

Mid-Holocene and historical palaeoecology of the Albufera de València coastal lagoon

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ABSTRACT

Mid-Holocene and historical palaeoecology of the Albufera de València coastal lagoon

The Albufera de València coastal lagoon is one of the largest oligohaline lagoons in the Iberian Peninsula. Highly polluted and threatened by plans for urban development, it has been protected as a Natural Park since 1986 to preserve its environment and surroundings, mostly consisting of ricefields and a forested coastal sand bar. Restoration plans focus on recovering the water quality and submerged macrophyte cover that occupied most of the lagoon in the 1950's. Until recent studies, little was known about the wetland's palaeoenvironmental history. To improve this knowledge, we analysed the Holocene evolution of the lagoon based on sedimentology, geochemistry and microfossils (foraminifera, diatoms, ostracods and pollen remains) from four cores. Two were collected in the sand bar, and two from the central lagoon. In combination with previous work, our new data show that the lagoon remained brackish for most of its history since 8700 cal BP, with the frequent presence of accompanying freshwater taxa from 7000 to 3400 cal BP. Notwithstanding chronological uncertainties, some episodes of decline in the abundance of microfossils seem to match aridity events Bond 5 (8.2 ky BP) and Minorca 7 (7.5-7.2 ky BP), the latter marking the switch from a dominance of arboreal vegetation to grasses. The most important change in the water body consisted of a sharp change at the beginning of the 19th century from a brackish to an oligohaline lagoon, driven by anthropogenic hydrological control associated with the expansion of ricefields. Later on, by the 1960-1970's, the growing population impacts of agricultural, wastewater and industrial effluents launched a major eutrophication process that would eventually sharply reduce the benthic vegetation and invertebrate communities and promote the phytoplankton dominance of the ecosystem in a turbid state. Although our multiproxy study has increased understanding of the lagoon's history, somewhat supported by documentary evidence, further palaeoecological research in different parts of the wetland would help define the causes of heterogeneous timing of changes in this large, shallow, complex system. Notwithstanding the need for further research, there is a clear priority for managers and the society to work on restoration efforts to drive the Albufera wetland towards one of the previous, less impacted, states of this worn-out and neglected ecosystem.

Key words: Palaeolimnology, pollen analysis, NPP, diatoms, Ostracoda, Foraminifera, isotopes, XRF, climatic events, coastal lagoon evolution, Iberian Peninsula

RESUMEN

Paleoecología de la laguna costera de la Albufera de València durante el Holoceno medio y en época histórica

La laguna costera de la Albufera de València es uno de los mayores lagos oligohalinos de la Península Ibérica. Fuertemente contaminada y amenazada por planeamientos de desarrollo urbanístico, fue finalmente protegida como Parque Natural en 1986, con el fin de preservar la cubeta y sus ambientes aledaños, los cuales consisten fundamentalmente en arrozales y un bosque sobre la barra arenosa costera. Los planes de restauración se centran en recuperar la calidad del agua y la cobertura de macrófitos sumergidos que ocupaban la mayor parte de la laguna en los años 50. Hasta la publicación de algunos trabajos recientes, se conocía bien poco de la historia paleoambiental esta zona húmeda. Con el fin de mejorar esta falta de conocimiento, estudiamos la evolución de la laguna durante el Holoceno mediante análisis sedimentológicos, geoquímicos y de microfósiles (foraminíferos, diatomeas, ostrácodos y restos polínicos) de cuatro registros. Dos de ellos fueron obtenidos en la barra arenosa, y otros dos del centro del lago. En combinación con trabajos anteriores, nuestros nuevos resultados muestran que la laguna permaneció como un ambiente salobre durante la mayor parte de su historia desde 8700 cal BP, con presencia frecuente de taxones dulceacuícolas acompañantes entre los 7000 y 3400 cal BP. A pesar de la incerteza de la cronología, se observan algunos episodios de reducción de abundancia de microfósiles acuáticos que parecen corresponderse con los eventos de aridez Bond 5 (8.2 ky BP) y Menorca 7 (7.5-7.2 ky BP), este último coincidiendo con un cambio notable de dominancia de vegetación arbórea a herbácea. El cambio mayor en el sistema acuático consistió en una transformación drástica a principios del s. XIX de una laguna salobre a una oligohalina, producida por un control antropogénico de la hidrología, asociado a la expansión del cultivo del arroz. Más tarde, entre 1960 y 1970 aproximadamente, el incremento poblacional y los impactos asociados de la agricultura, las aguas residuales y los efluentes industriales provocaron un proceso extraordinario de eutrofización que conllevaría una fuerte reducción de la vegetación sumergida y las comunidades de invertebrados, promoviendo la dominancia del fitoplancton de un sistema que pasó a un estado de alta turbidez. Aunque nuestro estudio con múltiples indicadores haya aumentado nuestro conocimiento de la historia de la laguna, con la ayuda de evidencias documentales, un mayor esfuerzo de investigación paleoecológica en diferentes zonas del humedal ayudaría a definir las causas de una dinámica temporal heterogénea en este extenso y complejo humedal. A pesar de esta necesidad de nuevas investigaciones, actualmente existe una prioridad para los gestores y la sociedad, de trabajar en esfuerzos de restauración que lleven a la zona húmeda de la Albufera hacia uno de los estados previos menos impactados de este ecosistema ampliamente sobreexplotado y desatendido.

Palabras clave: Paleolimnología, análisis polínico, palinomorfos no polínicos, diatomeas, Ostracoda, Foraminifera, isótopos, XRF, eventos climáticos, evolución de lagunas costeras, península ibérica

INTRODUCTION

*“València té els matins lluent,
pel sol que juga amb el mar
i corre per l’Albufera”*

Al-Russafí de València (12th century)
version by J. Piera (1983)

As poets have sung for centuries, the Albufera lagoon is recognized as a keystone symbol of landscape beauty in the area of València and, in modern parlance, is of very high value as an ‘ecosystem service’ in the semi-arid Mediterranean climate. As a scarce and valuable water resource, it has long been threatened by intensive agricultural, industrial and demographic development, however, which has ultimately had a severe impact on the aquatic ecosystem and its surrounding catchment. Its current status is one of a highly polluted and artificially-regulated

water body, mostly used as a dam for ricefield irrigation and as a deposit for sewage outflow (Vicente & Miracle, 1992; Soria, 2006). An urban development plan designed in the 1960’s for the transformation of a forested area on the sand bar between the lagoon and the sea caused widespread environmental protest and resulted in the designation of the wetland ecosystem as a Natural Park in 1986 (Fundació d’Amics del Parc Natural de L’Albufera, 2000). In spite of this, the sad story of the ongoing process of eutrophication and degradation of water quality, and recent attempts at restoration, are well documented (Soria, 2006, Miracle *et al.*, 2012). Knowledge of a lagoon’s pre-impact state is essential for effective restoration, but almost no data are available either on limnology or landscape biodiversity prior to the first quarter of the 20th century, particularly for ages previous to the publication of the work by Cavanilles (1795).

What was the origin of the lagoon? What was the impact of the marine transgression following the Pleistocene-Holocene climatic transition? Was its (pre-) historical limnology similar to observations of the first half of the 20th century by Pardo (1942)? Archaeological and historical sources point to a very long history of human occupation around the Albufera wetland system, with extensive resource exploitation, providing evidence which suggests growing impacts since early prehistorical times up to drastic habitat modification and desiccation of large areas of the lake during the past few centuries (Mateu *et al.*, 1985; Rosselló i Verger, 1995; Sanchis Ibor, 2001).

The first palaeolimnological work in the lagoon was carried out by Margalef & Mir (1973), who found diatom-based evidence for a marked salinity decrease in the top 20 cm of two short cores. Similar differences between surface and deeper (up to 85 cm) sediment samples from the bottom of the lagoon were also found when analysing the malacological composition (Robles *et al.*, 1985), with a remarkable abundance of the lagoon cockle *Cerastoderma glaucum* (Bruguière, 1789) in the deeper zones of the three short cores extracted. These authors conclude that the lagoon was previously brackish, in contrast to the present-day freshwater (oligohaline) state. Considering the scarcity of palaeoecological studies since these works (but see recent research by Carmona *et al.*, 2016), and keen to understand the evolution of the wetland ecosystem, the senior author (MRM) of the present text launched a multi-proxy project in 2002. From this effort, papers have been published on the stratigraphy and evolution of the Albufera, mostly based on ostracod remains (Santisteban *et al.*, 2009; Marco-Barba *et al.*, 2012; 2013a; b), but much information remains unpublished. In this paper we strengthen previous inferences by incorporating additional proxy data for the history of the lagoon and its catchment, including pollen, foraminifera and diatoms. These new proxy data support and build up on the palaeohydrological interpretations previously provided only by lithology and Ostracoda remains from two littoral cores and, most importantly, also add new landscape palaeoenvironmental reconstructions based on pollen analysis, since the end of the early

Holocene. A new core from the centre of the lake is thoroughly analysed using high resolution XRF analysis and ostracod community and geochemical data to compare it with previous records from other areas of the lake and therefore contribute to unveil the spatial coordinated or heterogeneous response of the lake to human impacts and environmental changes. Furthermore, the new core expands the time period previously analysed for a shorter core (which encompassed from the 18th to 20th century), providing a wider time window down to earlier Middle Ages.

Previously, the origin of the lagoon was thought to date to the maximum marine Holocene transgression at c. 6000 y BP (Mateu *et al.*, 1985; Ruíz & Carmona, 2005), but our results to date (Santisteban *et al.*, 2009; Marco-Barba *et al.*, 2013a), and those of recent publications (Carmona *et al.*, 2016), suggest that a brackish wetland was already present by 8700 cal. BP, whose enclosing sandbar was probably located to the east of the present-day coastline. This earlier origin is somehow in agreement with the ontogeny of other active coastal lagoons since c. 8000 BP in Southern France (Mateu *et al.*, 1985). Other coastal lagoons appeared since at least 7400 BP in the south of the Iberian Peninsula (Almería; Goy *et al.*, 2003), or since 7500-7600 cal. BP in the nearby sites of Elx (Blázquez & Usera, 2010) and Almenara, with a previous brackish marsh in Almenara during the earlier drier period (Blázquez *et al.*, 2017). Furthermore, the Mesolithic remains of *Cerastoderma glaucum* (not dated but considered older than 7000 BP) found in the adjacent hills to the west of the present Albufera de València (Mateu *et al.*, 1985) also support such early origin. It is difficult to say to what extent prehistoric societies might have modified the landscape, other than hunting and gathering for food. Palaeopalynological records from other Mediterranean coastal areas of the Iberian Peninsula suggest evidence for anthropic effects as early as the Boreal period (8000-9000 y BP), and presence of *Olea* and *Vitis*, added to inland deforestation during the following millennium (López-Sáez & López-García, 1999). Later, at c. 7500 cal. BP, the archaeological remains in the region indicate the beginning of the Neolithic agricultural and pastoral practices (Bernabeu *et*

al., 2014, Bernabeu-Aubán *et al.*, 2016). Recent, historical human impacts on the landscape and the limnology of the lagoon have been severe, but it might be possible that they started long ago. Here we try to unveil part of the long history of the lagoon and infer climatic and human effects on its long-term dynamics.

METHODS

Study area

The Albufera de València (Fig. 1) is one of the largest oligohaline lagoons of the Iberian Peninsula. It has an area of 2320 Ha with a mean depth

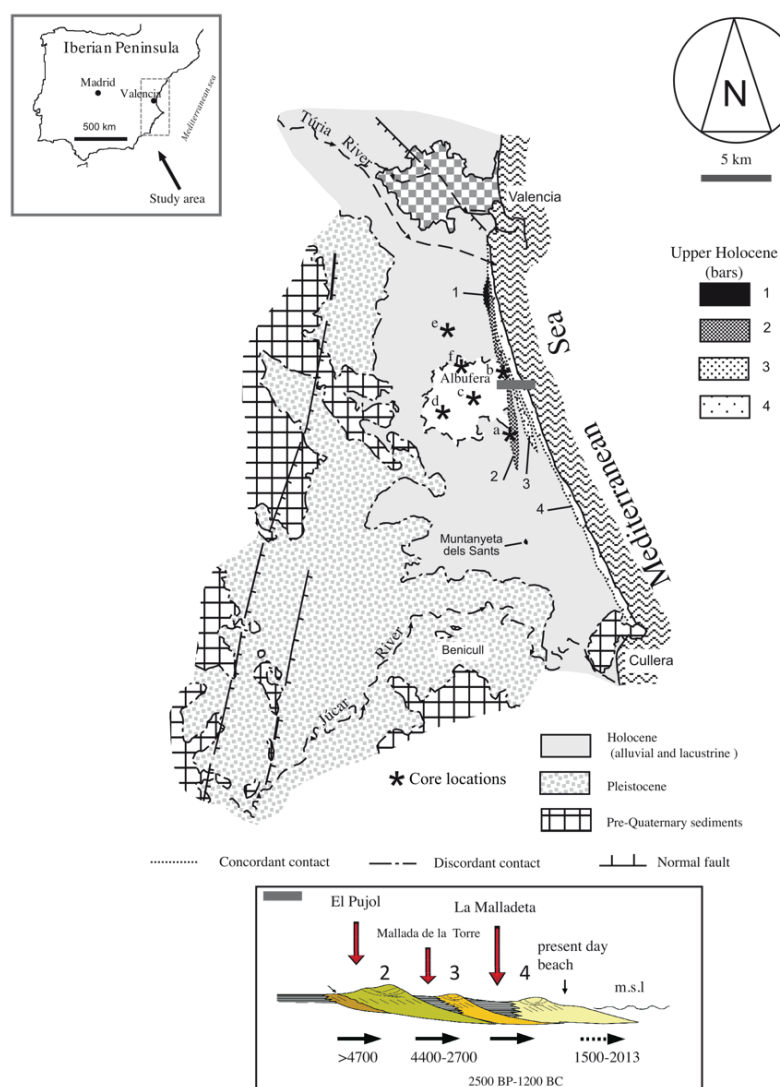


Figure 1. Geological and lithological composition of the studied area in Albufera de València, showing the location of the cores analysed or discussed in the text. A lithological transversal cut of the sand bar is also shown (after Santisteban *et al.*, 2009). Core locations: a, Core Palmar; b, Core Pujol; c, Core Centre; d, Core Antina; e, core in Carmona *et al.* (2016); f, core in Rodrigo *et al.* (2010). *Composición geológica y litológica del área de estudio en la Albufera de València, así como localización de los registros estudiados o discutidos en el texto. Se muestra también un corte transversal de la barra arenosa (a partir de Santisteban *et al.*, 2009). Localizaciones de los registros: a, Core Palmar; b, Core Pujol; c, Core Centre; d, Core Antina; e, registro en Carmona *et al.* (2016); f, registro en Rodrigo *et al.* (2010).*

of 1 m, separated from the sea by a sand bar (≈ 1 km wide). It is enclosed on the Quaternary floodplain lying between the alluvial fans of Túria (North) and Xúquer/Júcar (South) rivers. These rivers drain the southeastern sector of the Iberian Mountain System (mostly composed of Cretaceous and Jurassic limestones); the precipitation regime is characterized by a marked seasonal pattern, such that peak flash floods may reach 3000 m³/s. Although the fluvial hydrology is modified by various dams, the rivers retain the capacity to transport gravels, silt and clay sediment to the lower reaches. The Túria River sediment load contributed to the formation during the Holocene of the sand bar that protects the Albufera from the sea (Carmona & Ruiz, 1999). The sediments are transported by coastal drift currents towards the south and deposited by wave action during seasonal eastern storms. According to Santisteban *et al.* (2009), the sand bar is composed of four prograding units (Fig. 1). The oldest one (pre-4700 y BP) is moderately eroded. The second and the third have the configuration of spit beaches developed at the southernmost part of the Holocene Túria delta, and the last unit was formed in historical times.

Climatic and climate-driven events such as sea-level change, storm events and river floods have affected the Albufera's hydrology, ecology,

water chemistry composition and landscape throughout its history. With accelerated impacts likely to have been initiated by the development of irrigated rice paddies and commercial and population expansion during the Industrial Revolution (towards the mid 19th century), the Albufera de València is currently a hypereutrophic and highly polluted lagoon (Vicente & Miracle, 1992; Marco-Barba *et al.*, 2013a,b).

