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VEGETATION CHANGES AND HYDROLOGICAL FLUCTUATIONS IN THE CENTRAL EBRO BASIN (NE SPAIN) SINCE THE LATEGLACIAL PERIOD: SALINE LAKE RECORDS

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Abstract

Although the Central Ebro Basin (Northeastern Iberian Peninsula) is both the northernmost semi-arid area in Europe and one of the regions with the largest biodiversity, it has been insufficiently studied in terms of past climate variability due to the scarcity of suitable sites for palaeoenvironmental analyses. Previous studies from ephemeral saline lakes in the area, mainly based on palynological data, show abrupt and rapid arid/humid transitions throughout the last glacial cycle highlighting a complex palaeohydrological evolution. New cores from two saline lakes (La Playa and La Salineta) in the Los Monegros area provide multi-proxy records including sedimentology, geochemistry, and pollen indicators. This study, together with a detailed and comprehensive review of the main saline records from the Central Ebro Basin, enables us tos reconstruct a comprehensive picture of the palaeoclimate evolution during the last glacial cycle. One of the main results of this study is the alternation of humid and dry phases as a characteristic of the climate evolution during the Lateglacial. Additionally, the study suggests an important role of the increased flow from the Pyrenean rivers during deglaciation in the hydrological balance of the Central Ebro Basin. It is found that the Early Holocene is the wettest period over the sequence studied contrasting with the arid Middle Holocene interval, which is frequently absent as a result of intense aeolian erosive processes. Although anthropogenic activity partially masks the climate signal from the palynological data in the uppermost part of the sequences studied, there are some sedimentological evidences for a climate change during the last 2000 years resulting in a recovery of average saline lake levels in the Central Ebro Basin.

Keywords: Playa-lake systems, Palynology, Sedimentology, Palaeohydrological fluctuations, Vegetation cover.

1. Introduction

The Mediterranean region of the Iberian Peninsula is one of the territories with the greatest biodiversity in southern Europe and, consequently, is more exposed to significant decline in terms of future global warming (IPCC: Houghton et al., 2001). This area constitutes the northernmost semi-arid region in Europe and it is remarkable from an ecological point of view due to the high variability in ecotones, including Euro-Siberian to Mediterranean ecosystems, as a result of the strong topographic climatic and geographic gradients from the highest Pyrenees peaks (> 3000 m a.s.l.) and the lowlands of the Central Ebro Basin (~ 400 m a.s.l.). Its uniqueness has also been well documented during the last Glacial cycle in relation to both northern Europe and eastern Mediterranean regions (Prentice et al., 1992, 1998; Harrison et al., 1993, 1996; Yu and Harrison, 1995; Cheddadi et al., 1997; Valero-Garcés et al., 2000a, 2004; González-Sampériz et al., 2005). Particularly remarkable is the evidence of numerous abrupt and rapid arid/humid transitions throughout the last glacial cycle that highlight the complex palaeohydrological evolution of North-eastern Spain (Valero-Garcés et al., 1998, 2000a).

The location of the Iberian Peninsula at the southernmost position of the westerly winds and its simultaneous dependence on both the North Atlantic and sub-tropical climate may explain its present climatic singularity (Sumner et al., 2001) and distinctive response to glacial and Holocene global climatic changes. Additionally, strong climatic and geographic gradients and topographic contrasts have contributed to this region's marked physiographic heterogeneity, thus making the reconstruction of the palaeoclimate variability for the area particularly challenging. Given the long history of human activities in North-eastern Spain (Utrilla and Rodanés, 1997; Valero-Garcés et al., 2000b), it is not easy to discern between cultural and natural landscapes, adding greater complexity to the palaeoenvironmental reconstruction. In fact, climate scenarios modelled for European areas usually do not succeed when considering the reconstruction of vegetation cover or lake levels in the Mediterranean region of Spain (Harrison et al., 1996; Prentice et al., 1998; Davis et al., 2003).

Consequently, more records from hydrologically sensitive areas are necessary to better understand the disimilarities and to reconstruct a coherent history of effective moisture fluctuations for the North-eastern regions of the Iberian Peninsula during the last glacial cycle. However, most palaeoclimate records in this region are located in high mountains or in coastal areas and very few sites are from low-elevation areas in the inner part of Spain (Davis, 1994; Taylor et al., 1998; Dorado-Valiño et al., 1999; González-Sampériz, 2004) and even fewer records spanning since the Lateglacial period are available (Valero-Garcés et al., 2000a, 2004; González-Sampériz et al., 2005). Archaeological sites and geomorphological records have provided some reconstructions, although the records are highly fragmented (Peña-Monné et al., 1996; Gutiérrez-Elorza et al., 2002; González-Sampériz, 2004). The only available lacustrine records from the lowlands of North-eastern Spain are from saline lakes (Fig. 1). The semi-arid climate and the presence of large endorheic regions have favoured the development of a large number of small saline lakes in the lowlands of the Central Ebro Basin (NE Spain) (Ibañez, 1975; Castañeda, 2002). However, this type of record presents several well-known problems (i.e., short sequences, few fertile layers in palynological terms, lack of sedimentary continuity, reworking and contamination for radiocarbon dating, complexity of evaporitic systems, poor preservation of biologic indicators, etc.,) that must be considered with caution in any palaeoenvironmental study.

Several studies have shown the potential of these Ebro Basin playa-lake records (Fig.1 and Table 2) as palaeoclimate archives (Pueyo-Mur, 1979; Pueyo-Mur and Inglès-Urpinell, 1987; Pérez-Obiol and Roure, 1990; Stevenson et al., 1991; Davis, 1994; Burjachs et al., 1996; Schütt, 1998; Giralt et al., 1999; Valero-Garcés et al., 2000a,b, 2004; Roc et al., 2002; Rodó et al., 2002; Moreno et al., 2004; González-Sampériz et al., 2005). To date, the results obtained from the Central Ebro Basin indicate that more humid conditions were established during some periods of the Lateglacial, as was already suggested by the location of vegetation refuge areas in the same region (Valero-Garcés et al., 2000a; González-Sampériz et al., 2004). The results are coherent with the hypothesis that, at least for some periods, the ice-age climate of the western Mediterranean was characterized by cold winters, with relatively higher effective moisture (precipitation minus evaporation ratio) and summer droughts (i.e., Harrison et al., 1996). Increased flow from the Pyrenean rivers during the deglaciation could also have played a significant role in the palaeohydrological cycle in the Central Ebro Basin during the Lateglacial and the Early Holocene (Valero-Garcés et al., 2004; González-Sampériz et al., 2005). Moreover, the usual lack of Middle Holocene deposits suggests an intensification of deflation processes pointing to intense arid conditions during that interval. Several sites in the Ebro Basin highlight an increase in the effective moisture during the last few centuries (Davis, 1994).

Unfortunately, all these records are somehow incomplete, and a global study describing the climate variability in the Central Ebro Basin (north-eastern Spain) since the Lateglacial period is still lacking. In addition, most records are mainly based on pollen studies and lack the analysis of moisture fluctuations from other palaeoenvironmental indicators. Hence, both a multi-proxy approach and a regional review of the playa-lake records studied are required to take into consideration the observed regional heterogeneity and to enable it to be represented in global palaeobiogeographical models. The essential goal of this study is to provide a comprehensive picture of the palaeoclimate evolution of the Central Ebro region for the last glacial cycle to improve our understanding of the palaeoenvironmental variability in North-eastern Iberia.

We describe in this paper two new sequences from saline lakes located in the Los Monegros region (Central Ebro Basin, north-eastern Spain): La Playa and La Salineta records. The combined analysis of pollen, sedimentary facies, geochemistry, stable isotopes and ^{14}C dating allow us to reconstruct the hydrological fluctuations and the variations in the vegetation cover since the Lateglacial. Additionally, we provide a review of the available data in the Central Ebro Basin to characterize the water balance evolution in playa-lake systems and the regional vegetation during the Lateglacial, the Early, the Middle and the Recent Holocene periods.

