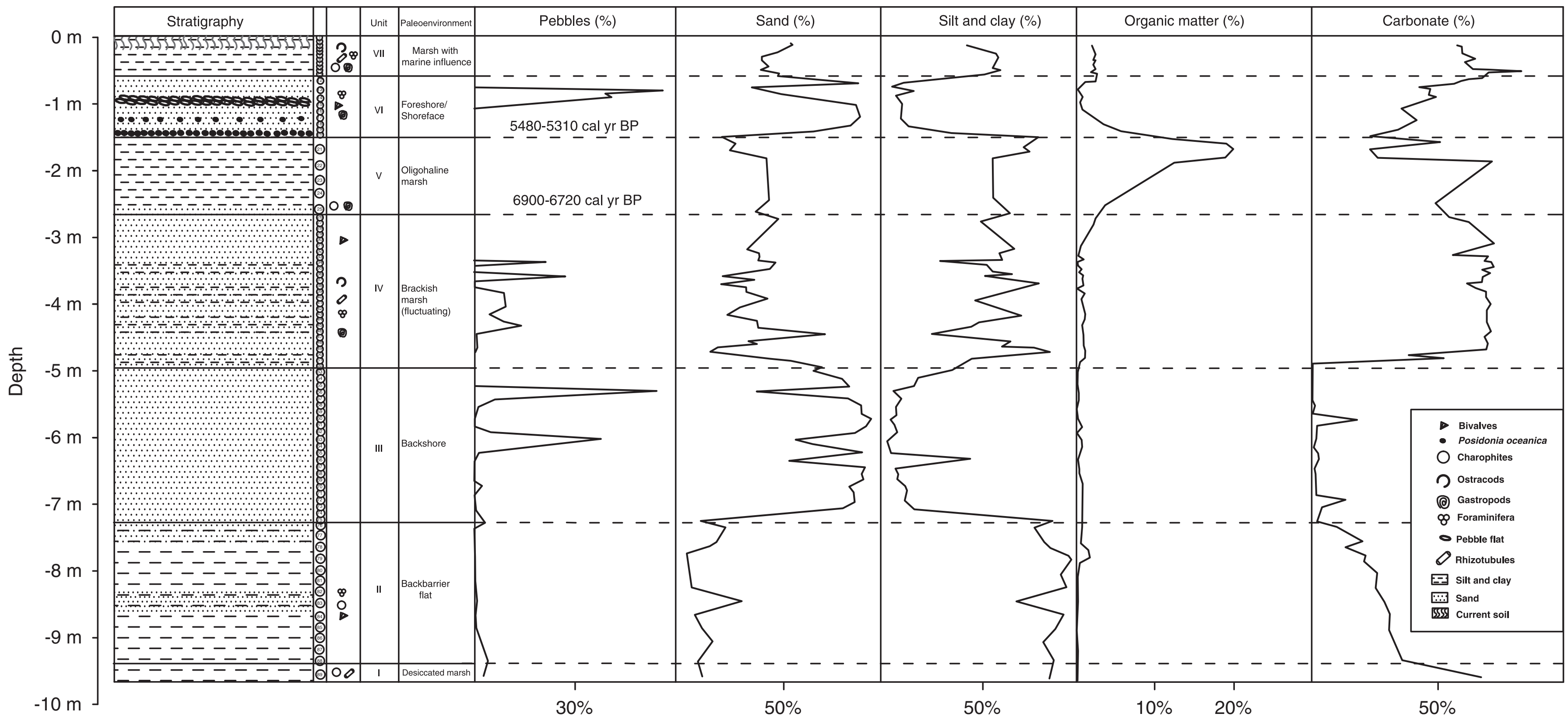

Figure 5. Stratigraphic column of the S-4 core. Textural distribution (%), % organic matter, % CO_3Ca. Palaeoenvironmental interpretation.