Core material and dating

Four sediment cores were extracted from the Albufera lagoon (Fig. 1). Two long sequences were collected in the sand bar: El Palmar, 18.5 m long, and Pujol, 16 m long. The extraction methods, lithology and ostracod palaeoecology and chronology for the El Palmar core are described by Santisteban *et al.* (2009) and Marco-Barba *et al.* (2013a), encompassing a period from 8700 to 3400 cal y BP. The same methods of extraction and ostracod analysis apply to core Pujol, and these and its lithological description, in relation to core El Palmar are also included in Santisteban *et al.* (2009). Unfortunately, no radiocarbon dates are available for core Pujol, but Santisteban *et al.* (2009) provide a stratigraphical correlation with core El Palmar. The remaining two, shorter, cores were extracted from the inundated central part of

Table 1. Radiocarbon dates obtained for Core Centre, and material and laboratory details. The last two columns indicate the estimated (est.) calendar years from sediment accumulation rates and other proxies (historic data, magnetic susceptibility and XRF analysis), and the corresponding reservoir effect (R(t)) calculated from the estimated dates. See text for further explanations. *Dataciones de radiocarbono obtenidas del core Centre, y detalles del material y del laboratorio de análisis. Las últimas dos columnas indican la edad en años calendario estimada (est.) a partir de las tasas de acumulación del sedimento y otros indicadores (datos históricos, susceptibilidad magnética y análisis XRF), así como el efecto reservorio (R(t)) correspondiente, calculado a partir de las fechas estimadas. Véase el texto para mayor explicación.*

Depth (cm)	¹⁴ C date (uncal. yr BP)	¹⁴ C date (cal. yr BP)	Material	Laboratory	Lab. Code	Est. date (cal. yr AD)	R(t) (yr)
89	1460 ± 30	995 ± 65	shell	Beta Analytic	313444	1772	817
94	1340 ± 30	875 ± 55	shell	Beta Analytic	313445	1744	669
135	2655 ± 30	2794 ± 55	pollen	Poznań Radioc. Lab.	Poz-19788	1450	2294
140	2400 ± 30	2030 ± 80	shell	Beta Analytic	313446	1400	1480
225	3090 ± 30	2850 ± 80	shell	Beta Analytic	313447	550	1450
229	3520 ± 35	3789 ± 100	pollen	Poznań Radioc. Lab.	Poz-18865	510	2349
233	22260 ± 140	22265 ± 285	pollen	Poznań Radioc. Lab.	Poz-18288	470	n.d.

the lagoon. The lithology, chronology, ostracod palaeoassemblages and geochemistry of the shortest (63 cm long encompassing the early 18th to the end of the 20th century) core Antina were presented by Marco-Barba *et al.* (2013b). Finally, a 240 cm core (Core Centre) was taken in July 2006 from a point in the middle of Albufera de València (UTM: 30S728065/4357504; Fig. 1). It was extracted using a Livingstone corer with 8 cm diameter inner liner and kept in a polyethylene tube. The core was analysed at 0.5 cm resolution for magnetic susceptibility (MS) with a GEOTEK core logger at the Limnological Research Center (LRC) of the University of Minnesota (USA), and was then subdivided in two halves. One half was used for imaging (DMT core scanner) colour, grain-size descriptions and ITRAX XRF core scanning; the other half was sampled for fossil content and geochemical analysis.

For Core Centre, seven radiocarbon dates (Table 1) were obtained from mollusc shells (*Cerastoderma glaucum*) and pollen concentrates selected from subsamples with high organic matter content. The radiocarbon measurement ('BP') was calibrated to calendar years ('cal.BP') using OxCal v3.10 software, with the Intcal04 curve for pollen and the Marine04 curve for shells (Hughen *et al.*, 2004; Reimer *et al.*, 2004; Bronk Ramsey, 2005) and later corrected for the reservoir effect in aquatic environments (see details in the results section). To determine age and sediment accumulation rates for the past 200 years a twin short (1 m) gravity core was extracted in the same location for ²¹⁰Pb-¹³⁷Cs dating. ²¹⁰Pb was measured at 4–6 cm depth intervals by means of its granddaughter product ²¹⁰Po (Eakins & Morrison, 1976). Activity was measured for 1–6 × 10⁵ s with ion-implanted surface barrier detectors and an Ortec alpha spectroscopy system. The ¹³⁷Cs values were confirmed by gamma spectrometry on an EG&G Nuclear ultra-low background well detector. All dating analyses were performed at Minnesota's St. Croix Watershed Research Station. Unsupported ²¹⁰Pb was calculated by subtracting supported activity from the total activity measured at each level; supported ²¹⁰Pb was estimated from the asymptotic activity at depth (the mean of the lowermost samples in the core). Dates and

sedimentation rates were determined according to the cf:cs. (constant flux: constant sedimentation model, Appleby and Oldfield, 1978) with confidence intervals calculated by first-order error analysis of counting uncertainty (Binford, 1990).

XRF and geochemical analysis

The main geochemical elements Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Rb, Sr, I, Zr, Ba and Pb were analysed every 5 mm from the bottom to 66 cm depth and every 2 mm from 66 cm to the top of Core Centre on the ITRAX XRF core scanner at the Large Lakes Observatory of the University of Minnesota (Duluth, USA) using 30 sec count time, 30 kV X-ray voltage and an X-ray current of 20 mA. The obtained values are given as counts per second, although high correlations have been found between ICP-OES and XRF-scanner data for some elements in different studies (Boyle, 2000; Moreno *et al.*, 2010). The XRF results for each element were transformed to arcsine of the square root of proportions; the data matrix was analysed by means of PCA (Principal Components Analysis).

The subdivision of Core Centre was carried out at approximately 2 cm intervals for the bottom metre and every 1 cm (high resolution) in the upper metre. In total, 72 samples were obtained for different analysis (geochemistry, mineralogy and micropalaeontological studies). Aliquot subsamples (between 0.3–0.7 g) were weighed, dried at 105 °C during 2 h and weighed again to determine water content and dry weight per gram of fresh sample. The remaining sediment was heated at 460 °C for 7.5 h to determine organic matter content (loss on ignition; LOI) and subsequently at 950 °C for 8 h to obtain the concentration of carbonates per sample, calculated from CO₂ loss (Heiri *et al.*, 2001). Subsamples were also taken to measure total nitrogen (TN) and phosphorus (TP) content. Samples were digested according to Valderrama (1981) modified for sediments. All samples were also submitted to a conventional digestion procedure with sulphuric acid and potassium persulphate for phosphorus analysis (APHA, 1992; Ferree & Shannon, 2001).

Diatom analysis

To assess limnological variation in the littoral and profundal zone, and for comparison with vegetation history, the El Palmar (long edge core) and lagoon centre (Antina) sequences were selected for analysis. Diatoms were prepared using standard techniques (Battarbee *et al.*, 2001), mounting slides with Naphrax®. Where diatoms were preserved, El Palmar samples were counted initially at ca. 10–12 cm resolution and at higher resolution (min. 3 cm) in zones of good preservation, comprising 65 samples. A full count (> 500 valves) was possible in 12 subsamples and diatom species presence was noted for a further 8 samples in which diatoms were rare. A full count was possible in 13 samples prepared at approximately 4 cm resolution (range 2 – 8 cm) in the upper 53 cm of the Antina sequence, with rare preservation below. Diatoms were identified using Krammer & Lange-Bertalot (1986, 1988, 1991a and 1991b), adopting updated diatom nomenclature. Counts were converted to percentage data and displayed using Tilia (Grimm, 1991–2015). Zone boundaries were defined using constrained incremental sum of squares analysis (CONISS; Grimm, 1987). Diatom-conductivity reconstruction was carried out based on the European Diatom Database Combined Salinity training set (Battarbee *et al.*, 2000), using weighted averaging with inverse deshrinking in the programme C2 (Juggins, 2007), and data from this and the Spanish diatom-conductivity training set (Reed, 1998) were used to aid interpretation. The abundance of fragilarioid taxa (facultative planktonic group), which have very broad ecological tolerance ranges, is problematic for quantitative reconstruction, so these taxa were omitted in application of the transfer function to El Palmar.

Foraminifera analysis

Foraminifera remains were analysed from a total of 62 samples from El Palmar core, 64 samples from Pujol, 12 samples from the Antina sequence and 49 samples from Core Centre. Sediment samples were air dried and then submersed in warm water to separate the organic matter from

foraminifera. No other chemical products were used, to avoid damaging agglutinated foraminiferal shells, which are common in lagoonal environments. Samples were then sieved under a smooth water flow using a 62 µm mesh. The remains were dried prior to analysis under the stereomicroscope. A minimum number of 300 individuals per sample were picked for species determination and counting. The data were analysed for diversity changes over time using the effective number of species approach (Jost, 2006), by means of diversity of order 0 (S = species richness) and order 1 (e^H = exponential of Shannon diversity using natural logarithms).

Ostracod analysis

Subsamples from core Centre were processed for ostracod analysis using a modified version of Griffiths & Holmes (2000), and explained in detail in Marco-Barba *et al.* (2013a,b) for cores El Palmar and Antina. Similarly, for Core Centre, between 10 and 15 g of wet sediment were weighed, air dried and then wet-sieved for 30 minutes through 400 and 250 µm pore size meshes. Species were identified following mostly Athersuch *et al.* (1989), Meisch (2000) and Poquet *et al.* (2008). We noted the states of preservation (SP) of shells as described in Marco-Barba *et al.* (2013a). Only valves belonging to good preservation states (A and B) were included in multivariate analysis (see below).

Between 1 and 137 *Cyprideis torosa* adults per sample (adult females and males) were measured for carapace length, as this is known to potentially vary with salinity (Mezquita *et al.*, 2000). The percentage of noded animals per sample (van Harten, 1975; Marco-Barba, 2013a) was also calculated to assess salinity variation (Vesper, 1972a,b; van Harten, 1975; Marco, 2010; Frenzel *et al.*, 2012; Marco-Barba *et al.*, 2013a).

Between four and 20 *C. torosa* valves were analysed per sample of Core Centre for shell oxygen and carbon isotopic variation. Analyses were performed on single adult valves by preference; in the absence of these, juveniles of late growth instars (A-1 and A-2) were pooled in groups of 4 or 5 valves. Adults and juveniles, and males and females, were analysed separately.

Between two and 10 analyses were carried out per sample to determine the valve calcite isotopic ratios $^{18}\text{O}/^{16}\text{O}$ and $^{13}\text{C}/^{12}\text{C}$. Ostracod valves were cleaned for geochemical analysis using the method described in Ito (2001). Cleaned valves were analysed mostly using a Kiel-II online carbonate preparation device coupled to a Finnigan MAT 252 stable isotope ratio mass spectrometer (University of Minnesota) and a few samples (60 samples $\approx$ 159 valves) using a MAT 251 (Michigan) mass spectrometer, both connected to a Kiel carbonate preparation device. Analytical precision was typically $< 0.1\text{‰}$ for both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$. Samples were run from the same levels in the two different labs to ensure that the different analytical protocols did not affect the results.

The number of valves per 10 g of dry sample ($N = 70$ samples) was log transformed ($\log_{10}(\text{number of valves} + 1)$) for ostracod stratigraphical analysis. A constrained cluster analysis was performed applying the CONISS method and the Edwards & Cavalli-Sforza distance (Grimm, 1987). The whole transformed data matrix was ordered with PCA.

Correlations between *C. torosa* shell lengths and isotope ratios ($\delta^{18}\text{O}_{\text{vpdb}}$ and $\delta^{13}\text{C}_{\text{vpdb}}$) were performed using either Pearson (when data was normally distributed) or Spearman (for not normally distributed data) correlation techniques. Palaeosalinity reconstruction of lagoon Albufera from Core Centre was carried out using ostracod-based weighed averaging transfer functions based on the species' optima and tolerances as detailed in Marco-Barba *et al.* (2013b).

Palynological analysis

To provide a long record of vegetation history, with high resolution analysis of recent change, pollen analysis was carried out in two selected sequences – the long core, El Palmar, and the short central core, Antina. Subsamples were selected to span the range of lithological zones in El Palmar (62 samples) and at 1 cm resolution (53 samples) in Antina. The preparation of pollen, non-pollen palynomorphs (NPPs) and palynological microcharcoal samples followed standard methods outlined in Goeury & Beaulieu (1979) but adapted by Burjachs *et al.* (2003). The

sediments were reduced by HCl, humic acids washed in NaOH, floated in dense Thoulet liquor, and filtered with a glass fibre filter which was subsequently destroyed with 70 % HF. All steps were followed by washing and centrifuging with distilled water. The final residue of each sample was mounted in preparation for biological microscopy diluted with glycerin. *Circa* 150–500 pollen grains of terrestrial taxa were counted using an Olympus CX41 microscope fitted with x15 oculars and x40/60 objectives. For El Palmar, results are presented for 33 samples in which a representative count was possible; pollen preservation was poor in the remaining 29 samples.

Cyperaceae, *Typha/Sparganium*, *Polygonum* t. *persicaria*, *Ruppia*, *Potamogeton*, *Myriophyllum* and *Lemna*-type have been excluded from the pollen sum to avoid overrepresentation by local littoral taxa. All pollen types are defined according to Moore *et al.* (1991), Reille (1992, 1995, 1998), Beug (2015) and Cerealia-type was defined according to the morphometric criteria of Andersen (1978), Faegri & Iversen (1989) and Tweddle *et al.* (2005). Non-pollen palynomorph (NPP) identification followed van Geel (1978, 2001), van Hove & Hendrikse (1988) and Revelles *et al.* (2016). To calculate the percentages of NPPs an independent basic sum of the pollens has been made. Pollen concentration (PC) is expressed in pollen grains/g of dry sediment following the volumetric method (Loublier, 1978). Pollen and NPPs were compiled and plotted using Tilia (Grimm, 1991–2015). Pollen and NPPs zones were established using the stratigraphically constrained square root transformation (CONISS) (Grimm, 1987).

RESULTS

Cores El Palmar and Pujol

The long, littoral sedimentary sequences of Palmar and Pujol were described by Santisteban *et al.* (2009). Further information on the chronology, ostracod palaeoecology, geochemistry and palaeoenvironmental interpretation of El Palmar was provided by Marco-Barba *et al.* (2013a). Usera *et al.* (1990; 1995; 2006; 2007a,b) and Usera & Alberola (2011) also provide brief notes

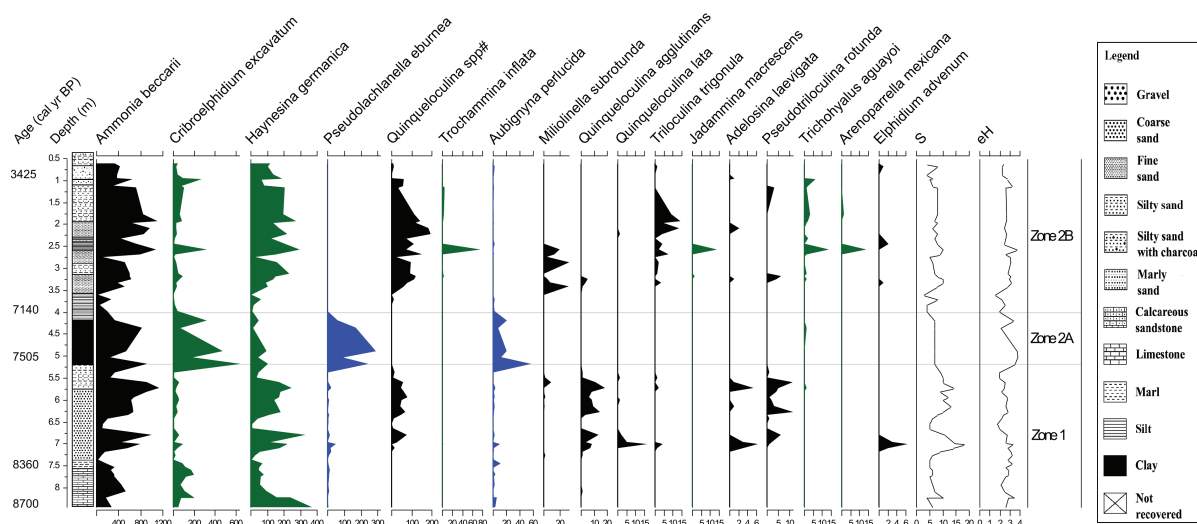


Figure 2. Summary stratigraphic diagram of foraminifera abundances in Lake Albufera core Palmar showing taxa present at minimum > 5 individuals. Green: species tolerant of relatively low salinity in brackish waters (other than *Ammonia* spp.); blue: those considered less tolerant to low salinity. The diversity of order 0 (S = species richness) and order 1 (e^H , where H = Shannon diversity), and zone boundaries defined by constrained cluster analysis are shown on the right. *Gráfico estratigráfico resumen de los foraminíferos del core Palmar de la laguna de la Albufera, mostrando las especies con un mínimo de individuos > 5. Verde: especies tolerantes a salinidades relativamente bajas en aguas salobres (aparte de *Ammonia* spp.); azul: aquellas poco tolerantes a bajas salinidades. A la derecha se muestran la diversidad de orden 0 (S = riqueza de especies) y orden 1 (e^H , donde H = diversidad de Shannon), así como las zonas definidas mediante análisis constreñido de clasificación.*