2. Description of the area and sites studied

2.1. Present-day climate

The Central Ebro Basin is the northernmost area of truly semi-arid climate in Europe. The climate is Mediterranean with a strong continental influence characterized by very hot summers, cold and dry winters, and low rainfall (300-350 mm yr^{-1}) due to the rain-shadow effect of the Iberian Range (Capel Molina, 1981; García-Vera, 1996). The high insolation and evapotranspiration (1000 - 1500 mm/year), and the prevalence of strong dry NW winds also contribute to an annual water deficit, especially during summer. The seasonal pattern of precipitation in the central and eastern regions of Iberia is not typically Mediterranean, but bi-modal, with the highest rainfall in spring and autumn and the lowest in winter and summer (Rodó et al., 1997). The mid-winter period is particularly important for groundwater recharge because this is the time when low temperatures restrict evapotranspiration (García-Vera, 1996).

2.2. Vegetation formations

The present landscape in the Central Ebro Basin is a steppe, mostly dedicated to agriculture. Vegetation cover is less than 50% and dominated by cereal crops and steppe taxa, leaving small patches of open parkland dominated by *Pinus halepensis, Quercus coccifera* and *Juniperus thurifera*, and/or a dense shrubland with *Rhamnus lycioides, Rosmarinus officinalis, Globularia alypum, Ephedra nebrodensis, Ephedra fragilis, Thymelaea tinctoria, Pistacia lentiscus, Phillyrea angustifolia, Brachypodium ramosum* etc., depending on topography and soil type. Mesophytes are here restricted to particularly humid canyons, as in the Sierra de Alcubierre near Zaragoza (Blanco et al., 1997). Nitrophylous and gypsophylous plants are abundant: *Salsola vermiculata, Atriplex halimus, Artemisia herba-alba, Peganum harmala, Ferula communis, Malcomia africana*, *Marrubium alysoon*, *Ononis tridentata, Gypsophila hispanica, Helianthemum squamatum, Cistus clusii,* etc. The margins of the saline lakes are dominated by halophytic plant communities, i.e., *Salicornia* and other taxa of the *Suaedetum brevifoliae* association (Braun-Blanquet and de Bolòs, 1957; Peinado-Lorca and Rivas-Martínez, 1987).

The long history of human occupation in the area has contributed to the transformation of the landscape since the Neolithic (Davis, 1994; Utrilla and Rodanés, 1997; Gutiérrez-Elorza and Peña-Monné, 1998; González-Sampériz, 2004), resulting in deforestation practices to agriculture expansion (mainly cereal crops) and pastoralism activities. So, an open steppe landscape with an important ruderal and nitrophylous component is developed and the forest and shrub formations are located only in isolated small patches.

2.3. Geological and Hydrological setting

The Ebro Basin is a large depression surrounded by the Pyrenees to the north, the Iberian Range from the west to the southeast, and the Catalan Ranges to the east. It is mostly filled with Tertiary continental deposits mainly composed of limestones, marls and gypsum formations (IGME, 1971, Ramírez, 1997) (Fig. 1). Most lake depressions in the Central Ebro Basin occur in groups, particularly on the central plateau of Los Monegros (about 100, 60 of them flooded every year) and in the Bajo Aragón area (Ibáñez, 1975; Pueyo-Mur, 1979; García-Vera, 1996). The genesis of the depressions has been related to dissolution of the Tertiary evaporite substrate, preferential water circulation through fault lines, differential erosion, and deflation (Benito et al., 1998; Sánchez-Navarro et al., 1998). Some depressions in the Ebro Basin originated during the Lower and Middle Pleistocene (Benito et al., 1998). However, geomorphologic criteria and the presence of *Elephas meridionalis* indicate that many depressions also formed during the Upper Pleistocene (van Zuidam, 1980).

The Monegros plateau is a topographically elevated area, bounded to the South by the Ebro River and characterized by its tabular landforms and endorheic character. Two main aquifers have been defined in the Late Oligocene and early Miocene evaporite-bearing formations underlying the hydrologically-closed basin of Los Monegros (García-Vera, 1996). Stable isotope data suggest that groundwater, rainwater, and runoff (estimated at less than 10% of the rainfall) are the main water input to the lakes (Samper-Calvete and García-Vera, 1998). Groundwater recharge takes place at the interfluves and highlands and its range is estimated from 20-45 mm/yr. Three sedimentary units have been described in the Los Monegros plateau (Samper-Calvete and García-Vera, 1998). Most of the lakes are located in the Intermediate unit (Lower Miocene), and only a few (La Salineta among others) occur in the Upper lacustrine unit (Upper Miocene – “Aragoniense”), north of the main Los Monegros endorheic system. Both aquifers are fed by precipitation and the lower one supplies most of the water to the different playa-lakes. However, playa-lakes located in the Upper unit, such as La Salineta, would also receive water discharges from the upper aquifer (Samper-Calvete and García-Vera, 1998). Field and satellite observations carried out during several years (1985-2000) confirm that La Salineta and La Playa are among the playa-lakes with a longer wet cycle (more than six months a year)

(Castañeda, 2002). However, the high variability over the years studied is closely related to the fluctuations in the precipitation pattern. La Salineta is essentially the most sensitive playa-lake in the Los Monegros basin to rainfall variability. We have selected two lakes in the area: La Salineta because of its unique hydrology, and La Playa, which at 1.72 km^2, is the largest playa-lake in the Los Monegros area.

2.3.1. La Playa

La Playa lake (340 m a.s.l., 41º25’00"N, 0º11'10"W) is located near the town of Bujaraloz (Zaragoza). Available limnometric data (Castañeda, 2002) show a maximum water depth of 51 cm during winter, and complete desiccation during summer. The brines are of (Cl^-)-$(SO_4^{=})$-(Na^+)-(Mg^{2+}) type and undergo strong seasonal oscillations in concentration because of groundwater input, evaporation and progressive salt precipitation (Pueyo-Mur, 1979). Present-day sediments are calcitic, organic-rich mud with abundant gypsum microcrystals and without the halite crust characteristic of other playa-lakes in the area.

A detailed geomorphological study showed three stepped levels of lacustrine terraces and a set of *yardangs* associated to the lacustrine terraces (Gutiérrez-Elorza et al., 2002). The oldest terrace (T3) is located at 7.5 m above the modern lake floor, the intermediate T2 at 3.5-3 m has the greatest extent, and the youngest one (T1) is located at 0.3-0.5 m. Although the terraces are not dated, they represent periods of high lake level and posterior incision.

2.3.2. La Salineta

La Salineta lake (325 m a.s.l., 41°28’55”N, 0°09’30’’W), located 1.5 km south of the town of Bujaraloz (Zaragoza), is a seasonal playa-lake that holds water longer than most of the other lakes in the Los Monegros area. Water chemistry is dominated by sodium-chloride and salinities can reach values up to 200 g/l. A thick, soft and wet halite crust covers the surface during the summer. Groundwater is typically of magnesium-sulphate or calcium–sulphate type with an average TDS of 5 g/l. Hydrological modelling suggests that the upper aquifer discharges one third of the total recharge (5822 m^3/yr) into La Salineta lake, and that the lower aquifer contributes with waters with long residence times and high chloride and sodium contents. This hydrology explains both the perennial nature of the lake and the presence of the thickest salt layers (Samper-Calvete and García-Vera, 1998).

The modern La Salineta lake (20 ha surface) is inset within a much larger palaeolake, whose deposits have been eroded and form cliffs up to 4 m surrounding the present lake. The cliffs are well developed at the windward SE end of the basin. The palaeolake sediment surface sits almost level with the rolling plains of the steppe and it is visible over the ploughed ground as an area of gray lacustrine clays. In some short section, remains of small cliff (1 m high) mark the boundary of the maximum extent of the lake.