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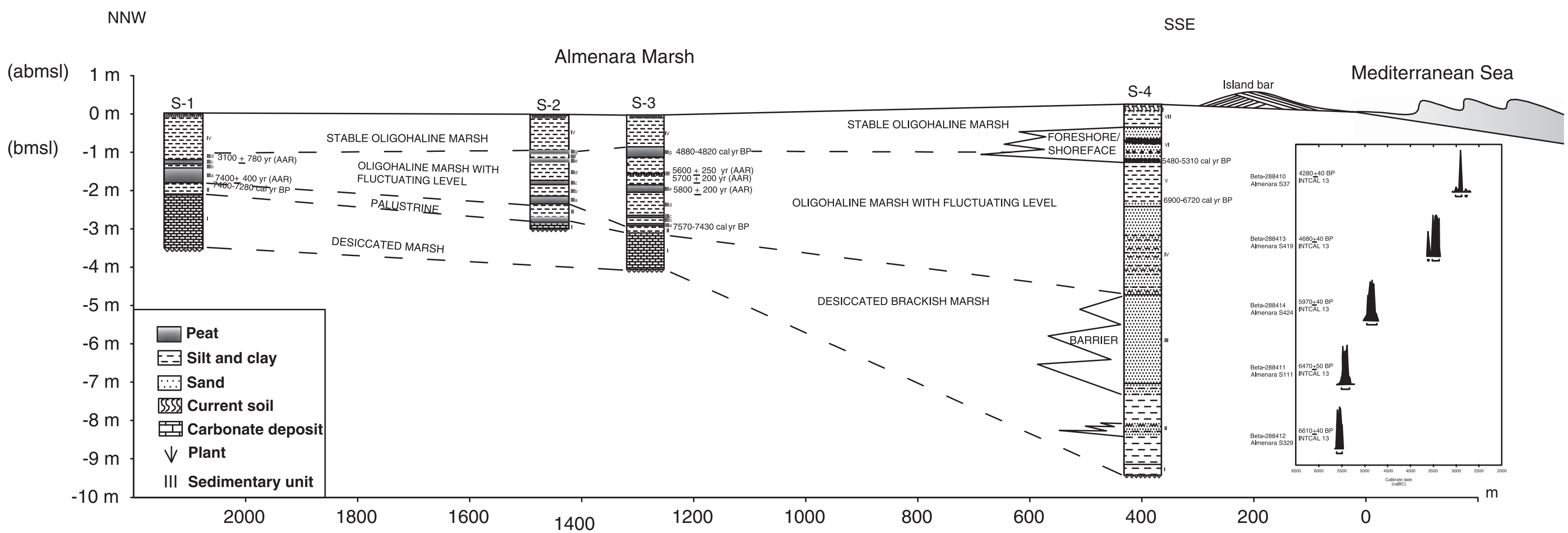

Figure 6. Correlation of the cores and proposed paleoenvironmental interpretation. AAR, amino acid racemization; amsl, above mean sea level; bmsl, below mean sea level; NNW, north-northwest; SSE, south-southeast.