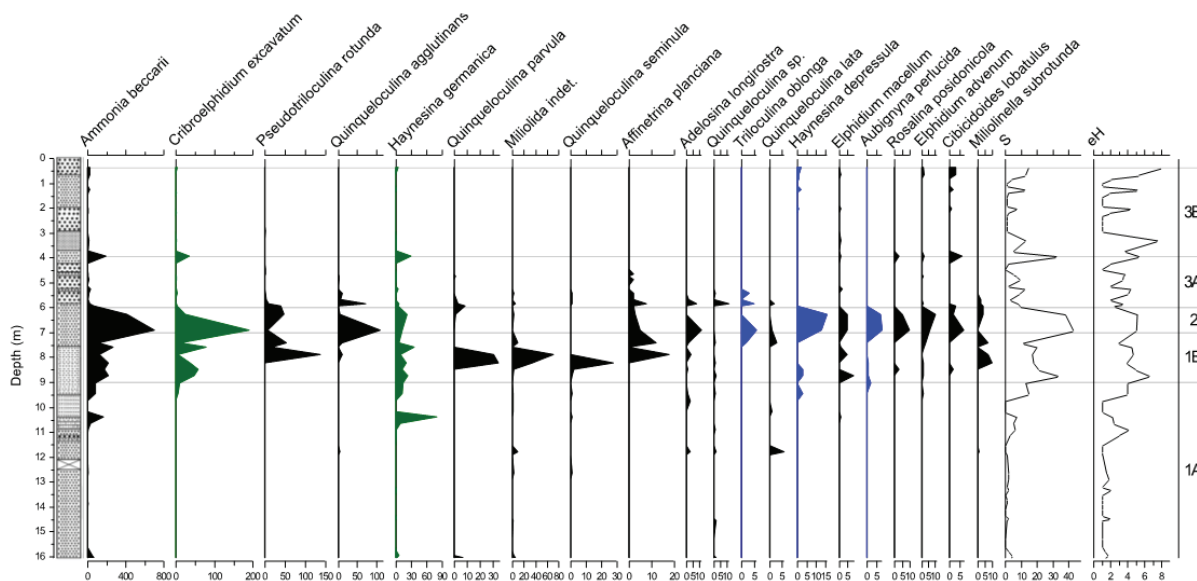


Figure 3. Summary stratigraphic diagram of foraminifera abundances in Lake Albufera core Pujol showing taxa present at minimum > 5 individuals. Green: species tolerant of relatively low salinity in brackish waters (other than *Ammonia* spp.); blue: those considered less tolerant to low salinity. The diversity of order 0 (S = species richness) and order 1 (e^H , where H = Shannon diversity), and zone boundaries defined by constrained cluster analysis are shown on the right. Sediment legend as in figure 2. *Gráfico estratigráfico resumen de los foraminíferos del core Pujol de la laguna de la Albufera, mostrando las especies con un mínimo de individuos > 5. Verde: especies tolerantes a salinidades relativamente bajas en aguas salobres (aparte de *Ammonia* spp.); azul: aquellas poco tolerantes a bajas salinidades. A la derecha se muestran la diversidad de orden 0 (S = riqueza de especies) y orden 1 (e^H , donde H = diversidad de Shannon), así como las zonas definidas mediante análisis constreñido de clasificación. Leyenda de la columna sedimentaria como en la figura 2.*

on the foraminifera of these cores and other parts of the lagoon. Here we incorporate new and extended palaeoecological data from foraminifera, diatom and pollen analysis.

Foraminifera

A total of 46 927 foraminifera were identified from core El Palmar, belonging to 47 species. The most abundant species through the sequence were *Ammonia beccarii* (Linné, 1758), *Criboelphidium excavatum* (Terquem, 1875) and *Haynesina germanica* (Ehrenberg, 1840) (Fig. 2). Three (sub-)zones could be distinguished based on constrained cluster analysis. Zone 1 (850–520 cm) was rich in species but dominated by the three aforementioned taxa, resulting in relatively low e^H diversity values. The base of zone 2 (subzone 2A, 520–400 cm) shows a marked change in species dominance, with reduced species richness (S) but important peaks of *C. excavatum*, *Pseudolachlanella eburnea* (d'Orbigny, 1839) and *Aubignyna perlucida* (Heron-Allen & Earland, 1913), promoting increased evenness and consequently high ecological diversity of order one (e^H). The upper subzone (subzone 2B, 400–50 cm) shows again relatively high and constant S and e^H values.

In Pujol, the identification of 5744 foraminifera individuals yielded a higher number of species, with a total of 93 different taxa. Again, *A. beccarii* was the dominant species, together with *C. excavatum*, *H. germanica* and *Pseudotriloculina rotunda* (d'Orbigny in Schlumberger, 1893) (Fig. 3). Furthermore, *Quinqueloculina agglutinans* (d'Orbigny, 1839) is also occasionally abundant. The basal 7 m (subzone 1A, 1600–900 cm) of the sequence show the lowest diversity, with an increase to higher values in the next subzone (1B; 900–700 cm depth), corresponding to mud and clay lacustrine deposits during a regressive period (Santisteban *et al.*, 2009). Foraminiferal diversity reaches maximum peaks in the following Zone 2 (700–600 cm depth), during a sandy beach phase in a transgressive period (Santisteban *et al.*, 2009). The upper zone (Zone 3; 600–50 cm) is variable in species composition, but shows a return to lower diversity and number of individuals collected, similar to subzone 1A.

Diatoms

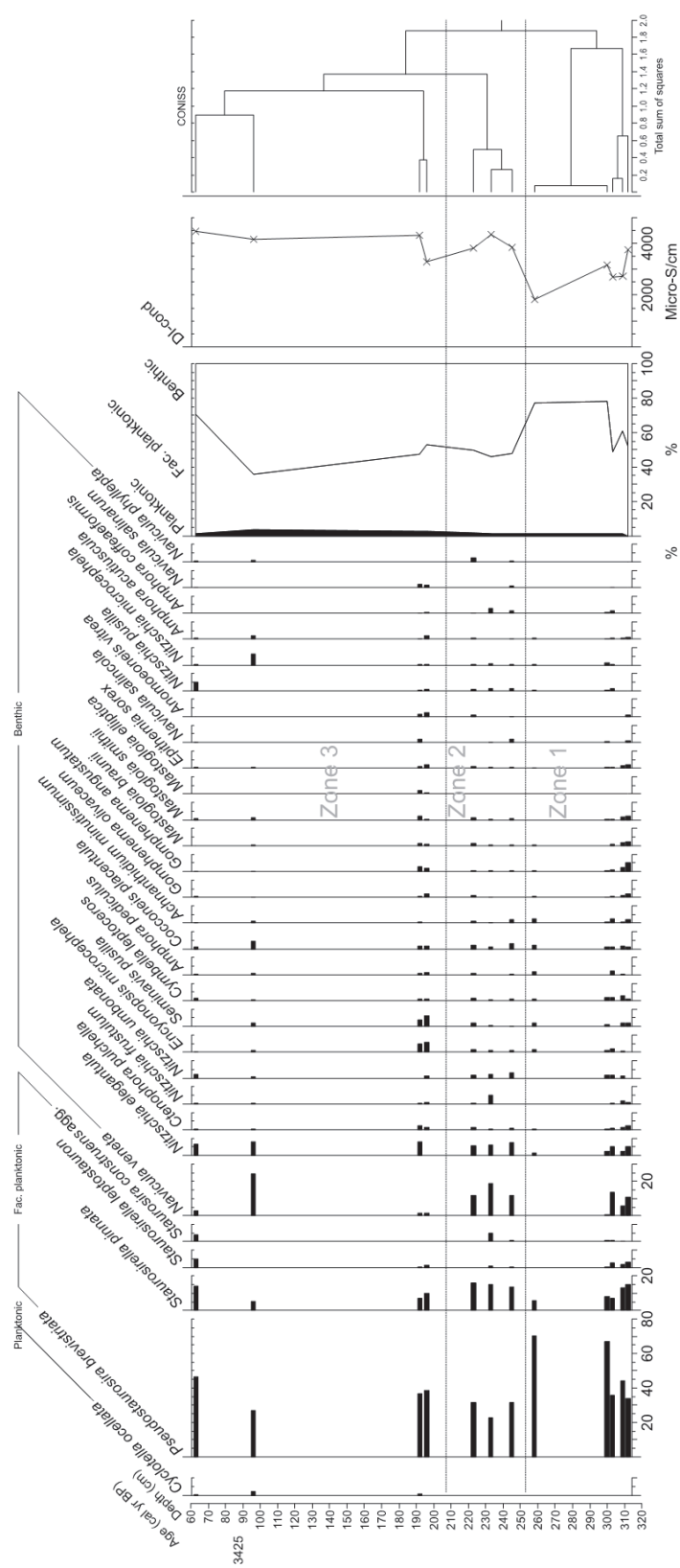
Diatoms from El Palmar (Fig. 4) are only preserved from 312 cm to 63 cm depth, from the mid Holocene onwards. Samples where diatoms were present but too sparse for a full count (99, 112, 178, 209, 269, 274, 288, 319, 326 and 341 cm depth) all contain robust taxa which are resistant to dissolution, but of a similar character to zones of better preservation. Three diatom zones can be recognised, but the sequence essentially shows little evidence for major limnological change. The sequence is dominated by benthic and facultative planktonic (FP) taxa throughout. Planktonic taxa are rare. The taxa are all common in the modern environment of Spanish saline lakes (Reed *et al.*, 2001) and are mainly those which tolerate slightly brackish (oligosaline) to mesosaline waters. This is reflected in the complacency of the diatom-inferred conductivity (DI-Cond) curve, which fluctuates around the oligo-mesosaline boundary of 3000 $\mu\text{S}/\text{cm}$.

Zone 1 (341.5–251.5 cm) is dominated by FP taxa, and *Pseudostaurosira brevistriata* in particular. A range of benthic taxa, including obligate saline species such as *Mastogloia braunii* and *Amphora coffeaeformis*, are present at up to 50 % abundance. Planktonic taxa are present at < 2 %. The presence at low abundance of *Achnanthes minutissimum*, a freshwater species common in streams, may indicate the influence of freshwater inflow to the lagoon. The uppermost sample exhibits minimum DI-Cond, a sample which is dominated to 80 % by FP taxa.

Zone 2 (251.5–209.5 cm) is marked by a reduction in the relative abundance of *P. brevistriata*, accompanied by slight increases in benthic taxa including *Navicula veneta*. Some obligate saline taxa in the *Mastogloia* genus decrease in abundance but the continued occurrence of others (*A. coffeaeformis*, *Nitzschia elegantula*, etc.) suggests no marked shift in limnology.

Zone 3 (209.5–63 cm) is a zone of particularly poor diatom preservation. The zone boundary is again marked by subtle shifts in diatom species assemblage composition, such as a slight increase in obligate, saline *Seminavis pusilla*. The first presence of plankton at > 2 % abundance at 96 cm depth is that of a *Cyclotella ocel-*

Figure 4. Summary stratigraphic diagram of diatom abundances in Lake Albufera core Palmar. The conductivity reconstruction (DI-cond) and dendrogram derived from constrained cluster analysis are shown on the right. *Diagrama estratigráfico de abundancias de diatomeas del core Palmar de la laguna de la Albufera. A la derecha se muestra la reconstrucción de la conductividad (DI-cond) y el dendrograma resultante de un análisis de clasificación.*



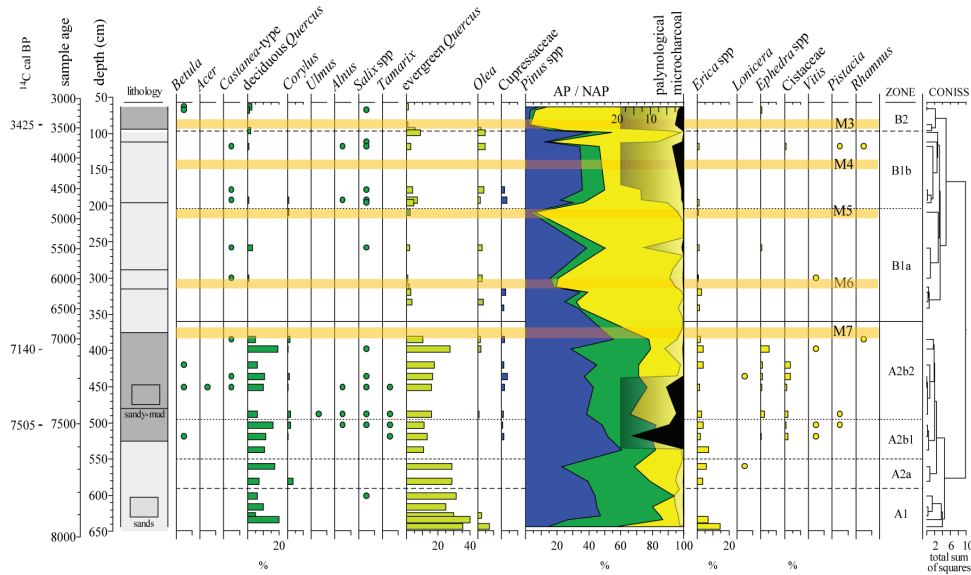


Figure 5. Stratigraphic diagram of pollen percentages (trees and shrubs) and palynological microcharcoal in Lake Albufera core Palmar. The black microcharcoal palynological curve corresponds to the real values (x10000), while its degraded plot corresponds to an exaggeration x20. The zones defined by constrained cluster analysis are shown on the right. The dots mean less than 1 %. The orange bands mark the Minorca events (Frigola *et al.*, 2007). *Diagrama estratigráfico de porcentajes polínicos (árboles y arbustos) y microcarbones palinológicos del core Palmar del lago de la Albufera. La curva negra de los microcarbones palinológicos corresponde a los valores reales (x10000), mientras que el gráfico sombreado corresponde a una exageración x20. A la derecha se muestran las zonas establecidas por el análisis de clasificación constreñido. Los puntos indican valores < 1 %. Las bandas anaranjadas corresponden a los eventos de Menorca (Frigola *et al.*, 2007).*

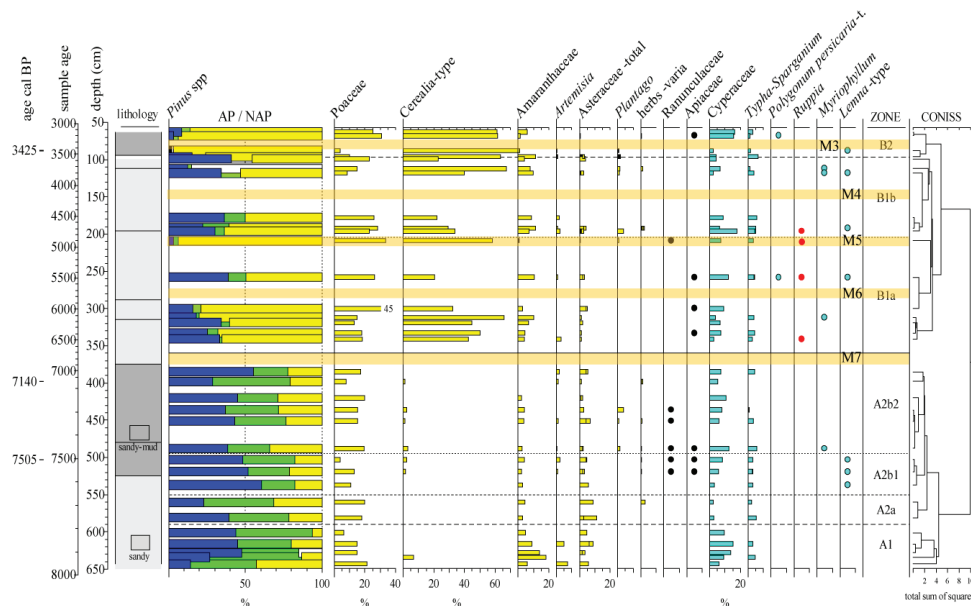


Figure 6. Stratigraphic diagram of pollen percentages of herbs in Lake Albufera core Palmar. The zones defined by constrained cluster analysis are shown on the right. The dots mean less than 1 %. The orange bands mark the Minorca events (Frigola *et al.*, 2007). *Diagrama estratigráfico de los porcentajes de polen de hierbas en el core Palmar de la laguna de la Albufera. A la derecha se muestran las zonas definidas por un análisis de clasificación constreñido. Los puntos indican valores < 1 %. Las bandas anaranjadas corresponden a los eventos de Menorca (Frigola *et al.*, 2007).*

lata, a freshwater taxon of broad tolerances which can withstand low salinity.