3. Material and methods

A multi-proxy study combining pollen, sedimentary facies, elemental and stable isotope geochemistry was applied to two new saline lake sequences located in the Los Monegros region (Central Ebro Basin, North-eastern Spain): La Playa and La Salineta lakes (Fig. 1). A 162 cm long core was collected in 2002 with a modified 5-cm diameter Livingstone corer in La Playa lake, close to the western margin. The Miocene bedrock was reached at the bottom of the sequence. The same method was employed to retrieve a 87 cm long core from the central area of La Salineta lake in July 2004. However, the bedrock was not reached in this saline lake.

Both sediment cores were split, described and sampled for grain-size analyses, carbonate and organic matter content, mineralogical and elemental composition and stable isotope every 2 to 10 cm. In addition, samples for pollen analyses were obtained every 10 cm in both sequences. Sedimentary facies were identified based on colour, lithology, and sedimentological structures and textures.

Samples for grain size analyses were treated with 10% hydrogen peroxide in a water-bath at 80ºC to eliminate the organic matter; then, a dispersant agent was added and ultrasound treatment was used prior to measurement. Gypsum crystals were not removed. Finally, grain size of the samples was determined using a Coulter laser size analyzer. Total Carbon (TC) and Total Inorganic Carbon (TIC) contents were determined by a UIC model 5011 CO_2 Coulometer for La Salineta samples while organic matter content was determined by loss-on-ignition analyses at 450ºC and carbonate content with a Barahona calcimeter for La Playa samples. X-ray diffraction (XRD) analyses were performed using an automatic Siemens D-500 x-ray diffractometer: Cu kα40 kV, 30 mA, and graphite monochromator. Identification and quantification of the different mineralogical species present in the crystalline fraction were carried out following a standard procedure (Chung, 1974). Accordingly, the intensity of the main peak of every mineral (in counts) obtained with *Macdiff* software has been corrected and used for quantification procedures. After acid digestion of the samples, analyses for the main elemental composition were performed by atomic emission spectrometry using an inductively coupled plasma ICP-OES with solid state detector (Perkin Elmer Optima 3200 DV). Oxygen and carbon isotopic compositions were analysed in bulk-sediment samples of La Salineta core following standard procedures, and the isotopic values are reported in the conventional delta notation relative to the PDB standard. The $\delta^{13}C$ values of organic matter were measured after carbonate removal with HCl 1:1. Analytical precision was better than 0.1‰ for $\delta^{18}O$ and $\delta^{13}C$ in carbonates and organic matter.

Pollen analysis follows the standard procedure described by Moore et al. (1991) and Dupré (1992), using the classical chemical treatment by HF, HCl and KOH with mineral separation in heavy liquid (Thoulet: density 2.0). Exotic *Lycopodium clavatum* tablets (Stockmarr, 1971) of a known concentration were added to estimate the pollen concentration and a minimum of 250 pollen grains for slide were counted. Results are expressed here in relative percentages, excluding spores and hydro-hygrophytes from the pollen sum. The diagrams were constructed using the *Psimpoll* (Bennet, 2002) and *Corel Draw* programmes. Pollen zones have been defined following the main vegetation trends and accordingly to sedimentological criteria.

The chronology of these sequences is hampered by the absence of terrestrial remains and the very low organic matter content. Due to this difficulty, the AMS ^{14}C dates have been obtained using pollen concentrates, an efficient technique when terrestrial macro-rests are scarce (Brown et al., 1989; Vandergoes and Prior, 2003; González-Sampériz et al., 2006). A sample at 80 cm depth in La Playa and a sample at 65-67 cm depth in La Salineta were dated (8.773 ± 73 ^{14}C yr BP and 2081 ± 38 ^{14}C yr BP, respectively, Table 1). These dates were calibrated using

CALIB 5.1 software and the INTCAL04 curve (Reimer et al., 2004), and the mid-point of 95.4% (2σ probability interval) was selected. Although two pollen samples near the base (at 160 and 140 cm depth) from La Playa core were concentrated and analyzed by AMS dating, no results were obtained because organic carbon content was too low (Table 1).

4. Results and interpretation

4.1. The sediment record

Playa lake core sediments are composed of gypsum, carbonates, clays and quartz. Gypsum is the only evaporitic mineral that is preserved; most of the others are seasonally dissolved during rainy periods (Pueyo-Mur and Inglès-Urpinell, 1987). Both of the cores studied are composed of decimeter-bedded, massive, greenish and gray, gypsum-rich carbonatic sediments with several intercalated quartz-rich silts and evaporitic (halite, gypsum and other sulphates) layers. Seven sedimentary facies have been identified after integration of visual description, microscopic observation, grain-size, and sediment composition analyses (Table 2). Facies 1-3 are massive carbonatic mud (carbonate percentage between 5 and 30%) with variable mineral composition (calcite or dolomite) and presence of gypsum as micro and macro-crystals (usually as lenticular crystals of about 100 μm). Facies 4 represents a higher detrital influence, as denoted by the increase in clay minerals and quartz. Facies 5 is a laminated organic-rich mud only present in the uppermost units of La Salineta core. Facies 6 and 7 are evaporite facies with different colour, texture and composition. Facies are described in detail in Table 2.

In general, grain-size in these saline lake sediments reflects the size of the gypsum crystals, providing some additional indication of their genesis. The abundance of clay minerals and quartz is taken as a marker of increased detrital input, mainly caused by aeolian activity in these dry areas that are highly exposed to deflation. Coherently, both Al and Fe, as elements that form part of clay minerals and oxides, are also indicative of detrital input to the lake basins. Although variable throught time, runoff processes are less important in this sedimentary context due to the flat topography and the arid climate. Due to the abundance of limestones in the Tertiary continental deposits that constitute this region, detrital calcite is a common component of the lake sediments. Increasing calcite content associated with higher quartz or clay minerals contents is interpreted as a reflection of higher detrital input to the lake. Higher calcite content, without increasing quartz or clay contents, is interpreted as authigenic in origin. Furthermore, the presence of dolomite since Miocene limestones have a low Mg content (1.6% MgCO3) and dolomite-and magnesite-rich facies are minor (Quirantes, 1978; Mata et al., 1988), is a proxy for more concentrated waters with a high Mg/Ca ratio that usually occur during dry periods. This is also supported by the isotopical study carried out on the dolomite crystals formed in the nearby Salada Mediana (Valero-Garcés et al., 2000c). A complete study of the processes that lead to dolomite formation in the Los Monegros saline lakes is now in progress but SEM morphologies and preliminary stable isotope data point to sinsedimentary or early diagenesis processes (Calvo et al., 2005).

Gypsum crystals are the result of i) direct precipitation from concentrated lake waters as a response to seasonal evolution or ii) precipitation from interstitial waters due to evaporative pumping or other early diagenetic processes (Pueyo-Mur, 1979; Pueyo-Mur and Inglès-Urpinell, 1987). Both processes lead to the formation of lenticular gypsum crystals, as those observed in the cores in some intervals. Therefore, it is not possible to discern only from the observed morphology primary minerals (precipitated from lake waters) from those formed during the early stages of diagenesis. However, total absence of gypsum nodules, gypsum-crusts or cements discards late diagenesis as a main origin for the gypsum occurrences in La Playa and La Salineta.

A black, sapropelic layer generally occurs below the evaporite crust in these saline lakes (Pueyo-Mur, 1979), indicating a good preservation of the organic matter and activity of bacteria under reducing conditions. Algal mats are also frequent (Pueyo-Mur, 1979; Valero-Garcés et al., 2000a) although their preservation potential seems to be reduced. As biological producers change, increased organic productivity might be related to periods of increased salinity (ref) and also to freshwater stages. (ref). Therefore, intervals with higher organic matter content, in the absence of other indicators, cannot be directly related to higher lake levels in wetter climates (a climatic scenario that usually favours both higher biological productivity and better preservation).

4.1.1. The sediment record of La Playa lake

The 162 cm long core from La Playa saline lake has been divided in five sedimentological units (P1 to P5) that are organized in three sedimentary sequences (Fig. 2): Sequence P-I would correspond to Unit P1; Sequence P-II would include Unit P3 and P2 and, finally, Units P5 and P4 would conform the Sequence P-III. The three sequences are bounded by erosive surface that represent *hiati* probably caused by periods with increased desiccation and aeolian erosion.