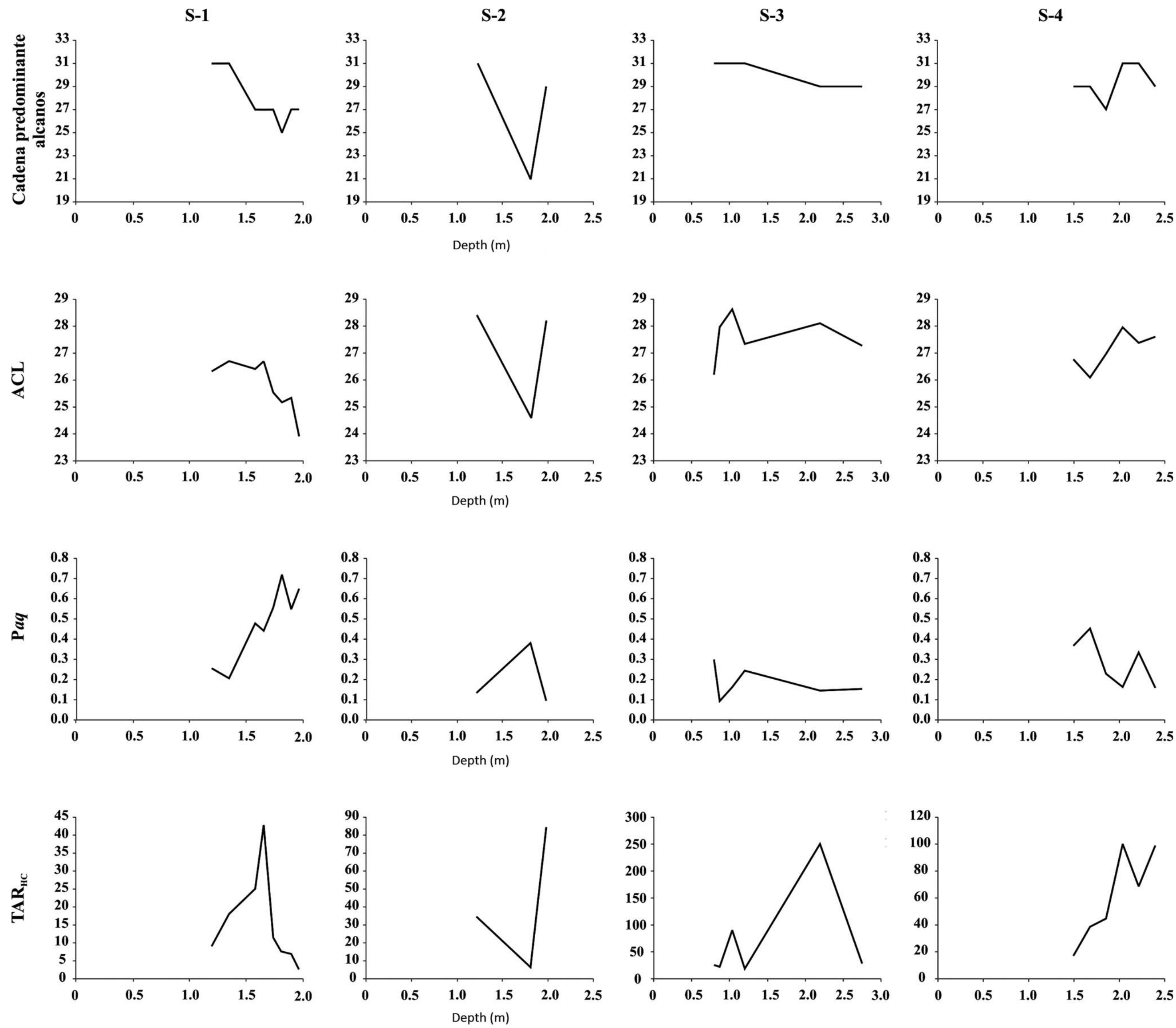

Figure 7. Bioindicators: alkanes, the average chain length (ACL) index, P_{aq} index (aquatic proxy), and TAR_{HC} index (terrigenous/aquatic ratio).

barrier (Sanjaume, 1985; Rosselló, 1993) as the result of the growth of a submarine bar between 5500 and 6000 ^{14}C yr BP.

The geochemical study of the peat beds (Fig. 7) indicates a predominance of herbaceous plants, as indicated by the strong presence of alkane C_{31} and even macrophytes, as reflected by the predominance of alkanes C_{27}, C_{21}, and C_{25}. Aquatic plants predominate in the peat from S-1, and grasses in peat from S-3. The P_{aq} index also indicates the importance of macrophytes at the edges of the basin (S-1). The TAR_{HC} index has high values in all cases, which means that the algal contribution is very small, except in the deepest peat of the S-1. Therefore, the peat found originates from the development of herbaceous and other terrestrial plants. In a geochemical analysis of the peat, López-Buendía et al. (1999) found a low marine influence in this deposit, and Mediato (2016) reported peat deposits with a descent in the water level of the lake attributable to regional climate factors. In Mediterranean marshes, peat deposits are related to hot and humid periods; in Almenara, this interpretation is also supported, but the herbaceous vegetation dominant in the peat with respect to the Charophyta (aquatic plants) that dominate in the intercalated levels suggests that the level of the marsh descended during the period in which the peat was formed.

Unit IV (S-1, S-2, and S-3) was deposited through a progressive upward facies change. This unit is detrital with quartz sand deposition (S-1), but there is a simultaneous syngenetic carbonate deposition as well. As a whole, the biofacies shows greater stability of water bodies and increased depth in this part of the basin compared with the deposit of unit III. At the top of this unit, emersion facies are recognized, immediately prior to the current soil, with rhizotubules and lenticular carbonate and gypsum concretions. Intrasedimentary gypsum formation causes higher saturation than in older beds. Near the coast (S-4), this unit correlates with units VI and VII.