Pollen and NPP

In general, the lower half of the sequence is richer in species and total pollen abundance, allowing greater resolution, whereas the top 350 cm show lower abundance and even barren samples (Figs. 5-8).

The vegetation of Zone A (643-380 cm, Fig. 5) is dominated by *Pinus* spp. and *Quercus* spp., representing an open forest with scrubs, which include mainly *Erica* spp., Cistaceae, *Pistacia* sp., with some presence of *Ephedra* sp. suggesting sand dune habitats (Fig. 5). There is a smooth declining trend of the arboreal pollen towards the top of the sequence, but arboreal pollen abundance is almost always above 70-80 %. Riparian vegetation is scarcely represented, with presence of *Corylus* sp., *Alnus* sp., *Ulmus* sp., *Salix* spp. and *Tamarix* spp. Probably originating from the surrounding mountain areas, some pollen from *Betula* sp., *Acer* sp., *Castanea*-type and deciduous *Quercus* sp. is observed also in this zone. At the bottom of the zone (643-600 cm, zone A1), the high relative abundance of Amaranthaceae (Fig. 6) indicates saline influence in the wetland area; Cyperaceae also occurs, with an approximately negative covariation with Amaranthaceae, suggesting a heterogeneous and variable wetland with variation in soil salinity. From this period on, the Amaranthaceae decline, but are present throughout this zone, while Cyperaceae remains more stable.

Unlike pollen remains, non-pollen palynomorphs (NPPs) are present from the bottom of the sequence (c. 8600 cal. BP at 850 cm) (Figs. 7, 8). The base of the sequence (850-760 cm, subzone A1a) is poor in NPPs, but at the top of this subzone (A1b) the percentages of megaspores (Fig. 7) are remarkably high. The rest of zone A (700-350 cm) is more diverse (Figs. 7, 8), including mainly algae (*Gloeotrichia*), fungal (hyphae) and undetermined microzoological remains (type 52).

The upper Zone B (340-63 cm) shows a large shift of vegetation towards a major reduction in arboreal cover, to less than 50 %. Wild grasses (Poaceae) increase up to c. 40 %, and Cerealia-type show an exceptional expansion to

above 50 %. We think that this pollen comes from dune grasses, since we know that some of these species have a size of grain as large as the cultivated cereals (e.g. Joly *et al.*, 2007; Farooq *et al.*, 2015). Besides the major change at c. 340 cm, other notable events of a sharp reduction in arboreal pollen occur at 310, 210 and 90 cm depth.

Regarding NPPs, Zone B exhibits higher diversity and abundance of fungi and algal remains than Zone A, with a clear increase of *Botryococcus* spp. (Fig. 7). Polyporisorites also increase in abundance (Fig. 8) but megaspores disappear from this zone. The presence of eggs of parasitic worms (Nematoda) is notable throughout this zone. Charcoal peaks tend to correspond to maximum values of AP, when there is more forest mass available to burn (Burjachs & Expósito, 2015).

Core Antina

Marco-Barba *et al.* (2013b) previously described the chronology, sedimentology and ostracod palaeoassemblages and geochemistry of this sequence, generating the first palaeoenvironmental interpretation of the sequence. Here we add new data on pollen, foraminifera and diatom palaeoassemblages to improve the reconstruction of the recent history of the lake and its surrounding landscape.

Foraminifera

Only ten species of foraminifera (Fig. 9) were found in this short core (8373 individuals counted), and they were present only at the bottom part (70-50 cm). The species *Ammonia tepida* (Cushman, 1926), *C. excavatum* and *H. germanica* dominated, and were the only species present at the top samples (Zone 2) that contained foraminifera. There is a remarkable peak in abundance of *Trichohyalus aguayoi* (Bermúdez, 1935) at 55 cm, just when most species have disappeared or show low mean abundances.

Diatoms

Diatoms (Fig. 10) are well preserved throughout, apart from at the start of the sequence, below 60 cm. The sample at 60 cm only contained

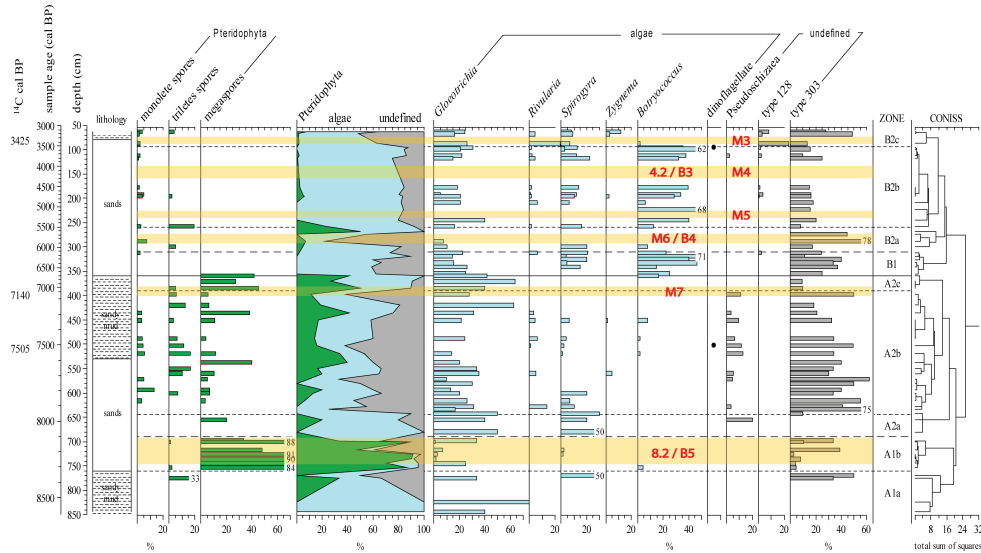


Figure 7. Stratigraphic diagram of Pteridophyta spores, algae and undefined NPPs percentages in Lake Albufera core Palmar. The zones defined by constrained cluster analysis are shown on the right. The dots mean less than 1 %. The orange bands mark the Minorca (Frigola *et al.*, 2007) and Bond events (Bond *et al.*, 1997). *Diagrama estratigráfico de los porcentajes de esporas de Pteridophyta, de algas y de NPPs no definidos en el core Palmar de la laguna de la Albufera. A la derecha se muestran las zonas definidas por un análisis de clasificación constreñido. Los puntos indican valores < 1 %. Las bandas anaranjadas corresponden a los eventos de Menorca (Frigola *et al.*, 2007) y eventos Bond (Bond *et al.*, 1997).*

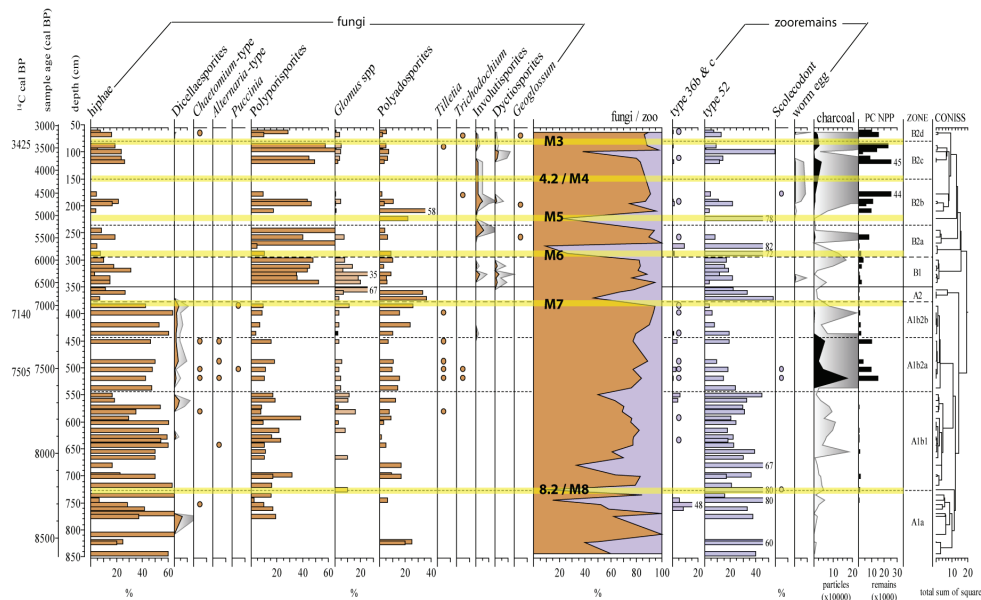


Figure 8. Stratigraphic diagram of fungi, zooremain NPPs percentages, absolute frequencies of palynological charcoal and total concentration of NPPs in Lake Albufera core Palmar. The zones defined by constrained cluster analysis are shown on the right. The dots mean less than 1 %. The yellow bands mark the Minorca (Frigola *et al.*, 2007) and Bond events (Bond *et al.*, 1997). The curves exaggeration factor is variable, in order to better visualize its evolution. *Diagrama estratigráfico de los porcentajes de hongos, restos de NPPs zoológicos, frecuencias absolutas de carbones palinológicos y concentración total de NPPs en el core Palmar de la laguna de la Albufera. A la derecha se muestran las zonas definidas por un análisis de clasificación constreñido. Los puntos indican valores < 1 %. Las bandas amarillas corresponden a los eventos de Menorca (Frigola *et al.*, 2007) y eventos Bond (Bond *et al.*, 1997). El factor de exageración de las curvas es variable, para poder visualizar mejor su evolución.*

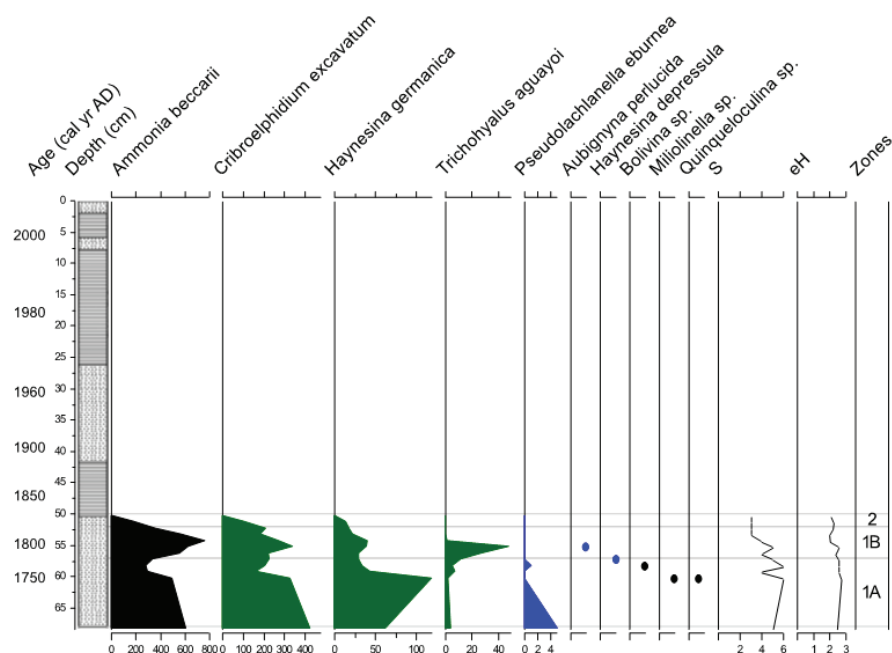


Figure 9. Summary stratigraphic diagram of foraminifera abundances in Lake Albufera core Antina showing taxa present at minimum > 5 individuals. Green: species tolerant of relatively low salinity in brackish waters (other than *Ammonia* spp.); blue: those considered less tolerant to low salinity. The diversity of order 0 (S = species richness) and order 1 (e^H , where H = Shannon diversity), and zone boundaries defined by constrained cluster analysis are shown on the right. Sediment legend as in figure 2. *Gráfico estratigráfico resumen de los foraminíferos del core Antina de la laguna de la Albufera, mostrando las especies con un mínimo de individuos > 5. Verde: especies tolerantes a salinidades relativamente bajas en aguas salobres (aparte de *Ammonia* spp.); azul: aquellas poco tolerantes a bajas salinidades. A la derecha se muestran la diversidad de orden 0 (S = riqueza de especies) y orden 1 (e^H , donde H = diversidad de Shannon), así como las zonas definidas mediante análisis restringido de clasificación. Leyenda de la columna sedimentaria como en la figura 2.*

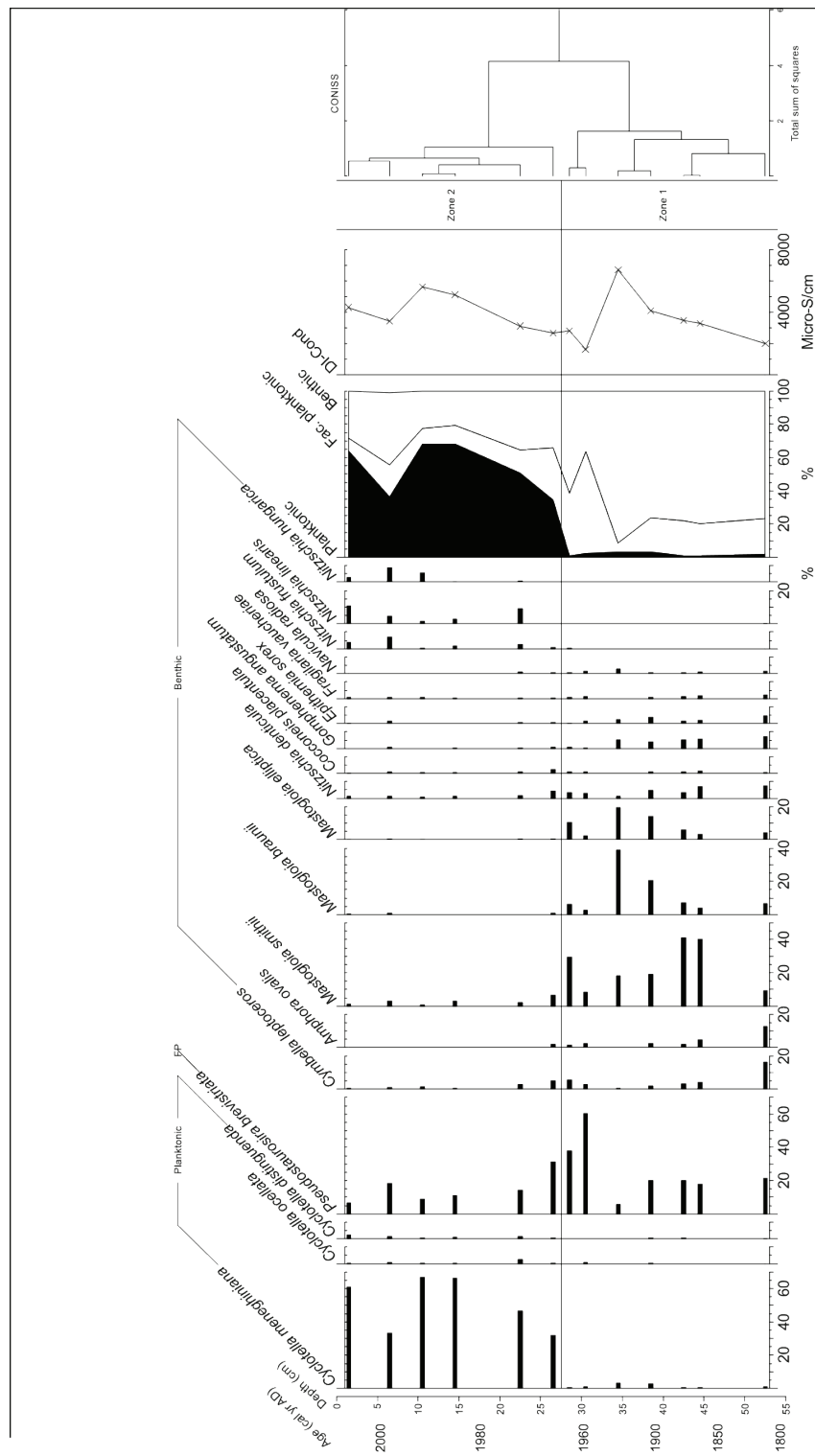
fragments of two species, *Campylodiscus clypeus* and *Diploneis bombus*, both of which indicate high conductivity. Above, the sample at 56 cm is more diverse, preserving some species not present in other dissolved samples: *Epithemia argus* and *Amphora libyca* (in addition to *D. bombus* and *M. braunii*), but again indicates high salinity (Ben Khelifa, 1989; Reed, 1998).