Unit P5 is divided in two subunits: (1) Subunit P5b (Facies 7 and 3) overlies the Miocene substratum and represents the first lacustrine sedimentation that incorporates some of the gypsum fragments reworked from the base; and (2) Subunit P5a (Facies 2) composed of massive dolomitic mud with the highest detrital content of the whole sequence (clay minerals and quartz) and maximum values of Al and Fe. These features indicate an important aeolian contribution and, additionally, concentrated waters to precipitate dolomite during Subunit P5a. Unit P4 is characterized by the alternation of Facies 7 and 2, the increasing content in gypsum, and generally low organic matter contents. This increment in the gypsum context suggests a change towards drier conditions and even more concentrated waters than in the previous unit. Therefore, over the Miocene gypsum substratum, the sediments of Sequence P-III were deposited in an ephemeral sulphate-carbonate saline lake system undergoing less concentrated (carbonate-dominated; Unit P5a) and more concentrated (gypsum-dominated; Unit P4) brine stages.

An abrupt increase in calcite content is detected at the onset of Sequence P-II after deposition of the massive gypsum-rich interval. The bottom part of Unit P3 (Subunit P3b) is characterized by high quartz, clay minerals and calcite contents, and high values of Al and Fe (Facies 4). Subunit P3a is composed by Facies 1 characterized by low gypsum abundance, probably indicating less concentrated waters in a scenario with more flooded stages in the playa-lakes. On the contrary, Unit P2 is depleted in carbonates and both microscopic observations and grain size indicate the presence of large gypsum crystals, up to 2-3 mm (Facies 3). Sequence P-II would represent deposition in an ephemeral playa-lake complex where more humid intervals alternate with arid events when the saline lake was probably dry during long periods. The driest scenario is represented by the beginning of the sequence (Subunit P3b) where the synchronous increase in quartz, calcite and clays (together with Al and Fe peaks) suggest that deflation was very significant at that time, pointing to the dominance of dry areas and stronger winds. A marked change towards more humid conditions is observed in Subunit P3a where decreasing detrital calcite and quartz contents could indicate lower salinity compared to the previous interval. This system would be coherent with the characteristic wetter scenario of the Early Holocene. The presence of gypsum-rich sediments along Unit P2 may indicate a tendency towards increased aridity, may be related to the transition towards the Middle Holocene.

Finally, Sequence P-I (Unit P1) is composed by massive, brownish-gray mud with abundant gypsum micro-crystals (Facies 1). It is noticeable the enrichment in Na (and halite) towards the top, marking the preservation of halite minerals in recent sediments of an ephemeral saline lake. Calcite content increases (not related to quartz-rich sediments), suggesting a new stage of more diluted waters that has been observed in other saline lakes in the Central Ebro Basin during recent times (Davis, 1994).

The interpretation of this sedimentary record highlight a depositional history characterized by the evolution from a carbonate-producing lake (Units P5, P4 and P3) towards a more sulphate-producing saline lake (Unit P2), ending with the present-day ephemeral saline lake system (Unit P1).

4.1.2. The sediment record of La Salineta lake

Five sedimentary units (S1 to S5) have been defined in the 87 cm long core from La Salineta based on sedimentological, mineralogical and geochemical criteria (Fig. 3, Table 2). These units can be organized in three sequences bounded by observed erosional *hiati*. The process triggering the formation of these *hiati* would be similar to that postulated for La Playa sequence: long dry periods with increased desiccation and posterior aeolian erosion. Unit S5 and S4 (Sequence S-III) are both characterized by the presence of massive, greenish gray dolomitic mud (Facies 3 and 2). Gypsum is almost absent except as isolated cm-long crystals at the base of the sequence. Dolomite percentages reach 60% of the crystalline fraction. The high content in clays and quartz in these two units could indicate stronger aeolian contribution. Gypsum and halite content increases right after Unit S4 suggesting the establishment of a sulphate-chloride saline system. Sequence S-II comprises Unit S3 and it is composed of massive, dark to light gray carbonatic mud with abundant mm-sized gypsum crystals (Facies 1). The occurrence of mm-thick evaporite (mainly halite) crusts and detrital (higher quartz and clay minerals contents) levels, points to significant changes in the lake's water balance. Units S2 and S1 conforms the Sequence S-I. Unit S2 is formed by massive, to faintly laminated, black to dark gray organic-rich mud likely indicating higher productivity or better preservation of the organic matter (Facies 5). Unit S1 constitutes the present-day saline crust composed by mirabilite, bloedite, halite and other sulphates that have not been quantified. It has an intermediate black level with the highest values of organic matter in the core.

The isotopic study was carried out on the bulk carbonate fraction without separating calcite from dolomite. However, XRD results clearly indicate that calcite is the dominant carbonate mineral and almost no dolomite is present (except for Sequence S-III, Fig. 3). Therefore, the isotopic values would likely reflect variations in the isotopic composition of calcite. In the upper units S1, S2 and S3 values of $\delta^{18}O$ are rather constant and similar to the calcite values of the nearby Salada Mediana (Valero-Garcés et al., 2000c). The similar isotopic compositions may reflect a detrital origin of the calcite from the same source through the sequence, or similar hydrological conditions for calcite precipitation in the lake waters. However, considering that most calcite is detrital, and that limestones from the Los Monegros area have a range of $\delta^{18}O$ values among –9 and 0 ‰ and a $\delta^{13}C$ of –5 to –2‰ (Arenas et al., 1997; Valero-Garcés et al., 2000c), the isotopic composition is likely to mostly reflect the composition of detrital calcite. Only in the lower sequence (Sequence S-III), the enriched $\delta^{18}O$ values would reflect the presence of authigenic dolomite, similarly as in Salada Mediana. (Valero-Garcés et al., 2000c). The $\delta^{13}C$ profile in bulk organic matter has relatively higher values than those in the longer La Salineta Core-Section (-27.2 to –23.2‰) (Valero-Garcés et al., 2004). In other saline lakes in the Ebro Basin, cyanobacterial mats have considerably heavier values (between –12.8‰ and –11.2‰) than terrestrial halophytic plants (between – 24 to –26‰ PDB) (Valero-Garcés et al., 2000c). The $\delta^{13}C_{org}$ curve shows three main intervals that are consistent with the sequences previously defined: Sequence S-III (more detrital and dolomite-bearing) shows the lowest values, pointing to a dominance of halophytic plants in a frequently desiccated lake. The lack of pollen data due to bad pollen preservation in this lower part of La Salineta sequence prevents a conclusive confirmation of this interpretation, although it suggests that poor pollen preservation occurred during desiccation phases (Fig. 3). The intermediate units S3 and S2 are characterized by a maintained trend towards higher values suggesting less terrestrial halophytic plants and an organic fraction dominated by lacustrine material. The pattern towards more negative values characterizes the upper unit (saline crust).

Both the sedimentological and stable isotopic data allow interpreting the depositional environment associated to the three sedimentary sequences in La Salineta core. Sequence S-III represents the record of a dolomite-producing lake system characterized by very frequent desiccation periods. The positive $\delta^{18}O$ values point to intense evaporative processes and dolomite formation probably linked to a more arid climate. Aeolian transport may have been important as reflected by the maximum values of clays and quartz while halophytic terrestrial plants would be dominant in the area as suggested by $\delta^{13}C_{org}$ values (-26‰). Sequence S-II would start at about 2000 cal yr BP corresponding to Unit S3. This interval would represent the deposit in an ephemeral playa-lake complex where gypsum-rich sediments point to a different brine composition likely indicating higher salinity. Finally, Sequence S-I begins with a sharp sedimentary change, suggesting that an unconformity formed after deposition of massive gypsum-rich interval (Unit S3). The first sequence corresponds to Units S2 and S1, sediments that were deposited during the present-day ephemeral saline lake. This is characterized by the higher content of the more soluble sulphates and the dark-gray, banded to black laminated nature of the sediments.