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The first (unit VI) is interpreted as shoreface deposits, with abundant *P. oceanica* rhizomes at the base. It has an association of stenohaline foraminifera and abundant eroded marine fauna. Euryhaline foraminifera shells are observed. This level presents a greater input of the marine environment to the basin compared with previous levels; its bottom (rhizomes) was ^{14}C dated at 5480–5310 cal yr BP. At the top, flattened pebbles at –0.6 m bmsl and the micropaleontological and sedimentologic characteristics suggest a foreshore deposit.

In unit VII of S-4, freshwater or oligohaline marsh conditions are observed and also higher stability, and this unit is associated with unit IV of the cores from boreholes drilled inside the marsh. In a geochemical study, López-Buendía et al. (1999) determined the marine influence in deposits located above the peat.

In other similar systems, the approach of the sea during the first stage of the Holocene transgression is manifested through the formation of brackish marshes, as in Albufera of Valencia (Carmona et al., 2016) and Almenara (according to the organisms in the carbonate deposit), although in the Pego and Jávea marshes, freshwater (peat) deposits are formed (Fumanal et al., 1993; Viñals, 1996). The advance of the Holocene transgression and its high stand during the middle Holocene allowed the consolidation of barriers that isolated restricted environments more effectively. At this time, lagoon deposits and brackish marshes such as Xabia and Pego are recorded (Fumanal et al., 1993; Viñals, 1996), as well as Albufereta (Blázquez and Ferrer, 2003; Ferrer and Blázquez, 2012) or marshes with a clear marine influence such as Elx (Blázquez, 2005; Blázquez and Usera, 2010) or the Albufera of Valencia (Carmona et al., 2016). In contrast, in the Almenara marshland, a paleoenvironment of oligohaline marshland is identified, indicating the effectiveness of the barrier in isolating the marsh from the marine environment and the importance of the action of the aquifer as a brake on marine infiltration.

Almenara marsh in its regional context and inside a global climatic model

The regional trend of evolution of the western Mediterranean coast proposed by various authors (Dupré et al., 1988; Rey and Fumanal, 1996; Blazquez and Usera, 2010; De Torres et al., 2010; Torres et al., 2014; Carmona et al., 2016) indicates that large sea-level oscillations cause the migration of restricted environments following rises or falls in sea level. In the infills developing in barrier island–lagoon systems following eustatic regressions, desiccated alluvial, marsh, and lagoonal facies are recorded, while during transgressions sediments in marine, littoral (facies barrier), or sea-connected lagoon and marsh facies evolve toward isolation and mellowing as the coastal barriers are strengthened.

The carbonate deposit that forms the basis of the Almenara record accumulated during the regression that preceded the Holocene transgression, marking an arid phase. This carbonate deposit is older than 7570 cal yr BP, and probably coeval to the stages of climate worsening of the Younger Dryas or even the arid period of 8200 cal yr BP and colder climate (Wanner et al., 2011). This carbonate deposit is the testimony of a previous brackish marsh, and this restricted environment is related to the level of the sea nearby. Therefore, it is more likely to have formed during the Holocene, coinciding with an arid period. This cold event (8200–7600 cal yr BP) is reflected in lower moisture and in the pollen records of many lakes in the Iberian Peninsula (Carrión, 2002; Davis and Stevenson, 2007; Vegas et al., 2010). In the Guallar and Hoya del Castillo lakes, a dramatic increase in microcharcoal particles from wildfires is observed at 8412–8060 cal yr BP (6462–6110 cal yr BC) in Guallar and 8326–7976 cal yr BP (6376–6026 cal yr BC) in Hoya del Castillo. In addition to aridity, strong winds and falling temperatures are inferred, as well as a cooling of the surface of the North Atlantic (Bond et al., 1997) because of the contribution of fresh and cold water from North American lakes (Clarke et al., 2004). Toward the coast, a well-sorted sandy deposit and barrier (backshore facies) can be associated with this carbonated unit. The total absence of organisms may reflect the long distance from the sea and possible coastal progradation, associated with an increased availability of sediment (Ferrer and Blázquez, 2012).