Zone 1 (52.5 – 27.5 cm) is dominated by *P. brevistriata* and a similar range of brackish taxa were present at lower abundance in the lake edge sequence. The dominant benthic taxa, *Mastogloia smithii* (fresh-brackish) *M. braunii* (obligate saline) and *M. elliptica* (obligate saline) are typical both of Spanish salt lakes and chloride-dominated estuarine/lagoonal waters. Plankton are represented at < 5 % abundance by *Cyclotella meneghiniana*, a species common in shallow waters (1-2m depth) of Spanish salt lakes (Reed, 1998). DI-cond tends to

fall in the mesosaline range of > 3000 $\mu\text{S}/\text{cm}$. A trend towards increased relative abundance of *M. braunii* and *M. elliptica* at the expense of the less salt-tolerant *M. smithii* is matched by peak DI-Cond of c. 7000 $\mu\text{S}/\text{cm}$ at 34.5 cm depth; FP taxa increase towards the upper zone boundary, with an associated reduction in DI-Cond to its minimum for the sequence, in the oligosaline range.

The transition to Zone 2 (27.5 – 0.5 cm) is marked by a sharp increase and subsequent dominance of planktonic *C. meneghiniana* at the expense of FP and the range of benthics present in Zone 1. A range of *Nitzschia* taxa (*N. frustulum*, *N. linearis* and *N. hungarica*) appear for the first time. *C. meneghiniana* is again a taxon of very broad tolerance. It is a common diatom of saline waters, but also of hypereutrophic or generally polluted fresh water (Mills & Ryves, 2012). Its high conductivity optimum drives the mainte-

Figure 10. Summary stratigraphic diagram of diatom percentages in Lake Albufera core Antina. The conductivity reconstruction (DI-cond) and dendrogram derived from constrained cluster analysis are shown on the right. *Diagrama estratigráfico de porcentajes de diatomeas del core Antina de la laguna de la Albufera. A la derecha se muestra la reconstrucción de la conductividad (DI-cond) y el dendrograma resultante de un análisis de clasificación.*



nance of DI-Cond at c. 4000 $\mu\text{S}/\text{cm}$, but this may be overestimated. The increase in *Nitzschia* taxa at the expense of *Mastogloia* points to a marked reduction in salinity.

Pollen

Subzone A1a: 61-55 cm

The percentage of arboreal pollen (AP) is relatively high (c. 40-80 %) at the base of the sequence, dominated by *Pinus* (pines), *Quercus* evergreen and *Q. deciduous* (Holm oak, oaks), *Olea-Phillyrea* (olive tree, wild olive, green olive tree) and Cupressaceae (Fig. 11). The shrub component is most represented by heathers (*Erica*). The relatively high abundance of Amaranthaceae and Artemisia, the scarcity of freshwater algae and low values of hygro-hydrophytes (Cyperaceae, *Lemna*-type, *Typha-Sparganium*, *Myriophyllum*), all point to the influence of salinity (Fig. 12).

Subzone A1b: 55-46 cm

Here, there is a general reduction in AP despite increasing tree diversity. While the bushes remain stable, wild grasses (Poaceae) and Cerealia-type pollen (up to 5.5 %) increase. The highest abundances of Faboideae and Asteraceae are noted in this subzone and the aquatic plant *Myriophyllum* onset its presence, although at low abundance. A small peak in Pseudoschizaea abundance, which is considered an NPP associated to erosion (Pantaleón-Cano *et al.*, 1996), is also noticeable (Fig. 13). This may indicate enhanced sediment input, maybe favoured by forest fires, as also suggested by a peak in microcharcoal at that time (Fig. 13).

Subzone A2: 46-38 cm

Forest vegetation (AP) recovers up to levels similar to those of subzone A1 (43-60 %). Pollen salinity indicators (Amaranthaceae) decrease even more now, and pollen from riparian trees (*Corylus*, *Alnus*), which have appeared in the previous subzone, now increase, as well as the relative abundance of algal remains and the aquatic plant *Myriophyllum*, suggesting fresher conditions of the water body. A peak of *Juglans* (walnut tree)

and the presence of *Morus* (used to feed silk moth caterpillars) indicate changes in land use with more importance of the trees cultivation.

Subzone B1: 38-30 cm

This subzone marks the onset of a new vegetation regime (Figs. 11 and 12). Initially, the climactic vegetation (oaks) retreats in favour of conifers (pines and Cupressaceae). By the end of this subzone, arboreal vegetation in general declines (particularly for *Olea* sp. and *Quercus* sp.), with a concomitant increase in grasses (Poaceae, up to 30 %, Fig. 12). The marked decrease in the aquatic plant *Myriophyllum*, and increase in fungi (type Polyadosporites, zone A2 in Fig. 13) suggest higher turbidity, possibly associated with eutrophication. This process may be also related to the rise in *Cosmarium* algal remains (zone A2 in Fig. 13). Most probably, the littoral areas of the lake suffered temporary variations in inundation through time, favouring the increase in Cyperaceae and grasses (Fig. 12).

Subzone B2a: 30-17 cm

Pine forests increase at this zone, although there is a reduction at the top of the subzone, related to fires, as indicated by microcharcoal increase (zone B1 in Fig. 13). Riparian areas seem now dominated mostly by bulrush (cf. *Typha*) rather than by common reed (cf. *Phragmites* included in Poaceae). The transition between the previous zone and this one is indicated by the input of detritic sediments (*Glomus* and, later, the type Pseudoschizaea), at the same time that there is an increase in microalgae *Spirogyra*, *Botryococcus* and *Pediastrum*, as a response to a relative reduction of *Cosmarium*. There is evidence throughout for cultivation (Cerealia), with the presence of mulberry trees (*Morus* sp.) At about 25 cm deep, the first presence of Myrtaceae occurs, probably indicating an increase in *Eucalyptus* plantations or extension of *Myrtus* (common myrtle).

Subzone B2b: 17-6 cm

This subzone is very similar to the previous one, but with evidence for a slight recovery of the

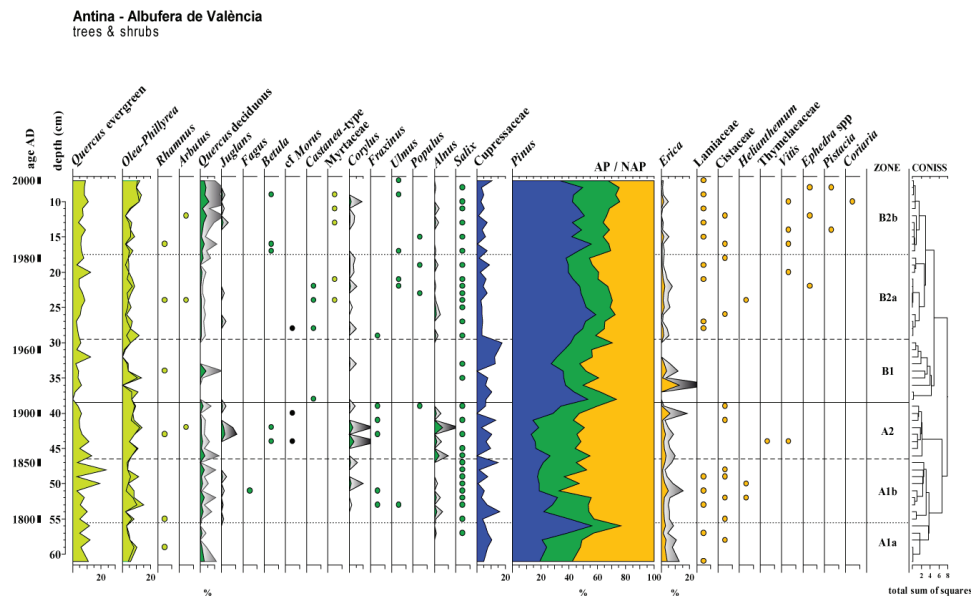


Figure 11. Stratigraphic diagram of pollen percentages in Lake Albufera core Antina. The zones defined by constrained cluster analysis are shown on the right. The dots mean less than 1 %. The curve exaggeration factors are variable, in order to better visualize their evolution. *Diagrama estratigráfico de los porcentajes de polen en el core Antina de la laguna de la Albufera. A la derecha se muestran las zonas definidas por un análisis de clasificación constreñido. Los puntos indican valores < 1 %. El factor de exageración de las curvas es variable, para poder visualizar mejor su evolución.*

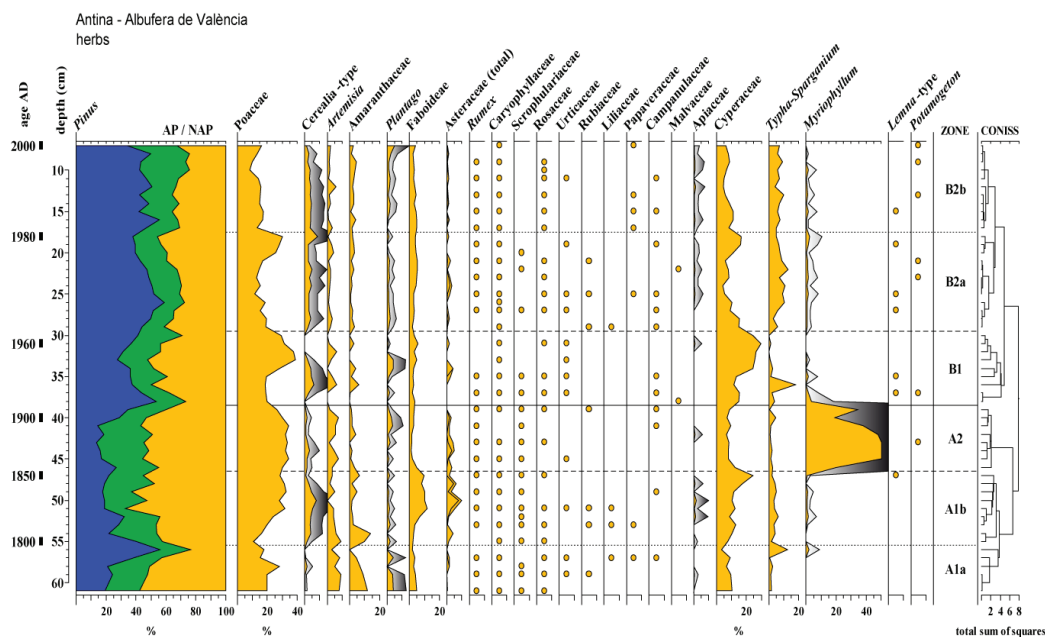


Figure 12. Stratigraphic diagram of pollen percentages of herbs in Lake Albufera core Antina. The zones defined by constrained cluster analysis are shown on the right. The dots mean less than 1 %. The curves exaggeration factor is variable, in order to better visualize their evolution. *Diagrama estratigráfico de los porcentajes de polen de hierbas en el core Antina de la laguna de la Albufera. A la derecha se muestran las zonas definidas por un análisis de clasificación constreñido. Los puntos indican valores < 1 %. El factor de exageración de las curvas es variable, para poder visualizar mejor su evolución.*

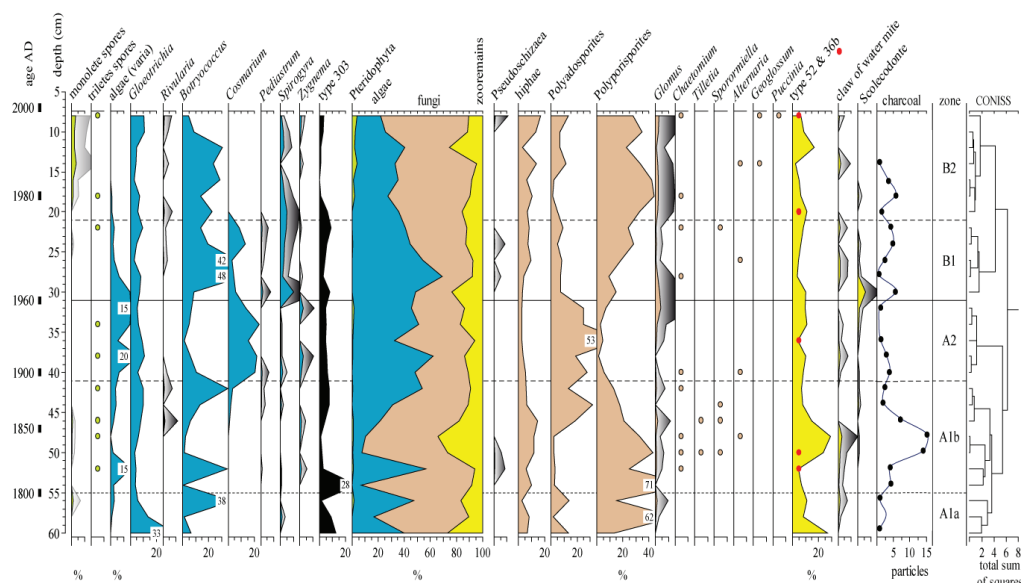


Figure 13. Stratigraphic diagram of Pteridophyta, algae, fungi, zooremain NPPs percentages and absolute frequencies of palynological charcoal in Lake Albufera core Antina. The zones defined by constrained cluster analysis are shown on the right. The dots mean less than 1 %. The curves exaggeration factor is variable, in order to better visualize their evolution. *Diagrama estratigráfico de los porcentajes de Pteridophyta, algas, restos NPPs zoológicos y frecuencias absolutas de carbones palinológicos en el core Antina de la laguna de la Albufera. A la derecha se muestran las zonas definidas por un análisis de clasificación constreñido. Los puntos indican valores < 1 %. El factor de exageración de las curvas es variable, para poder visualizar mejor su evolución.*

forest, along with the constant presence of Myrtaceae and cultivated cereals. No *Morus* remains are observed anymore. Freshwater taxa (Cyperaceae, *Typha/Sparganium*, cf. *Phragmites*, Pteridophyta monolete spores) continue to dominate over saline indicators (Amaranthaceae, *Artemisia*).

Core Centre

A brief summary of the top part of this core and its interpretation was previously given by Marco-Barba *et al.* (2012a). In this paper, we provide a detailed description of the stratigraphic sequence (Fig. S1, available at <http://www.limnetica.net/en/limnetica>), including the chronology (Fig. 14), information on chemical composition and a detailed XRF analysis of the sediments (Figs. 15, 16, S2 (available at <http://www.limnetica.net/en/limnetica>)), so as on foraminifera remains (Figs. S3 (available at <http://www.limnetica.net/en/limnetica>), 17) and ostracod palaeoecology and geochemistry (Figs. S4 (available at <http://www.limnetica.net/en/limnetica>), 18, 19).