4.2. Palynological data

The study of pollen records along the Central Ebro Basin to improve our understanding of environmental changes is limited to playa-lake systems as they are the only existing deposits in this semi-arid region (González-Sampériz, 2004). The main regional and local features and the evolution of the vegetation cover can be deduced from the palynological records. Additionally, hydrological fluctuations of saline lakes could be inferred from the presence and abundance of aquatic plants. In this section we present new pollen data from two saline lakes from the Los Monegros region (La Playa and La Salineta). A complex mosaic landscape with steppe formations, coniferous forest and Mediterranean shrubs, close to mesothermophytes refuge areas has been previously proposed for the Lateglacial and Holocene in the Central Ebro Basin (Pérez-Obiol and Roure, 1990; Stevenson et al., 1991; Davis, 1994; Burjachs et al., 1996; Valero-Garcés et al., 2000a, b, 2004; Roc et al., 2002; González-Sampériz et al., 2005). In addition, fluctuations in the abundance of herbaceous halophytic plants in relation to aquatic plants help to highlight several periods with different moisture balance characteristics (from desiccation periods during arid conditions to higher water levels during more humid climates or particular edaphic conditions). To illustrate this relationship, the opposite variations of steppe taxa (*Artemisia*) and halophytes *versus* aquatic plants from La Playa and La Salineta records are represented in Fig. 4. Anthropogenic influences in more recent periods are also detected in the palynological spectra by the presence of some taxa, such *Cerealia* type and *Olea*.

4.2.1. Pollen sequence of La Playa record

La Playa record is chronologically one of the oldest sequences of the Central Ebro Basin, together with La Salineta Core-Section from Valero-Garcés et al. (2004) and Salada Mediana (Valero-Garcés et al., 2000a). Although this record is dated as Early Holocene at 80 cm depth (from the 162 cm long core), sedimentological and palynological results point to the presence of Lateglacial sediments at the base of the sequence. The increase of *Olea* and the presence of *Cerealia* type at the top of the sequence confirm that the upper 30 cm (sedimentary Sequence P-I) represent some undetermined moment during the last 2000 years BP. Therefore, the *hiatus* observed among Sequences P-II and P-I (Fig. 2), may correspond to, at least, the eroded Middle Holocene sediments. Although the pollen sequence of La Playa was studied previously by other authors (Pérez-Obiol and Roure, 1990; Stevenson et al., 1991), the inexistence of a chronological control and some taxonomic differences (*Juniperus versus* microspores, *Carpinus/Ostrya versus Myriophyllum spicatum*) prevent a good correlation with the record presented here. In this pollen sequence, as in all records from NE Spain, *Pinus* is the dominant arboreal taxum throughout the whole record (González-Sampériz et al., 2005). The rest of the AP group (*Juniperus*, evergreen and deciduous *Quercus*, mesophytes and thermophytes) usually represents a minor percentage. The steppe component of the landscape is mainly formed by *Artemisia, Ephedra distachya* and *Ephedra fragilis* types, Chenopodiaceae, *Lygeum spartum*, Compositae, *Plantago* and *Urticaceae*. The evolution in composition and proportion of the hydro-hygrophytes and the ratio with halophytes (Chenopodiaceae) reflects the water balance in the basin (Fig. 4).

Samples from the bottom of the core (sedimentary Units P4 and P5) were palynologically sterile likely due to the poor pollen preservation as the result of oxidation processes during aerial exposure in dry periods. Four pollen zones (PZ) have been defined for the rest of the sequence (Fig. 5). In PZ-P4 (120-110 cm depth), the spectra show the most arid and cool/cold period of the whole sequence, with the minor proportion of AP (around 40%) and the maximum of *Artemisia* (20%) and *Ephedra distachya* type. It corresponds to the upper part of the sedimentary Unit P3b, interpreted as the driest period from sedimentological and geochemical indicators (Fig. 2). This evidence is supported by: i) the mentioned high percentages of steppe taxa (*Artemisia, Ephedra*, *Plantago,* Chenopodiaceae, Asteroideae and Urticaceae); ii) the presence of *Abies* at 120 cm depth, unique in the record, and coherent with other Lateglacial pollen sequences in the region (González-Sampériz, 2004); iii) the low values of pine and other arboreal curves; and iv) the minor proportions in the sequence of some significant aquatic taxa as *Myriophyllum* and *Ruppia*. Nevertheless, Chenopodiaceae values and the low but still presence of these two last mentioned aquatic taxa indicate that La Playa (the largest playa-lake basin in the Central Ebro Basin) still functioned as an ephemeral saline lake and the groundwater levels remained close to the surface.

In PZ-P3 (110-80 cm depth), the AP proportion is still low but increases towards the limit between PZ-P3 and PZ-P2 reaching up to 60%. It corresponds with the sedimentary Unit P3a and the general tendency of pollen curves indicates a decrease in arid conditions. The lower percentages of steppe taxa and the slight increment in aquatic plants, mainly *Myriophyllum*, are coherent with the more humid conditions associated with the Early Holocene in the region (Montserrat, 1992; Davis, 1994; Stevenson, 2000; González-Sampériz, 2004). The PZ-P2 (80-30 cm depth) coincides with the sedimentary Unit P2 and it is characterized by fluctuations mainly in the pine, AP, Poaceae, *Artemisia, Lygeum spartum, Rumex*, Urticaceae, Boraginaceae, Lamiaceae, Cyperaceae and *Myriophyllum*'s curves. Towards the top of this pollen zone, *Artemisia* and *Ephedra distachya* type almost disappear, *Juniperus* and *Ephedra fragilis* type decrease, *Ruppia* remains present and *Myriophyllum* and *Potamogeton* increase. All these evidences indicate the reduction of xeric conditions and the record of the most humid period in the sequence, marked by the highest proportion of *Myriophyllum*. Sedimentologically this interval corresponds to a clear increase in organic matter content at 55 to 35 cm depth. Finally, at the top of the La Playa record (PZ-P1, 30 uppermost cm; sedimentary Unit P1) the anthropogenic influence in the landscape is evidenced by taxa related to agriculture and grazing activities (ruderals, *Cerealia* type presence and *Olea* expansion, new increase of *Artemisia*). The hydro-hygrophytic pollen group is the most varied in composition of the sequence (Cyperaceae, *Typha, Sparganium, Ruppia, Potamogeton, Myriophyllum*, etc.,) perhaps in relation to better preservation of pollen grains during present-day conditions.

The problematic chronology of the three previously defined sequences due to the scarce terrestrial organic remains together with the presence of discontinuities in the record makes it very difficult to assign a time period to each sequence. However, comparison with other nearby records (Salada Mediana, Valero-Garcés et al., 2000a; La Salineta Core-Section, Valero-Garcés et al., 2004) and the results obtained from the palynological study enable us to define these three different periods. Sequence P-III may correspond to Lateglacial; Sequence P-II starts with an arid period followed by a more humid Early Holocene, and probably, finishes with the beginning of the transition to the more arid Middle Holocene; and Sequence P-I possibly represents the resume of the sedimentation after the medieval times and modern times. Therefore, La Playa core indicates large climatic and moisture fluctuations during the Late Glacial and Holocene periods in the Central Ebro Valley. Despite the absence of a chronology, the three sequences described may correspond to the three terraces defined by Gutiérrez-Elorza et al. (2002). These terraces would represent three stages of lacustrine deposition and posterior incision of the playa-lake system.

4.2.2. Pollen sequence of La Salineta record

La Salineta record covers the last 2000 years and the pollen sequence indicates a semiarid-Mediterranean vegetation cover, similar to current formations of the Central Ebro Basin (Fig. 6). Throughout the whole sequence, *Pinus* is the main arboreal component, next to *Juniperus* and evergreen *Quercus* with lower percentages. Thermophylous shrubs compose the rest of the AP group with some mesophytes (*Salix, Corylus, Alnus, Populus*) and *Tamarix,* controlled by soil-moisture conditions. The increase in *Olea* at the top of the sequence corresponds to the increase in olive cultivation since the Middle Ages and particularly after the 18th century (Davis, 1994).