Despite the use of two different dating methods, there is consistency between the data provided by both methods and the regional sequence, supported by numerous authors. The first marshland deposits of Almenara related to the eustatic rise of MIS 1 comprise peat dated to 7570 cal yr BP (S-3) and 7460 cal yr BP (S-1) together with the underlying marshy level. Several authors (Dupré et al., 1988; Rey and Fumanal, 1996; Viñals, 1996) indicate that the formation of freshwater or oligohaline marsh deposits is common at the base of the Holocene in these Mediterranean systems (Torreblanca, Benicassim, Nules, Pego, Jávea, etc.) because of the water-table rise linked to the eustatic rise, which favored the development of bogs in the area formerly occupied by ponds and marshes. In the Pego marsh, peat has been dated at 5330 ± 90 and 5200 ± 60 ^{14}C yr BP at two different points inside the basin, which might be correlated with beds of peat from Almenara (S-3) dated at 5800 ± 200, 5700 ± 200, and 5600 ± 250 yr (AAR) and 4880–4820 cal yr BP. The freshwater environment indicates the special importance of groundwater supply in this wetland from the middle Holocene onward (and lasting until today) because peat and marsh deposits of contemporary Mediterranean basins indicate brackish environments for that time point. For its part, the oligohaline and freshwater character of this environment suggests effective barrier closure from the marine environment.

In contrast, other authors (Mediato and Santisteban, 2006; Mediato et al., 2011a, 2011b; Mediato, 2016) argue that the peat deposits are because of episodes of descent of the level of the marsh in response to centimetric decline in the sea level. This in turn was because of the installation of low atmospheric pressure systems linked to changes in solar activity cycles and the variability of the NAO index (Zazo, 1999, 2006; Zazo et al., 2003). These authors indicate three episodes of eustatic rise recorded in the basin (7000–6500 cal yr BP, 5500–5300 cal yr BP, and 3500 cal yr BP), which are detected by the abundance of charophytes in the Almenara basin and coincide with those observed in other Spanish Mediterranean areas (Somoza et al., 1998; Goy et al., 2003; Zazo et al., 2008).

In any case, in the Almenara marshlands at least four peat deposits are recorded, interspersed with light-colored sediments made of biogenic remains that are freshwater markers in most of unit III (S-3). The younger peat deposits are dated at 4880 cal yr BP (S-3), and the most recent marsh sediment associated with unit III is dated at 3100 ± 780 yr (AAR) (S-1). The four peat beds are interpreted as changes in the water level of the marsh, which are also recorded on the coast (unit IV, S-4). Similarly, in nearby areas such as the Albufera of Valencia (Carmona et al., 2016), several moments of saturation of the lagoon and carbonate precipitation were recorded between 6450 cal yr BP and 3710 ± 130 cal yr BP, although, in contrast to the Albufera of Valencia, these changes occur in a lagoon that was connected to the sea and was therefore very sensitive to eustatic movements. Decreases in the water level are also detected for this period in other lacustrine basins of the Iberian Peninsula (Reed et al., 2001; Carrión, 2002; Martín-Puertas et al., 2008; Morellón et al., 2009; Aranbarri et al., 2014), which may indicate a more global cause related to climatic factors and independent of eustatic changes. However, for other authors (Zazo, 2006; Goy et al., 2003; Zazo et al., 2008) these episodes of climatic contrast may correspond to relative sea-level increases of a few centimeters. Regional comparisons suggest a correlation of North Atlantic Holocene cooling events with dry conditions across southern Iberia and northwest Africa (Fletcher et al., 2007). The peat dated in Almenara at 5800 ± 200 yr (5700 ± 200 and 5600 ± 250 yr) (AAR) correlates with the 5900 cal yr BP peak reported by Bond et al. (1997, 2001) and the end of the dry cycle at 6500–5900 cal yr BP reported by Wanner et al. (2011). The peat dated 4880 cal yr BP (and 4820 cal yr BP) correlates with the aggregate cycle 4800–4500 cal yr BP (Wanner et al., 2011). Even the end of the oscillating marsh facies dated to 3100 ± 780 yr (AAR) can be associated with the dry cycle at 3300–3500 BP (Wanner et al., 2011) and the installation in the Mediterranean area of a contrasting climate toward 4000–4500 yr BP, which persists today (Dupré et al., 1988; Carrión et al., 1999); this is explained by the change in the NAO from generally positive to variable, with intermittent negative conditions around 4500 cal yr BP (Olsen et al., 2012). Also, Sabatier et al. (2012) propose the increase in storm activity during Holocene cold events over the North Atlantic and Mediterranean regions, especially at 6300–6100, 5650–5400, 4400–4050, and 3650–3200 cal yr BP, among others.