Chronological framework

For the top of the core a ^{210}Pb -based cf:cs chronology was constructed from the near-exponential section of the twin core (14–35 cm), which yielded dates that match the ^{137}Cs record fairly closely, giving a sedimentation rate of 6 mm/yr for the twin core Centre (Fig. 14), after lithological matching. This is supported by the very high magnetic susceptibility peak at the top of Core Centre (30 cm depth) that coincides with an important flood event in 1957, which markedly affected Albufera lake (Fig. S1; Carmona & Ruiz, 2000). Thus, the chronology presented here is arranged to fit the radiocaesium results, with the flood event as a tie marker. The year 1850 AD at the base of ^{210}Pb profile could be placed at 75 cm in core Centre, which fits with a change in the Sr/Ca content (Figs. 14, 16) a shift of facies (top of *Cerastoderma* shells, Fig. S1) and coincides with a major expansion of the irrigation system at the beginning of the 19th century (Sanchis Ibor, 2001). A sedimentation rate of 4.2 mm/yr is

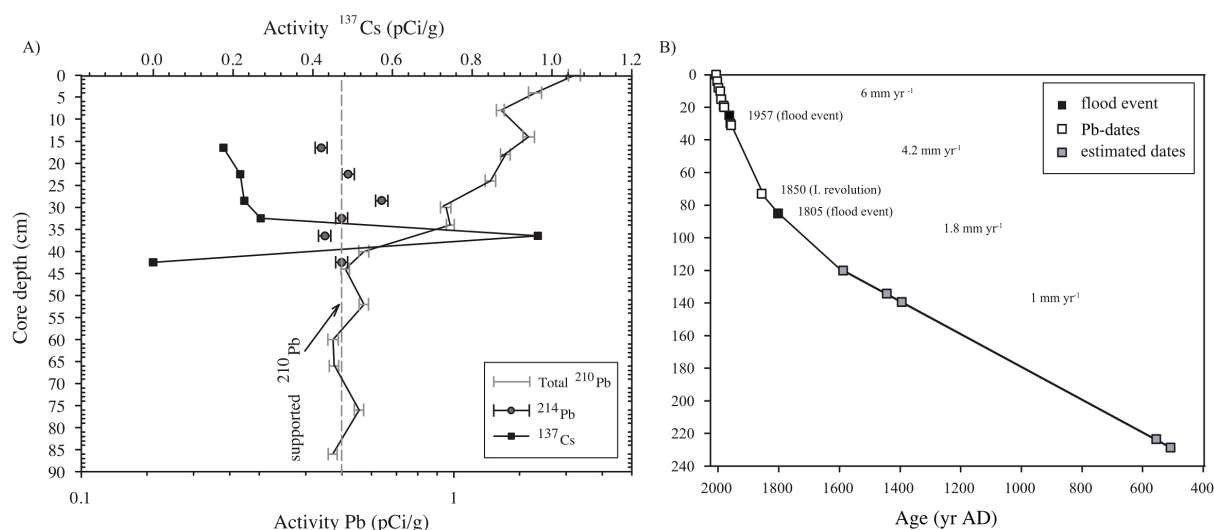


Figure 14. A) Radionuclide activities of ^{210}Pb (gray straight line), ^{214}Pb (gray circles) and ^{137}Cs (black squares) from Core Centre. Note that supported activity is also placed. B) Chronological model and sedimentation rates estimated from ^{14}C dates and historical data (see text). A) Actividades (pCi/g) de los radioisótopos ^{210}Pb (línea gris), ^{214}Pb (puntos grises) y ^{137}Cs (cuadrados negros) del Core Centre. También se indica la actividad basal. B) Modelo cronológico y tasas de sedimentación estimadas a partir de dataciones ^{14}C y datos históricos (ver texto).

estimated for the period 1850-1957 (Fig. 14). Just below that depth there are peaks in magnetic susceptibility and detrital elements (Figs. 15,16) that could be related to the very frequent acute storm episodes occurring in the wet years at the start of the XIX century (e.g. a very intense one in 1805; Carmona & Ruiz, 2000) involving again the rivers and water courses surrounding Albufera lake. So, we placed in our chronological model the year 1805 as corresponding to the magnetic susceptibility peak at 85 cm depth (Fig. 15). The peak could be additionally reinforced by the transportation of large volumes of sediment to transform the shallow peripheral parts of Albufera into rice paddies (increasing Ti/K) that took place mainly from the end of the 18th to the beginning of the 19th century. This chronology fits also with XRF results (Fig. 16); the Pb accumulation would increase after the start of the Industrial Revolution (starting between 1800-1850 AD in Europe and by the end of this period in Valencia, Renberg *et al.*, 2001; Bindler *et al.*, 2008), and Cu would increase with its use in the switch of rice cultivation from transplanting to direct seeding in the 1960's (Zaragoza Pérez, 1982).

The lower part of the chronological model (Fig. 14) is based additionally on radiocarbon dates (Table 1), which probably had a strong reservoir effect, but used to calculate sediment accumulation rate (SAR), plus historical data and XRF geochemistry. The reservoir effect can be very high and very variable (Sabatier *et al.*, 2010; 2012), especially when there is influence of fresh-water rich in (bi-)carbonates, so that measured ^{14}C dates in such context can be up to > 2000 yr older than expected, and strongly depends on alkalinity (Coularis *et al.*, 2016). This effect can apply not only to shelled invertebrates, but also to aquatic plants with aerial parts (Philippsen, 2013; Philippsen & Heinemeier, 2013). Therefore, shell and pollen ^{14}C dates from lake Albufera sediments could be much older than the finally calibrated dates, taking into account the strong influence of freshwater input throughout its history (e.g. Marco-Barba *et al.*, 2013a,b), with variable and high alkalinity in recent times (Soria *et al.*, 1987). Anyway, the lower part of the core has a very stable Cl content, indicating insignificant anthropogenic changes in the hydrology of the lagoon, thus, a relative stability in the reservoir

effect can be assumed, allowing average sediment accumulation rate (SAR) to be estimated from radiocarbon measurements of the same type of material at different depths. Average rates calculated independently from pollen and shell data for the lower part of the core showed similar values of around 1 mm/yr (SAR_{pollen}: 0.94-0.97 mm/yr and SAR_{shells}: 1.05-1.23 mm/yr). This was taken as the average SAR from the core base to 120 cm, after which a sharp CI decrease occurs (Fig. 16). This shift in the CI values is thought to be related to the construction of a gate in the outlet of the lagoon to the sea for fishing management in 1607, and consequently we assigned the date of 1600 yr AD to a core depth of 120 cm. This hydrological control, together with an increased drainage to this lagoon outlet from irrigation ditches, limited water interchange with the sea and reduced the salinity of the lagoon according to historical documents compiled by Sanchis Ibor (2001). Assuming that the depth of 120 cm corresponds to the first quarter of the 17th century, a SAR of 1.8 mm/yr could be assigned to the 75-120 cm interval (Fig. 14). These age estimates suggest that the results of shell analysis incorporate a reservoir effect (R(t)) much higher than the expected marine reservoir age in the Mediterranean Sea (about 400 years; Siani *et al.*, 2000), in accordance with observations in nearby coastal systems by Sabatier *et al.* (2010; 2012). This estimated effect was between 1450 and 2349 yr (Table 1) for our calibrated ¹⁴C dates (excluding a much older outlier at 233 cm core depth), higher for pollen than for shell material. Due to the large uncertainty of the reservoir corrections and sedimentation of older materials, the radiocarbon results have therefore only been used as relative measurements, and those of the uppermost stratum (above 120 cm core depth) have been excluded, because deposition occurred in different and more variable hydrological conditions. Still, we estimated also a reservoir effect of 669-817 yr for the two top calibrated dates.

Lithological facies descriptions

Clay and silt sediments with shell fragments mostly filled the lagoon alternating with layers of fine sandy material. Two sedimentary units (Unit

1 and 2) and five lithological facies (A, B, C, D, and E; described below) were recognised from Core Centre, based on visual inspection (Fig. S1). Magnetic susceptibility (MS), LOI, percentage of carbonates and X-ray fluorescence (XRF) profiles were used to better define these facies. Unit 1 was identified from the base of the core at 235 cm to 81 cm depth and unit 2 from 81 cm to the core top.

Levels making up facies A are characterized by different thickness varying between 3 cm and 18.5 cm (A1 to A6), all of them belonging to unit 1. This facies is formed by gray sandy silt sediments, carbonate grains and plant fragments. Bioclasts of gastropods and bivalves, mainly *Cerastoderma glaucum* (Poiret, 1789) valves, and also foraminifera could be found.

Facies B is formed by homogeneous fine silt sediments with gray coloration (Fig. S1). Seven levels were described at this lithofacies (B1-B7) with different thickness (between 4 cm and 30 cm), all located at unit 1. They are characterized by very low sand content, plant fibre remains of variable length and microscopic carbon particles. Bioclasts of molluscs and articulated valves were usually absent or scarce (facies B2-B7).

Facies C is formed by homogeneous ochre fine silt sediments highly enriched in plant remains. Five levels were identified (C1-C5) with different thickness and present in both units 1 and 2, usually made up of narrow layers (range 3 - 36 cm). Facies C1 and C3 were composed of plant remains of different lengths, bioclasts of molluscs and articulated valves of *Cerastoderma glaucum*. Facies A5/C2 showed the typical sediment composition of facies C although highly enriched in sand. Facies C4 and C5 are composed of soft pink (C4) and orange (C5) mud sediments with carbonate grains (C4) and are confined to unit 2.

Facies D is mostly composed of homogeneous silt, with two narrow layers with some fine sand at the top. Plant and mollusc remains are very scarce.

Facies E is formed by heterogeneous dark grey silt sediments, without plant and mollusc remains. Five levels were identified as lithofacies E1 to E5, always consisting of very thin layers (range 0.5 - 3 cm). The majority of these levels coincide with MS increases (Fig. 15), mainly at E4 and E5 with the highest MS peaks. Based on

the high content of detritic elements such as titanium, potassium and aluminum, this material was probably reworked and transported into the lake due to flood events.

XRF results

The high-resolution records of the most significant geochemical elements obtained by the XRF

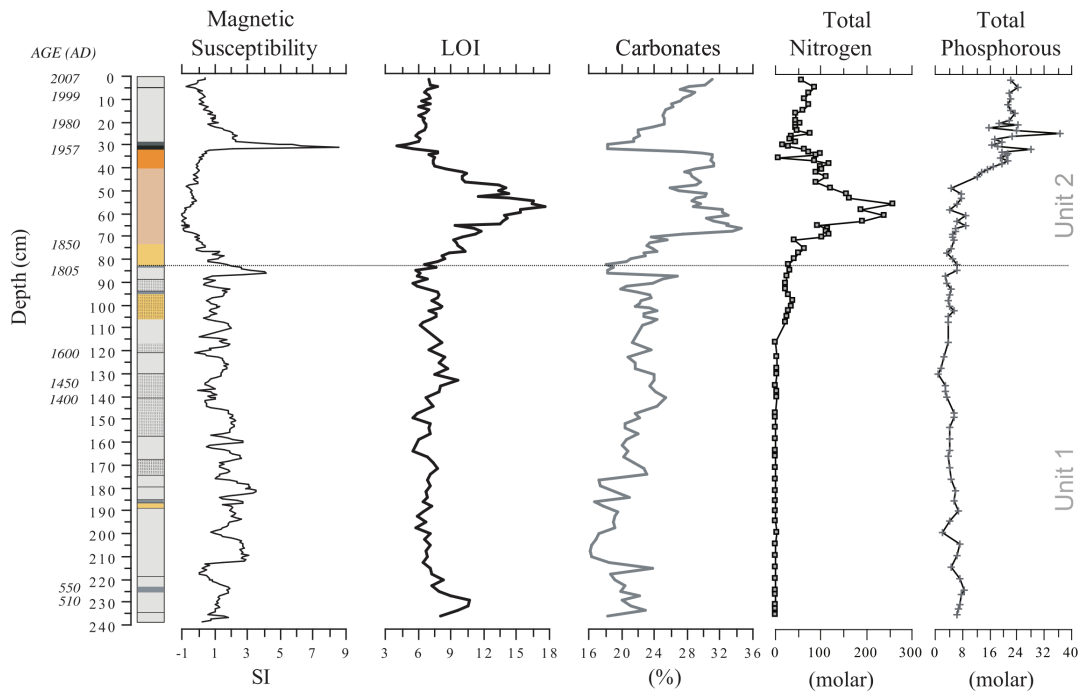


Figure 15. Magnetic susceptibility (MS), loss on ignition (LOI), % carbonates, total nitrogen (TN) and total phosphorus (TP) of Core Centre. *Susceptibilidad magnética (MS), pérdida por ignición (LOI), % de carbonatos, nitrógeno total (TN) y fósforo total (TP) del core Centre.*

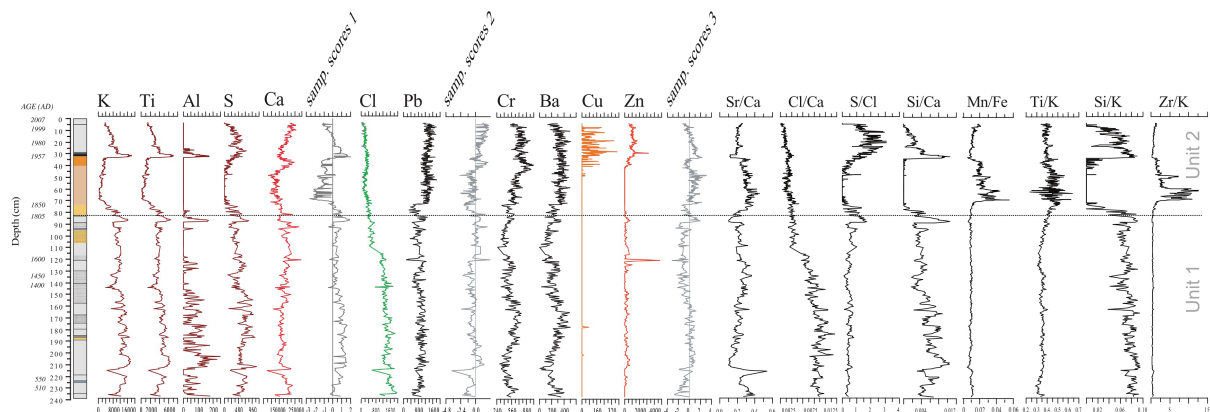


Figure 16. Stratigraphic diagram of geochemical XRF fluorescence data from Core Centre. The samples scores 1, 2 and 3 from a PCA are also plotted. See Figure S2. *Diagrama estratigráfico de los datos geoquímicos de fluorescencia XRF del core Centre. Se muestran además los valores de las muestras para los factores 1, 2 y 3 de un análisis de componentes principales (PCA). Ver Figura S2.*

analysis are plotted in figure 16. Two kinds of profiles are easily seen reflecting the distinct varying proportion of authigenic versus detrital elements with core depth. The variation of Ca and Sr can be mainly related to shell abundance (molluscs, ostracods, foraminifera, Sabatier *et al.*, 2010, 2012) (sedimentary unit 1) or to endogenic carbonate precipitation (unit 2). In the sedimentary unit 2 carbonate shells were very scarce and the increase in Ca and carbonates should be predominantly associated to precipitation of calcium carbonate due to high photosynthetic rates, first mediated by the development of aquatic macrophytes and, since the end of the 1960's (20–25 cm), by phytoplankton production, although some influence of clastic carbonate input from the watershed cannot be disregarded.

On the other hand, detrital elements, Ti, K altogether with quartz (Si) clay elements (Al, Fe, Rb), suggest allochthonous input materials (Cohen, 2003; López-Buendía *et al.*, 1999). Particularly, Ti and K are considered detrital elements from continental sources (Cohen, 2003; López-Buendía *et al.*, 1999), and are highly positively correlated with MS ($p < 0.01$) along the core, and negatively correlated with LOI and the proportion of carbonates ($p < 0.01$), suggesting that these elements were mostly deposited into the lake by inlets and particularly flood events. In addition, we find heavy elements mostly derived from human activities to increase their concentrations to the upper parts of the core; Cr and Pb increasing since about 80 cm depth and Cu and Zn later at the top of the sequence. Cl indicates the higher bottom salinity with an important shift at about 120 cm and progressively decreasing to the top of the sequence. Although this reduction in Cl content might also be related to a reduction in sediment grain size (and water accumulated therein), the salinity change is also supported by a reduction in foraminifera diversity and stenohaline marine ostracod relative abundance (see below).

PCA results (Fig. S2, available at <http://www.limnetica.net/en/limnetica>) confirm the opposite distribution between elements with detrital origin and characteristic of high erosive periods (or clastic input), and elements more characteristic of authigenic stable periods (or carbonate input). This is indicated by axis 1, which accounts for

most of the variance of the data (90 %). Detrital elements cluster with high positive scores, Ti, Fe and K showing the higher scores followed closely by Co, Rb, Si, and to a lesser extent by S and Al. High negative scores are displayed by Ca and Sr, followed by the compact group of Ni, Cr, Pb, and by Zr and Ba. Although explaining a low proportion of the total variance, the separation along axis 2 between Zn and Cu (positive scores) and Cl and As (negative scores) reflects salinity variation. The former two elements (usually related to chemical industrial activities, but also agricultural practices in the case of Cu) are more important at the very top of the core. Due to the proximity of the lake to the sea, Cl and As (a good pyrite indicator) variation probably indicate variation in marine influence. Cl was negatively correlated with the proportion of carbonates ($p < 0.01$), suggesting that sea water played an important role in the geochemical composition of the lagoonal sediments in the lower half of the core.