Pollen samples from the base of the sequence (sedimentary Units S5 and S4) were sterile (Fig. 6). Highly oxidizing conditions required to destroy the pollen are consistent with frequent desiccation periods in a dolomite-producing lake system. When these desiccation periods are prolonged in time, the associated aeolian erosion over dry lake surfaces could even produce a sedimentary *hiatus*, as the previously observed in the transition from sedimentary Sequences S-III to S-II.

In the rest of the sequence (77 cm long), four pollen zones are defined. PZ-S4, PZ-S3 and PZ-S2 correspond to the sedimentary Unit S3. The PZ-S4 (77-55 cm depth) is characterized by the highest proportion of *Juniperus* (until 20%), and increasing values of *Artemisia*. These assemblages indicate an arid climate, confirmed by the presence of Chenopodiaceae, *Lygeum spartum*, Compositae (Cichorioideae, Asteroideae and Carduae), *Plantago, Rumex* or Urticaceae among others, and low proportions of aquatic taxa. In PZ-S3 (55-35 cm depth) the AP values increase because the increase of *Pinus* and some expansion of evergreen *Quercus* and *Tamarix* (the latter is usually observed around playa-lake basins). *Cerealia* type and ruderals percentages remain constant or even decrease, and halophytic taxa (mainly Chenopodiaceae) and junipers are in low amounts, according to less arid conditions or some decrease in anthropogenic influences and activities around the lake. This situation changes in PZ-S2 (35-15 cm depth) where pines, and consequently the AP abundance, decrease. Abrupt changes in pollen content and in isotopic, geochemical and sedimentological indicators (i.e., sharp change of facies, dramatic increase in grain size or increments in Na and Mg) suggest the presence of a *hiatus* in the transition between this zone and the PZ-S1 (15-0 cm depth). In both PZ-S2 and S3, changes in aquatic taxa and Chenopodiaceae indicate fluctuations in the hydrological balance (Fig.4). Chenopodiaceae increased when desiccation periods in the playa-lake were more frequent, because these herbs grow on the salty surfaces, while hydrophytes (aquatics) as *Ruppia* (characteristic of saline lakes), *Potamogeton* and *Myriophyllum*, need a positive water balance with some water depth during the vegetative periods. Finally, the upper part of the sequence (PZ-S1, 15 cm top), corresponding to sedimentary Units S2 and S1, shows the effects of anthropogenic activities (agriculture) with the expansion of *Olea* and *Cerealia* type, and increasing nitrophylous taxa as *Rumex, Plantago*, Asteraceae or Brassicaceae.

The La Salineta sequence shows the evolution of a typical playa-lake system, with marked hydrological fluctuations during the last few millennia that depend on the variability in the seasonal rainfall. The sequence suggests the presence of a period of frequent desiccation prior to 2000 cal yr BP, and somehow more positive water balance afterwards. Along PZ-S2 and PZ-S1 sedimentation resumes during medieval times, according to the first expansion of *Olea* cultivations (Davis, 1994). Both regional and local vegetation are determined by the aridity indicating a Mediterranean steppe environment characterized by open herbaceous extensions with some isolated shrubs and trees, close to human-affected areas with farming and grazing.

5. Palaeoenvironmental implications

Despite the difficulties associated with palaeoenvironmental studies carried out in playa-lake records, sedimentological, palynological and isotopic analysis from saline lakes along the semi-arid Central Ebro Basin (north-eastern Spain) provide useful information to reconstruct the environmental and hydrological variability from the Lateglacial and during the Holocene. A detailed review of the previous studies available (Table 3), together with the new data presented here from La Playa and La Salineta playa-lake records, allow us to identify vegetation changes and moisture fluctuations during the Late Pleistocene and Holocene periods (Table 4).

6.1. Lateglacial

A complex mosaic landscape was developed in the Central Ebro Basin during the Lateglacial. Coniferous forest patches (*Pinus* dominance with presence of *Juniperus*), mesophytes (*Corylus*) and thermophytes (evergreen *Quercus*) refuge areas, and steppe formations with *Artemisia, Ephedra,* Compositae, *Helianthemum*, etc., coexist (González-Sampériz et al., 2005). Although throughout the Lateglacial several wet and arid intervals are inferred from playa-lake records, the lack of a good chronology prevents an accurate temporal location of these climatic fluctuations. The phases of increased effective moisture are indicated by the higher percentages of some aquatic taxa (mainly *Myriophyllum* or *Potamogeton* in Laguna de Gallocanta from Burjachs et al., 1996; or Salada Mediana from Valero-Garcés et al., 2000a). *Ruppia* (more saline water tolerant) is also present in pollen diagrams but in minor percentages. Usually, the aridity phases are marked by Chenopodiaceae increases since these plants cover the surface of playa-lakes when they are dry (i.e., Salada Mediana, Valero-Garcés et al., 2000a). The La Salineta Core-Section also shows important moisture fluctuations along the Lateglacial period reflected by drastic sedimentary changes and variable isotopic values pointing to the alternation of dry intervals (i.e., about 21 kyrs BP) with more humid stages (i.e., about 24 kyrs BP, just after the genesis of the lake basin) (Valero-Garcés et al., 2004).

Other clear examples of arid periods during the Lateglacial are the PZ-P4 from La Playa record presented here (higher proportion of *Ephedra distachya* and *Artemisia*)and the bases of Laguna Guallar and Hoya del Castillo sequences (highest values of *Ephedra distachya, Artemisia* and *Juniperus*; in Davis, 1994). In these three records, the pollen spectra indicate an arid period just prior to the Early Holocene. There are evidences from other terrestrial records (i.e., Banyoles, Valero-Garcés et al., 1998; Tramacastilla, Montserrat, 1992; El Portalet, González-Sampériz et al., 2006) that the Younger Dryas event had a clear arid (and cold) imprint in the Northeast Iberian Peninsula. Despite the absence of dates in this interval from the Los Monegros records, considering that La Playa, Laguna Guallar and Hoya del Castillo are the only pollen sites that have been studied in the Central Ebro Basin covering this time period and that present the same palynological signal, we suggest that this is a possible evidence of the arid Younger Dryas event. In the Playa lake record, the sedimentological and geochemical data also suggest a dry period. The increase of clay minerals, quartz and detrital calcite (Facies 4) points to an increase in deflation, a process that is more intense during arid periods. Nevertheless, the lack of dates throughout Sequence P-III of La Playa record, Laguna Guallar and Hoya del Castillo prevents us from totally discarding that these sediments corresponded to other arid and cold periods during the Lateglacial.

The data available support our interpretation that during the Lateglacial period, intervals of relatively freshwater conditions alternated with other more saline conditions. This situation is probably the reflection of the well-known arid-cold and wet-warm phases that characterized the Lateglacial global climate, such as the Dryas and the Bølling and Allerød periods (i.e., Grootes and Stuiver, 1997). In addition, in the Central Ebro Basin, increased flow from the Pyrenean rivers during the early deglaciation could play a significant role in the palaeohydrological conditions (González-Sampériz, 2004; Valero-Garcés et al., 2004) supplying water during generally drier conditions. Accordingly, the location of mesothermophytes refuge areas in Salada Mediana (*Corylus,* evergreen *Quercus*) confirms the existence of more humid conditions in the Central Ebro Basin, which was at least wet enough to provide soil moisture, during some periods of the Lateglacial (Valero-Garcés et al., 2000a; González-Sampériz et al., 2004, 2005).