The progressive rise in sea level during MIS 1 culminates in the foreshore deposits (S-4), which constitute the maximum surface flooding occurring at 5480 cal yr BP (a dating at odds with the 7000 cal yr BP age proposed by Mediato [2016]). The episode is testimony to the maximum influence of the marine environment in the Almenara marshlands during the Holocene. It implies that the barrier prograded into the marshland, as isochronous marsh facies have been recorded in the center of the basin. The faunal record indicates oligohaline water, which allows us to infer the effective closure of the barrier, the role of groundwater supply, and the very limited marine influence. This would explain the large proportion of herbaceous vegetation in peat accumulated at the center of the basin (S-3). In the Pego marsh (Dupre et al., 1988; Torres et al., 2014), Torreblanca (Segura et al., 1995), Benicassim (López-Buendía et al., 1999; Mediato, 2016), Albufereta (Ferrer and Blazquez, 2012), and Elche (Blázquez and Usera, 2010), a similar model is suggested: a sand barrier (dated around 5000 yr) intruding into a restricted environment where peat deposits developed (dated between 7790 and 8300 cal yr BP). The different facies distribution in contemporary wetlands (such as the Albufera of Valencia) may be because of the different tectonic framework of the basins. The Almenara marshland seems to have undergone a pronounced Holocene subsidence, which explains the intrusion of the marine environment around 5480 cal yr BP, 450 m farther inland than the present-day coastline and −1 m bmsl (S-4).

It is difficult to determine whether these changes are because of climate change, global or regional sea level, or a combination of the two. What is clear is that the marine influence is very limited (except in the maximum flooding surface), so the oscillations of the level of the marsh seem to be more related to climate change (and its influence on the contribution of the aquifer) than to oscillations in sea level of a few centimeters.

CONCLUSIONS

From the paleoenvironmental point of view, the Almenara marshland infill started at the beginning of the Holocene and continues until the present day, showing many facies. A generalized carbonate deposit marks the start of the sedimentation, overlain by a series of deposits interpreted as the final stage of the desiccation of a brackish marsh, which is separated from the sea by a barrier whose backshore facies deposits are recorded in the S-4 borehole. These carbonate deposits act as the impervious bottom of a freshwater marsh with fluctuating levels, with at least four cycles established from 7570 cal yr BP to 3100 ± 780 yr (AAR). These oligohaline or freshwater marsh environments were invaded by seawater in the form of shoreface/foreshore deposits at 5480 cal yr BP. At the top of the records, a more stable oligohaline marsh is established, even in the S-4 borehole record, which became established around 3100 ± 780 yr (AAR) and marks the current morphology.

Maximum surface flooding occurred at 5480 cal yr BP and was recorded in the area 450 m from the current coastline and at a depth of 1 m bmsl. After this episode, there was a fall in sea level, probably produced by coastal progradation, which produced more stable geochemical conditions in the marsh deposits and favored the precipitation of calcite and gypsum. The first deposits related to the Holocene transgression, in marsh facies, are dated to 7570 cal yr BP. The development of this marine deposit entailed a significant progradation of the marine environment and therefore the subsidence of this coastal shelf in recent times.

The predominance of oligohaline facies indicates the limited influence of the marine environment in the Holocene infill of the basin and stresses the importance of groundwater supply and the effectiveness of the barrier in isolating the area from the open sea.

There is a direct correlation between at least three peat bed deposits, dated by AAR and ^{14}C, and regional phenomena that affected the Northern Hemisphere related to Bond cycles, Wanner cycles, and the variability of the NAO index. Because of the limited marine influence and the lack of marine facies in the marshland record, the fluctuations in the level of the marsh are attributed to climate changes affecting groundwater input, although the development of sea-level movements of a few centimeters that affected solely the barrier is a possibility that should be borne in mind.

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SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/qua.2017.47

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