The ratios between elements (Fig. 16) clearly indicate shifting paleoenvironmental conditions; Cl/Ca show the salinity change, while Sr/Ca indicates a zone of change in the type of carbonates in the lower part of unit 2 at the onset of desalinization, when macrophytes were abundant and diminished afterwards. Contrarily, the S/Cl ratio indicates a reverse pattern for S, with peaks that may indicate sulphide-rich matter originated in anoxic conditions (Zwolsman *et al.*, 1993) at the top and bottom of sedimentary unit 2, but lower values at the more stable redox conditions of macrophyte development prior to eutrophication. Also, Si as well as clay elements show a very scarce concentration in this zone, altogether with detrital elements but the reduction of the later is much less marked. Thus, the ratio Ti/K shows a slight increase also in this zone. The Mn/Fe ratio marks also clearly this zone, with Mn higher values in the stable redox (macrophyte-dominated) zone, probably due to the faster oxidation of Fe (Zwolsman *et al.*, 1993).

Foraminifera

Selected common foraminifera taxa in Core Centre are shown in figure S3. This core was (almost) barren of foraminifera in the upper 70

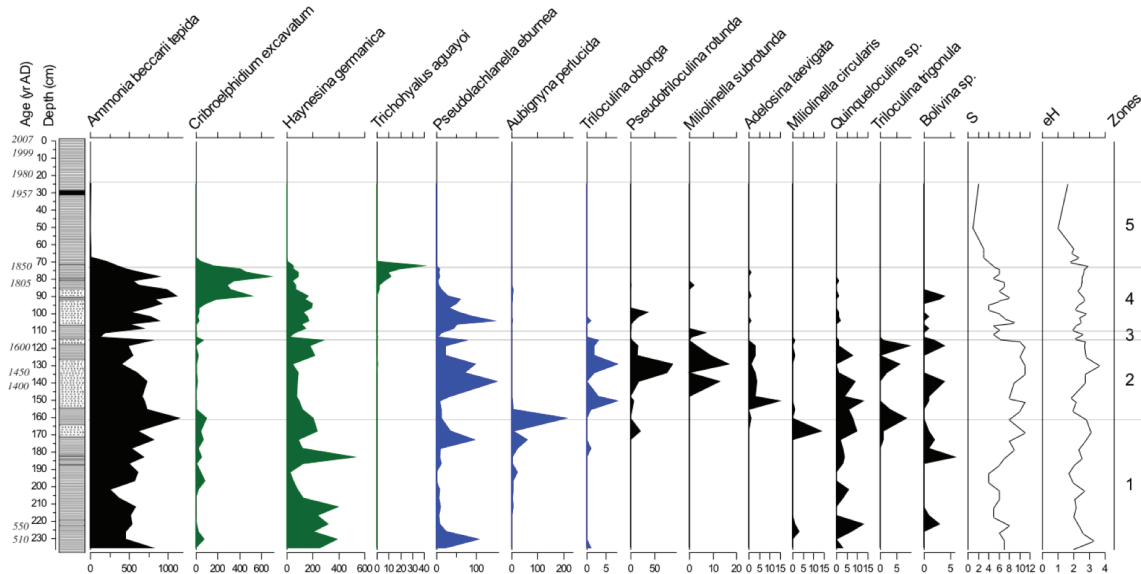


Figure 17. Summary stratigraphic diagram of foraminifera abundances in Lake Albufera core Centre showing taxa present at minimum > 5 individuals. Green: species tolerant of relatively low salinity in brackish waters (other than *Ammonia* spp.); blue: those considered less tolerant to low salinity. The diversity of order 0 (S = species richness) and order 1 (e^H , where H = Shannon diversity), and zone boundaries defined by constrained cluster analysis are shown on the right. Sediment legend as in figure 2. *Gráfico estratigráfico resumen de los foraminíferos del core Centre de la laguna de la Albufera, mostrando las especies con un mínimo de individuos > 5. Verde: especies tolerantes a salinidades relativamente bajas en aguas salobres (aparte de *Ammonia* spp.); azul: aquellas poco tolerantes a bajas salinidades. A la derecha se muestran la diversidad de orden 0 (S = riqueza de especies) y orden 1 (e^H , donde H = diversidad de Shannon), así como las zonas definidas mediante análisis constreñido de clasificación. Leyenda de la columna sedimentaria como en la figura 2.*

cm (Zone 5), with only one or two species present in some samples and at very low abundances (Fig. 17). As in the shorter core Antina, *A. tepida*, *C. excavatum* and *H. germanica* dominated the sequence. Zone 1 (235 - 161 cm) was relatively species-poor, but progressively increased in richness towards the top, attaining values close to the maxima recorded in the more diverse Zone 2 (161-114.5 cm). Zone 3 (114.5-111.5 cm) is characterized by a sharp and brief decline in abundance and diversity of foraminifera, which partly recover in Zone 4. An important peak in abundance of *C. excavatum* is observed in the top half of Zone 4, which ends abruptly at about 72 cm with the maximum abundances of *T. aguayoi*, in close similarity to the top of the foraminiferal sequence of core Antina.

Ostracod assemblages

We identified 100 952 ostracod valves, represent-

ing 18 species of ostracods from 15 genera in the Albufera Core Centre sequence. A selection of common species is shown in figure S4. Ostracods were absent from two of the 70 studied samples (at the top of the core), and 6 samples had only one species present (Fig. 18).

Cyprideis torosa together with *Loxoconcha elliptica* and *Xestoleberis nitida* were the most abundant species along the core. In addition, *Aurila arborescens*, *Candona angulata* and *Darwinula stevensoni* were also abundant, especially the first one in the lower part of the sequence. *Candona angulata* and *D. stevensoni* were abundant in the upper part and *Paralimnocythere psammophila*, *Cypridopsis vidua* and *Limnocythere innopinata* appeared with lower abundances. Other species present were very scarce.

Application of a stratigraphically-constrained cluster analysis to the ostracod assemblages allowed the differentiation of 4 main stratigraphical zones that could be further subdivided onto 7

different subzones (Fig. 18). The 4 main stratigraphic zones presented different assemblages regarding to their ecological recruitments (1: brackish; 1b: brackish-marine; 2: brackish; 3-4: freshwater).

Ecophenotypic response and isotope composition of Cyprideis torosa shells

The length of 2110 *C. torosa* valves (994 females and 1116 males) was measured from 57 subsamples (Fig. 19). LOESS regression was applied separately to female and male size changes through the core and showed that both followed the same pattern of variation in carapace length with depth through the core. Most *C. torosa* found at zones 1 and 2 showed smooth (unnoded) valves, but the percentage of *C. torosa* noded forms increased in zone 3, suggesting an important salinity decrease.

The isotope values for *C. torosa* shells ranged between -10.06 ‰ and 2.33 ‰ (mean value -5.45 ‰ $\pm$ 1.61) for $\delta^{13}\text{C}$ and between -4.98 ‰ and 3.29 ‰ (mean value of -0.18 ‰ $\pm$ 1.71) for $\delta^{18}\text{O}$ (Fig. 19). These two variables were not correlated for the entire sequence. $\delta^{18}\text{O}$ showed high variability

among individual valves in zone 1 (235-107), suggesting a mix of waters or evaporation processes during some periods. $\delta^{13}\text{C}$ remained fairly constant along this zone. Notable variation in $\delta^{18}\text{O}$ values occurred in zone 2 (107-73 cm). $\delta^{13}\text{C}$ increased towards the mid part of this zone (but decreasing in SD) and increased again towards the upper zone boundary. The most important changes were observed for both variables in subzone 3a (73-60 cm; Fig. 19). $\delta^{18}\text{O}$ dropped markedly towards the mid part of the subzone, reaching very low values. $\delta^{13}\text{C}$ also showed a decreasing trend, but less marked. $\delta^{13}\text{C}$ was highly variable in subzone 3b (60-39 cm), and the few isotopic shell analyses (2) performed for zone 4a show values that were somehow lower (but still in the range) as those of subzone 3b.

The isotopic results compared with previous data (Marco-Barba *et al.*, 2012b) for recent shells of *C. torosa* (Fig. S5, available at <http://www.limnetica.net/en/limnetica>) show that ostracod zones 1 and 2 fitted well within the range of values for typical brackish and hypersaline sites studied by Marco-Barba *et al.* (2012b). Also $\delta^{18}\text{O}$ results for zones 3 and 4 fit values corresponding to low salinity environments as compared with

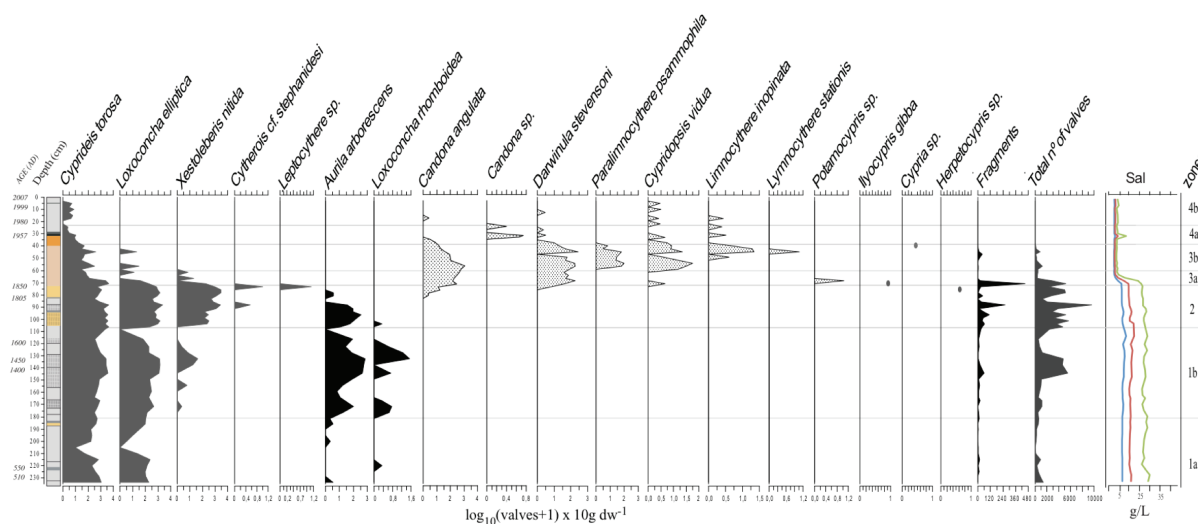


Figure 18. Stratigraphic diagram of ostracod abundances and reconstructed salinity (Sal) in Lake Albufera Core Centre. The zones defined by constrained cluster analysis are also shown. Dark grey: brackish species; black: brackish-marine species; light grey: freshwater species. *Diagrama estratigráfico de las abundancias de los ostrácodos y la salinidad estimada (Sal) en el Core Centre de la laguna de la Albufera. Se muestran además las zonas definidas por un análisis de clasificación constreñido. Gris oscuro: especies de aguas salobres; negro: especies con afinidades salobres-marinas; gris claro: especies dulceacuícolas.*

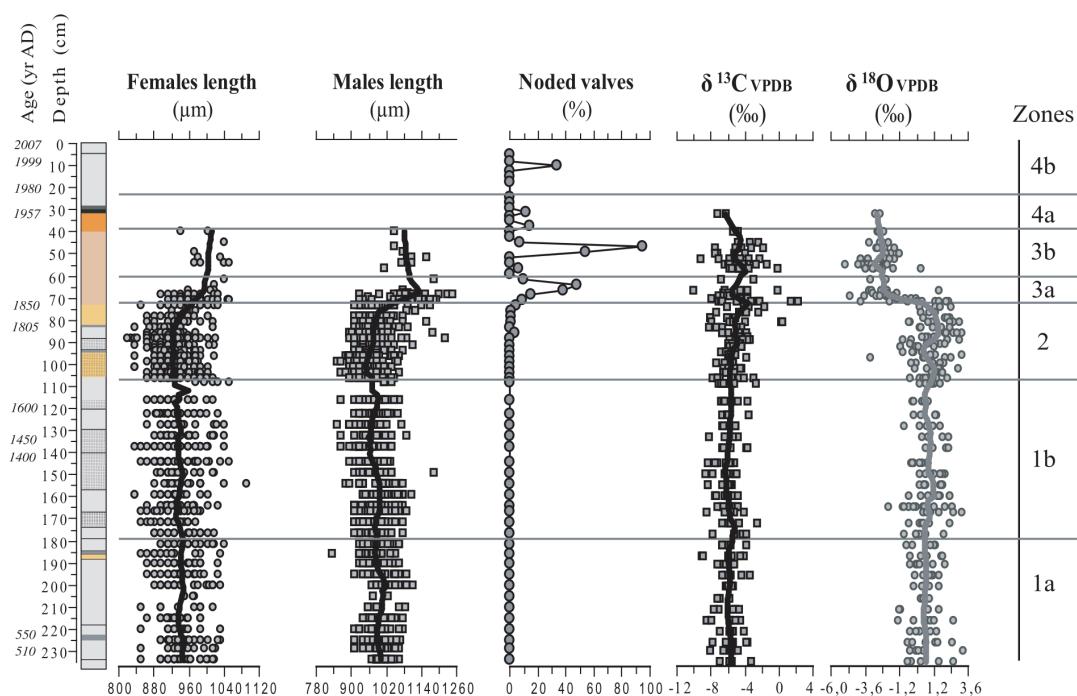


Figure 19. *Cyprideis torosa* measured carapace lengths for females and males, percentage of noded *C. torosa* valves and isotopical ratios ($^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$) performed on *C. torosa* shells along the sedimentary sequence of Core Centre. Loess regressions were performed for all ratios using average scale of 10. *Medidas de longitud de las valvas de Cyprideis torosa para machos y hembras, porcentaje de valvas nodadas de C. torosa y razones isotópicas ($^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$) de las conchas de C. torosa a lo largo de la secuencia sedimentaria del core Centre. Las regresiones Loess se llevaron a cabo para todas las proporciones utilizando una escala promedio de 10.*

previous geochemical data on recent ostracods obtained by Marco-Barba *et al.* (2012b) (Fig. S5). However, the data for $\delta^{13}\text{C}$ values are higher than expected given their $\delta^{18}\text{O}$ values, based on relationships defined by Marco-Barba *et al.* (2012b) in oligohaline spring ponds. This difference is expected from the different origin of water (ground- vs. surface) and by the much highest productivity of a lagoon compared to a spring pond with clear waters (Leng & Marshall, 2004).

DISCUSSION

The prehistoric Albufera lagoon (8700 – 3400 cal. BP)

Cores El Palmar and Pujol were extracted from the sand bar separating the lagoon from the sea, and their sedimentary analysis (Santisteban *et al.*, 2009) revealed the major influence of marine

transgression and regression events on its depositional history. As reported previously for El Palmar (Marco-Barba *et al.*, 2013a), both sequences are dominated by brackish water ostracod taxa (euryhaline and brackish stenohaline) rather than fully marine, species-rich (e.g. Ruiz *et al.*, 2000) assemblages, indicating that the area was not widely open to the sea during most of the Holocene (Fig. 20). The analysis of foraminifera and diatoms confirm the interpretation, as indicated by the dominance of *A. beccarii* and associated forams, and (where preserved) *Mastogloia* taxa and other obligate saline brackish diatoms. The exception is in the lower Pujol sequence, where peaks in foraminiferal diversity occur during a phase thought to represent a sandy beach in a transgressive period (Santisteban *et al.*, 2009), suggesting stronger marine influence in the northern part of the recent barrier, which is at present much closer to the seashore than Palmar.

For the same period, Carmona *et al.* (2016) also found a brackish lagoon foraminiferal community in the northern part of the Albufera wetland, in a site location occupied by ricefields since the early 19th century.