6.2. Early Holocene

Cool temperatures and/or higher precipitation during the Early Holocene were proposed by Harrison and Digerfeldt (1993) to explain higher lake levels observed throughout the Mediterranean at this time (Roca and Julià, 1997; Giralt et al., 1999; Reed et al., 2001). In addition, a temperature reconstruction from southern Europe (summer MTWA –mean temperature of the warmest month- and winter MTCO –mean temperature of the coldest month-) reflects wetter conditions during the Early Holocene (Davis et al., 2003) as it has already been proposed by the same author in some playa-lake systems from the Central Ebro Basin (Davis, 1994). The author bases this hypothesis in the expansion of *Pinus, Juniperus* and evergreen

Quercus forest observed in Laguna Guallar and Hoya del Castillo (Tables 1b, 3 and 4). Moreover, the increase in lake water levels is indicated by the low values of Chenopodiaceae (around 20%) and the *Ruppia* proportions in both pollen records (Davis, 1994). In La Playa record presented in this paper, we also observe during the Early Holocene (PZ-P3 and P2) a *Pinus* forest formation, low *Artemisia* and Chenopodiaceae percentages and the highest proportions of aquatic plants (*Ruppia, Potamogeton* and mainly *Myriophyllum*). In addition, the sedimentological analysis of La Playa indicates the presence of more diluted waters deduced from the dominance of low-gypsum sediments with higher organic matter content and the decrease in wind-transported quartz (Subunit P3a). Contrarily, the transition towards the more arid Middle Holocene would be indicated by the increase in gypsum and Mg towards the top of Sequence P-II. Thus, the Early Holocene was probably a relatively humid period in the Central Ebro Basin, with moderately long periods of high lake levels. However, a patched landscape with some steppe indicators persists, at the same time that coniferous forest formations increase and the mesothermophytes decrease pointing to the disappearance of the Lateglacial refuges areas.

6.3. Middle Holocene

Some areas of the Central Ebro Basin, such as the playa-lake records of Hoya del Castillo (Híjar, Teruel) and Chiprana (Chiprana, Zaragoza), show up to 80% of pine pollen (Davis, 1994) during the Middle Holocene (see radiocarbon dates in Table 1b). The usual high proportions and dominance of *Pinus* in playa-lake pollen records are related to sedimentary disturbances and *hiatus* indicators probably associated to aerial exposure and oxidation processes that caused low pollen preservation (Burjachs et al., 1996). Pine grains are very resistant and easy to identify even from their remains, favouring their over-representation in the pollen spectra. Davis (1994) deduced in the two records mentioned a forest retreat (decrease in *Juniperus* and evergreen *Quercus*) as a consequence of the aridity intensification during the Middle Holocene. Other evidence of a Middle Holocene dry period is described in the Salada Chiprana sedimentological record, where an ephemeral lake developed at that time (Valero-Garcés et al., 2000b; Davis, 1994).

The Los Monegros region and particularly the Bujaraloz area presented in this paper are the most arid zones of the Central Ebro Basin. Several sequences from that area have provided palaeoenvironmental information about the Lateglacial and the Early Holocene, although none presents a Middle Holocene record (i.e., La Playa lake, Figs. 2 and 5). In most cases, the Middle Holocene has been eroded and the Recent Holocene sediments lie directly above the Early Holocene material. In the La Playa record a clear sedimentary *hiatus* between PZ-P2 and PZ-P1 and the sedimentary Units P2 and P1 is observed. Similarly, an interruption of the sedimentation around 45 cm in depth is detected at Laguna Guallar (Davis, 1994), and the record continues afterwards during the Recent Holocene. Therefore, our data also support Davis' (1994) interpretation of Middle Holocene strong aridity in the Central Ebro Basin, particularly intense in the Los Monegros area, causing a large depression in the regional water tables and a general desiccation of the playa-lakes. The dry surfaces of playa-lake basins and the retreat of the vegetation cover due to the aridity would intensify the erosion processes. Deflation gave rise to an intense sweeping of the sediments causing a sedimentary *hiatus.*

Several archaeological sites occur around the saline lake basins in the Central Ebro Basin (Tilo, 1992). The scarce material preserved has been attributed to i) the Palaeolithic and Epipalaeolithic macrolithic periods (Lateglacial and Early Holocene), or ii) Bronze Age, Iron Age and mainly pottery of the Roman period. A good example of this type of archaeological sites in Los Monegros is the Cardell Valmateu settlement in Bujaraloz-Candasnos area (Tilo, 1992). There are no archaeological remains from the Neolithic culture (Middle Holocene) in the Los Monegros area and this has been interpreted as a consequence of the increased aridity that would have probably impeded human settlements. Furthermore, the aridity intensification of the Middle Holocene had a strong impact on the development of the Neolithic socio-economic activities such as agriculture and pastoralism and the resulting deforestation processes (Utrilla and Rodanés, 1997; González-Sampériz, 2004), increase of fire events and accumulation phases in gullies of the Central Ebro Basin (i.e., Las Lenas or La Morera, dated in 5910 BP and 6015 BP respectively by Peña-Monné et al., 1996). This scenario implies that the aridity crisis during the Middle Holocene was modulated by two factors: climate and human impact (González-

Sampériz and Sopena, 2002). The same situation was inferred for the rest of Iberia, particularly in the south-eastern region (Carrión et al., 2003), with a clear intensification of fire events and human impact since the last 4000 years BP.

6.4. Recent Holocene

Although most playa-lake sequences of the Central Ebro Basin record the Recent Holocene period, they usually cover only the last 1000 or 2000 years (references in Table 3). The arid climate that characterized the Middle Holocene probably continued for several millennia until the beginning of the moister Roman Period. The palynological data from these studies reflect an open and patched vegetation cover, which was very influenced by human activities, as reflected by the increased percentages of *Olea* and *Cerealia* type (i.e., PZ-P1 in La Playa record and PZ-S1 and S2 in La Salineta record; Salada Mediana, Valero-Garcés et al., 2000a; Salada Chiprana, Davis, 1994). The Chenopodiaceae and aquatic plants percentages (mainly *Ruppia*) indicate a seasonal unstable water depth in both saline lakes of this study (Fig. 4). Sedimentological indicators (i.e., organic-rich mud in La Salineta record, Fig. 3) point towards a slight recovery of the lake levels, compared to the previous interval. Therefore, landscape and hydrological conditions inferred from previous playa-lake studies, together with the new results from La Playa and La Salineta records, suggest a vegetation mosaic with slightly higher moisture availability.

In the AP, the coniferous component with the usual *Pinus* dominance persists in the landscape, but retreated by anthropogenic activities during the last centuries (Tables 3 and 4). This is interpreted from the two records presented in this paper (La Playa and La Salineta), and in previous studies from Laguna Guallar (Davis, 1994), La Playa (Pérez-Obiol and Roure, 1990; Stevenson et al., 1991), La Clota, el Rebollón and El Camerón playa-lakes (Pérez-Obiol and Roure, 1990), also located in the Los Monegros region. In the other sites from the Central Ebro Basin, such as Salada Pequeña and La Estanca playa-lake records from Davis (1994) in Alcañiz (Teruel), Salada Chiprana (Davis, 1994) and Laguna de Gallocanta (Davis, 1994; Burjachs et al., 1996; Roc et al., 2002) the same observations are made. Therefore, the detected fluctuations in *Pinus* curve's at the uppermost part of the pollen sequences could be ascribed to human activities, such as deforestation due to intensive agriculture or pastoralism practices, fire events related to a significant concentration of charcoal remains (as in Salada Chiprana, Davis, 1994), and recent reforestation policy.

To complete the patched AP formations in the region, several local features are observed in some particular sequences, such as the presence of *Juniperus* or *Quercus* in higher percentages than generally. Thus, *Juniperus* percentages are relatively important at La Playa record in Stevenson et al.'s work (1991) or at La Estanca in Alcañiz (Davis, 1994) where they are related to the establishment of *Juniperus* close to the basins (slopes of nearby hills). Additionally, important values of evergreen *Quercus* are observed due to the proximity of local forest communities or *Quercus coccifera* formations at Laguna de Gallocanta since Medieval times (Roc et al., 2002) and at La Playa lake in Pérez-Obiol and Roure's record (1990). As the last component of the AP formations, the percentages of mesophytes (*Betula, Fagus, Corylus, Alnus, Ulmus*), in spite of they are usually low, may indicate that these trees were present in the surroundings located in riparian formations or that their pollen grains reached the Los Monegros area by long-distance transport.