At about 8300 cal. BP, there is a change in the type of sediments (muddy to sandy), and a sharp reduction event in ostracod, foraminiferal and algal remains abundance, coincident with an important peak in megaspores (Fig. 20). Modern megaspores are produced by heterosporous lycopods and ferns (Traverse, 2007), and are considered a proxy for the presence of tall grasses and rushes common on the borders of freshwater and

brackish wetlands (Goodman *et al.*, 2008). Therefore, a relative increase may indicate a reduction in the inundated part of the lake in relation to the littoral area. If the chronology is accurate, this event might be related to the 8.2 event (Bond *et al.*, 1997), which could have triggered a reduction of the water table in the wetland at that time. Also, Carmona *et al.* (2016) relate the base of a sequence from the northwestern part of the lake, which consisted of a peat layer, to a potentially cold and dry period. This period is brief, and ostracod and foraminiferal communities rapidly recover. Subsequently, between about 7500 and 7100 cal. BP, another longer lasted and major reduction

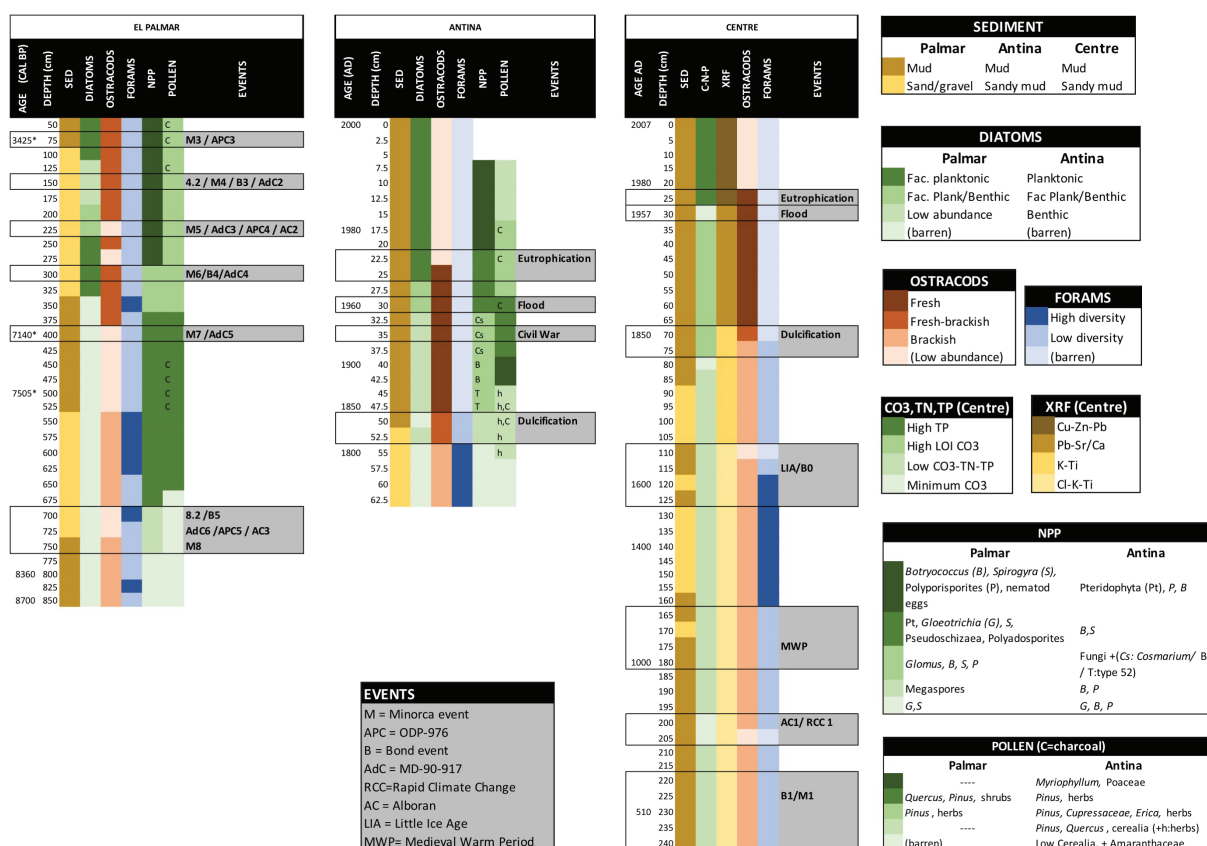


Figure 20. Summary of main changes detected for different proxies in the Albufera de València sequences of El Palmar, Antina and Centre. The chronological location of main events are to be taken as approximate, particularly for Core Palmar, considering the low resolution of the chronology. * ^{14}C cal. dates; other dates are estimated from the chronological models. See text for further explanations and for more detailed proxy sequences and interpretations. *Resumen de los principales cambios detectados para diferentes indicadores de las secuencias de El Palmar, Antina y Centre de la Albufera de València. La localización cronológica de los principales eventos debe considerarse aproximada, particularmente para el core Palmar, teniendo en cuenta la baja resolución de la cronología. * dataciones calibradas ^{14}C ; otras fechas son estimaciones a partir de los modelos cronológicos. Véase el texto para más explicaciones y mayores detalles de las secuencias de los indicadores y su interpretación.*

in ostracod abundance is recorded, coinciding with a shift in sediment composition, in foraminiferal composition and a reduction in species richness, and the common presence of soil fungal remains (Fig. 8, Fig. 20). This phase also suggests an aridity period, that might correspond to the M7 Minorca event (Frigola *et al.*, 2007), although it could also relate to an inland advance of the sand barrier (aggradation) at the point of core extraction (Santisteban *et al.*, 2009), reducing the lagoon to a series of (temporary) shallow interdune ponds (although no ostracod remains typical of temporary water bodies such as those described by Rueda *et al.* 2006 were observed).

Above this part of the sequence, proxy data indicate environmental changes that would create a wetland and landscape quite different to its previous state. Indeed the largest palaeoenvironmental change through the El Palmar core is observed at about 4 m depth (7140 cal. BP) (Fig. 20), when ostracods, diatoms and other algal remains (e.g. *Botryococcus*, *Gloeotrichia*, *Spirogyra*) start to show a more stable oligohaline (see e.g. Margalef, 1983) water body from here on. Diatoms are preserved for the first time at 312 cm depth, indicative of a shallow, brackish, environment. The salinity optimum of *P. brevistriata* is quite high because it will tolerate brackish water but it also occurs in fresh water, as do all of the facultative planktonic taxa encountered. The maximum abundance of these taxa in zone 1 (341.5–251.5 cm) could indicate lower salinity but is difficult to interpret. Shifts between facultative planktonic and benthic diatom taxa could also result from changes in water depth, but (in the absence of true plankton) are more likely to indicate changes in the proportion of reeds (FP) to mud/stone habitat. Ostracod palaeoassemblages and ecomorphogenetic changes provide more definitive evidence for lower salinity at the top of the sequence (Marco-Barba *et al.*, 2013a), but always in the oligohaline-mesosaline range. The reasons for intermittent diatom preservation are not clear; since there is no evidence for hypersalinity in samples containing sparse assemblages, it is more likely to be a function of a high energy environment (breakage and poor burial) in the turbid, shallow water of the littoral zone; the complete absence of diatoms at the base of the

sequence may be a function of low productivity prior to erosion of nutrients into the lake with deforestation (as suggested by pollen remains – see below), or could reflect more rapid burial with enhanced sediment input.

But not only major changes in the functioning of the water body are found, as also we observe major shifts in landscape vegetation, as suggested by palynological data. Prior to 7140 cal. BP, the vegetation was dominated by trees (*Quercus*) and bushes (*Erica*, *Cistus*), but above the layer that might indicate the M7 event (Frigola *et al.*, 2007), Poaceae (including *Cerealia*-type) dominate, suggesting a major climate change effect towards higher aridity, although this contrasts with the western Mediterranean increased precipitation at about 6000 BP suggested by general models (Roberts *et al.*, 2011), so as with the reduction in salt content in the lake as suggested by microfossils. Vegetation changes coincide with a change in the depositional environment (lagoonal to sandy lobes), so that the palynological change observed might also be related to the local development of grasses in these new sandy environments. Further decreases in arboreal pollen through the top half of the sequence are also coeval with known aridity events (M3–M6; Frigola *et al.*, 2007).

We cannot however rule out the potential influence of human impact on landscape changes at these early times. A hint to these effects is the frequency above 350 cm of egg cover remains of parasitic worms (Nematoda), probably related to increased cattle raising activities around the lake. Fire events (charcoal frequency) had already increased prior to deforestation, but charcoal remains subsequently increased in frequency in the top half of the sequence. Human populations are known to have occupied the territory near the lake (a few km inland and tens of km southward) and had used its resources (e.g. cockles, grain) at least since about 6000 BP (Mateu *et al.*, 1985; Martí-Oliver, 1988). Not too far, at about 50–70 km to the south, major vegetation changes during this period have been suggested to be human-induced through fires (Carrión & van Geel, 1999; Carrión *et al.*, 2010), and increased livestock activities at around 6200 cal. BP have been associated to forest decline near Neolithic settlements (Dupré, 1995; Badal *et al.*, 2012).

The historic Albufera lake (500 AD- 2007)

Unfortunately, according to the chronology of our cores, we have no data for palaeoenvironmental change between 3400 and 1500 cal. BP in the Albufera lagoon. However, a sequence analysed by Carmona *et al.* (2016) from the northwestern part of the wetland includes this period. These authors found no major difference in foraminiferal species composition from the oldest sediments, since c. 8200 up to 1000 cal BP, being dominated by *A. tepida*, *H. germanica* and *C. excavatum*, indicating a brackish coastal lagoon. This association is very similar to that found dominating the base of our shortest core Antina and most of the longer Core Centre.

The bottom half of Core Centre shows in general homogeneous traits in many proxies (Fig. 20), including elements detected by XRF, magnetic susceptibility, LOI, N and P content, ostracod geochemistry and shell size of *C. torosa*, so as in dominant species of ostracods (*C. torosa*, *L. elliptica*) and foraminifera (*A. tepida*, *H. germanica*). Still, some striking events can be observed and interpreted. First, there is an unusually rapid shift in various elements that decrease at 210-215 cm and increase to high values at 200-205 cm (an approximate estimated age of 700-800 AD) (Fig. 16). These include minimum values (and subsequent peaks) of K, Ti, Al, S, Ca, Cl, Si/Ca and inverted peaks in Sr/Ca. At the same point, there is a minor peak in magnetic susceptibility and minimum values in carbonate content. Also, the stratigraphy shows a remarkable absence of macroremains and a sudden drop in ostracod and foraminiferan abundance (Fig. 20). A potential explanation could be a flood event (increased sediment input and reduced density of shell remains) or some sort of rapid climate change. At this time, Moberg *et al.* (2005) found a peak in global temperature after a cold period. The established arid periods AC1 (Alborán events; Cacho *et al.*, 2001) and RCC1 (Rapid Climatic Change periods; Mayewski *et al.*, 2004) might also be responsible for such a rapid event. Unfortunately, we have no pollen data from this core to see if vegetation suffered some change at this time to validate this hypothesis. Another change in the lower sequence, from 180-160 cm (i.e.

1000-1200 yr AD), occurs when brackish (and some marine) ostracods and foraminifera increase progressively in abundance and diversity indicating more stable conditions in a brackish lagoon, at the time of the Medieval Warm Period. Later on, at about 1700 AD (110 cm depth), another sudden drop in ostracod and foraminifer abundance and diversity occur, probably related to reduced productivity at low temperatures during the Little Ice Age (although our chronological model has to be taken with caution).

The most important change through the last 1500 years in the lake record is observed at a depth of 70-75 cm in the Core Centre, and 50-55 cm in core Antina (Marco-Barba *et al.*, 2013b for ostracods, and this survey for other remains), both corresponding to the beginning of the 19th century. Here, the system changes completely from a brackish to an oligohaline lagoon. Diatoms and cladocerans (Marco-Barba *et al.*, 2012a) start to be common, while foraminifera disappear, at the same time that the ostracod palaeocommunity shifts from one dominated by unnoded, small, *C. torosa* and accompanying brackish species to one with noded and larger *C. torosa* and typical freshwater dwellers. Ostracod shell $\delta^{18}\text{O}$ drops and Sr/Ca values increase (Marco-Barba *et al.*, 2013b). Altogether this indicates a reduction in salinity from about 15 to less than 2 g/L (Marco-Barba *et al.*, 2013b). K, Ti, Al and S drop, and Pb, Cr and Ba increase, together with LOI, carbonates and N content. An initial increase in S/Cl may suggest increased sulphide (Zwolsman *et al.*, 1993) at the start of the freshening phase, probably indicating biomass decomposition at the collapse of the brackish adapted communities. The most intense human impact occurred during this period. The Spanish crisis at the beginning of the XIX century and the changes in the property of the surrounding land led to intensive agricultural expansion and to strong hydrological control of the Albufera de Valencia (Sanchis Ibor, 2001; Marco-Barba *et al.*, 2012; 2013b). The lagoon area was reduced in 6000 Ha and became hydrologically controlled for rice farming (Mateu, 1987; Sanchis Ibor, 2001). This increase in rice cultivated area may correspond to the pollen local signal of increased Cerealia-type remains in the Antina core, co-occurring with the

reduction in *Amaranthaceae*, indicators of more saline environments.

As a response to this drastic salinity change, the macrophyte community also switched from dominance by salt tolerant species such as *Lamprothamnium papulosum* (Wallroth) or *Chara aspera* Detharding ex Willdenow to freshwater species including *C. vulgaris* L., *C. tomentosa* L. and *C. hispida* L., as shown by previous research (Rodrigo *et al.*, 2010; Rodrigo & Alonso-Guillén, 2013), and including *Myriophyllum* sp., as indicated by the peak in our pollen data. The core depth of this freshening and the age model (based on ^{210}Pb - ^{137}Cs dating) provided by Rodrigo *et al.* (2010) fit very closely to our results. In contrast, Carmona *et al.* (2016) found that freshening took place much earlier, at about 820 cal. BP according to their ^{14}C dates. Notwithstanding potential chronological uncertainties, a possible explanation of these large differences might come from wetland spatial heterogeneity, as the site in Carmona *et al.* (2016) is much further inland and close to a ravine, which could have promoted the change to an oligohaline wetland in that area during wettest periods and/or with reduced flow connections with the main lagoon water body (i.e. it might be flowing only downstream to the central lake but not backwards, unless the site was fully open to the lake and wind could easily mix the waters).

At the beginning of the 20th century, the palaeolimnological data and geochemistry show no major changes (other than increased LOI and N content, related to the development of a macrophyte meadow and increased trophic state; Marco-Barba *et al.*, 2012a) but the pollen and NPP remains start to change, indicating a certain recovery of forested (*Pinus* spp.) areas, partially interrupted shortly during a time corresponding approximately to the Spanish Civil War (1936-1939). At the point when expanding forests retreat again (maybe because of logging for winter heating or cooking), an increase in *Cyperaceae* and *Poaceae* occurs, perhaps related to more intense use of wet areas surrounding the lagoon for cattle raising (*Plantago* in zone B1, Fig. 12, and *Polyadosporites* in zone A2, Fig. 13; López-Sáez and López-García, 2003), a long-standing practice since at least the late 13th centu-

ry (Rosselló i Verger, 1995) which is known to have continued during the 16th century (Sanchis Ibor, 2001), though perhaps reduced after ricefield expansion.

At the end of the first half of the 20th century, despite the huge ecosystem change, the water quality of the lake was still high, with a well-developed macrophyte community and rich in benthic and planktonic groups indicative of clear waters (Pardo, 1942; Fundació d'Amics del Parc Natural de L'Albufera, 2000). This is in agreement with the observed peak in chlorophytes with a preference for oligotrophic waters such as *Cosmarium* (see Margalef, 1983) in the Antina core. However, nutrient input to the lake continued to rise, particularly P, and *Cosmarium* started to be replaced by more tolerant groups such as *Botryococcus* or *Spirogyra* (Margalef, 1983).

By the end of the 60's and during the early 70's, an increase in human population, urban development and industrialisation, would definitely drive another major change in the lake towards its present hypereutrophic and polluted state, indicated by the diatom *Cyclotella meneghiniana*, for example. The lagoon was heavily artificially modified by this time. The previous rice field expansion had already caused a reduction of the area of the lake, with extensive use of fertilizers. Fine mud sediments, the absence of mollusc shells and macrophyte remains, reduced ostracod density and a major change in diatom composition favouring planktonic species, characterized this period. The reduction in benthic organisms (ostracods and diatoms) was driven by poor water quality, the loss of macrophytes and the anoxic conditions at the bottom sediments (Marco-Barba *et al.*, 2012a), coupled with increased productivity. The uncontrolled watersheds, agricultural residues and industrial spills into the lake modified the natural conditions of the system driving it to an hypereutrophic state. The collapse of macrophytes in a hypereutrophic system coincides with a prolonged peak in sediment sulphide (as S/Cl), added to pollution by heavy metals (Pb, Cr, Zn) and, consequently, to low water quality and the loss of biodiversity (Vicente & Miracle, 1992; Romo *et al.*, 2005; Poquet *et al.*, 2008; Marco-Barba *et al.*, 2013b). Hopefully, the effects of sewage diversion on

reducing nutrient load into the lake (Soria, 2006) might drive a future drop in the trophic conditions of Albufera and perhaps some recovery of the previously diverse benthic community.

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