In relation to the NAP component, steppe formations are dominant in the Los Monegros area throughout the Recent Holocene, with Chenopodiaceae, *Artemisia* and an increase in ruderals due to anthropogenic influences (see Tables 3 and 4 and La Salineta pollen diagram in Fig. 6). The main anthropogenic indicators are ruderals and crops such as *Cerealia, Vitis, Olea* and *Juglans*. The presence of the different cultures enables us to outline a basic chronology from the North-eastern Spain. Thus, the apparition of *Cerealia* type in pollen diagrams is ascribed to approximately 5000 years ago (López-García, 1986), the *Vitis* and *Juglans* crops expansion occurred during the Iberian and Roman period (Dupré, 1988) and the expansion of *Olea* is recognized since the Middle Ages (Stevenson et al., 1991; Davis, 1994). The fluctuations observed among quenopods and aquatics indicate a seasonal unstable water depth in saline lakes, as represented in Fig. 4 for La Playa and La Salineta records. *Myriophyllum* and *Potamogeton*, which were abundant during the Lateglacial and the Early Holocene records, are scarce now. However, *Ruppia* (more saline water tolerant) is always present. Coherently, sedimentological records indicates that the depositional environment was ephemeral saline lakes characterized by periods of higher regional groundwater recharges and thus increased biological productivity that alternate with periods of dry lake surfaces and formation of evaporites.

7. Conclusions

Despite the usual problems inherent in playa-lake sedimentary systems (i.e., frequent aeolian erosion and resulting *hiati*, poor pollen preservation, difficulty in obtaining an accurate chronological control, etc.,), this study underlines the potential of these records to reconstruct the palaeoclimate evolution in the Los Monegros area (North-eastern Iberian Peninsula). From the analysed features that are common in the previously studied saline lake records from the Central Ebro Basin and the new presented records from La Playa and La Salineta saline lakes, several climatic patterns are inferred since the Lateglacial period. Thus, the fluctuations of halophylous and aquatic taxa, in relation to changes in mineralogical and isotopic composition obtained in these deposits, indicate important fluctuations in the regional groundwater levels during the Lateglacial. Accordingly, the presence of an interval mainly characterized by maximum percentages of steppe taxa, together with sedimentological evidences of increased aeolian erosion, leads us to identify an arid period that could be related to the Younger Dryas period. By contrast, other episodes of the Lateglacial are characterized by higher percentages of some aquatic taxa, suggesting phases of increased effective moisture. Similarly, the Early Holocene was a more humid time interval in the Central Ebro Basin, as indicated by sedimentological observations (i.e., low gypsum content) and the development of forest formations although the same steppe indicators persisting in low percentages in the region than during the Lateglacial. It is likely that the increase of river flow associated with the deglaciation of the Pyrenees could have provided a considerable amount of water during the Lateglacial and Early Holocene periods. The lack of sediment records during the Middle Holocene in the Los Monegros area and the evidences of arid climate from other records in the Central Ebro Basin support the interpretation of a dry scenario for this interval. The lack of archaeological remains associated with the Middle Holocene (Neolithic) in this area confirms this hypothesis. Finally, the Recent Holocene is characterized by anthropogenic activities (deforestation, agriculture and pastoralism development, etc.) and a slight recovery in the groundwater recharges as suggested from both sedimentological and palynological records.

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References

Arenas, C., Casanova, J., Pardo, G., 1997. Stable-isotope characterization of the Miocene lacustrine systems of Los Monegros (Ebro Basin, Spain): palaeogeographic and palaeoclimatic implications. Palaeogeography, Palaeoclimatology and Palaeoecology 128, 133-155.

Benito, G., Pérez-González, A., Gutiérrez, F., Machado, J., 1998. River response to Quaternary subsidence due to evaporite solution (Gállego River, Ebro Basin, Spain). Geomorphology 22, 243-263.

Bennet, K., 2002. Documentation for Psimpoll 4.10 and Pscomb 1.03. C programs for plotting pollen diagrams and analysing pollen data. University of Cambridge. Cambridge.

Blanco, E., Casado, M., Costa, M., Escribano, R., García Antón, M., Génova, M., Gómez, A., Moreno, J., Morla, C., Regato, P., Sainz Ollero, H., 1997. Los bosques ibéricos. Una interpretación geobotánica. Planeta. Barcelona, 572 pp.

Braun Blanquet, J., de Bolos, O., 1957. Les groupements végétaux du bassin moyen de l'Ebre et leur dynamisme. Annales Estación Experimental de Aula Dei, vol.V, Zaragoza.

Brown, T; Nelson, D; Mathewes, R; Vogel, J., Sonthon, J., 1989. Radiocarbon dating of pollen by accelerator mass spectrometry. Quaternary Research 32, 205-212.

Burjachs, F., Rodó, X., Comín, F. A., 1996. Gallocanta: ejemplo de secuencia palinológica en una laguna efímera. In: Ruiz Zapata, B. (ed.) Estudios Palinológicos, XI Simposio de Palinología, Universidad de Alcalá, 25-29.

Calvo, J.P., B. Valero-Garcés, B. L., Pozo, M., Bellanca, A., Neri, R., Zingales, M., 2005. Recent dolomite in playa lakes of the Central Ebro Basin, Spain. 24th IAS Meeting on Sedimentology. Abstract Book 38, Oman.

Capel Molina, J.J.,1981. Los climas de España. Oikos-tau ediciones, Barcelona, 429 pp.

Carrión, J. S., Sánchez-Gómez, P., Mota, J.F., Yll, E.I., Chaín, C., 2003. Fire and grazing are contingent on the Holocene vegetation dynamics of Sierra de Gádor, southern Spain. The Holocene 13, 839-849.

Castañeda, C., 2002. El agua de las saladas de Monegros Sur estudiada con datos de campo y de satélite. Consejo de Protección de la Naturaleza de Aragón. Zaragoza, 158 pp.

Chung, F.H., 1974. Quantitative interpretation of X-ray diffraction patterns of mixtures: II. Adiabatic principles of X-ray diffraction analysis of mixtures. Journal of Applied Crystallography 7, 526 - 531.

Cheddadi, R., Yu, G., Guiot, J., Harrison, S. P., Prentice, I. C., 1997. The climate of Europe 6000 years ago. Climate Dynamics 13, 1-19.

Davis, B. A. S., 1994. Palaeolimnology and Holocene environmental change from endorheic lakes in the Ebro Basin, north-east Spain, Ph. D. Thesis, University of Newcastle upon Tyne, 317 pp.

Davis, B. A. S., Brewer, S., Stevenson, A. C., Guiot, J., Data Contributors., 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews 22, 15-17, 1701-1716.

Dorado-Valiño, M., Valdeomillos-Rodríguez, A., Ruíz-Zapata, M. B., Gil-García, M. J., de Bustamante-Gutiérrez, I., 1999. Evolución climática durante el Holoceno en la cuenca alta del Guadiana (Submeseta sur ibérica). Cuaternario y Geomorfología 13, 19-32.

Dupré, M., 1988. Palinología y paleoambiente. Nuevos datos españoles. Referencias. Serie de Trabajos varios (SIP). Universidad de Valencia, 160 pp.

Dupré, M., 1992. Palinología. Cuadernos Técnicos de la Sociedad Española de Geomorfología 5, 1-30.

García-Vera, M.A., 1996. Hidrogeología de zonas endorreicas en climas semiáridos. Aplicación a Los Monegros (Zaragoza y Huesca). Diputación General de Aragón, Zaragoza, 297 pp.

Giralt, S., Burjachs, F., Roca, J. R., Julià, R., 1999. Late Glacial to Early Holocene environmental adjustment in the Mediterranean semi-arid zone of the Salines playa-lake (Alicante, Spain). Journal of Paleolimnology 21, 449-460.

González-Sampériz, P., 2004. Evolución paleoambiental del sector central de la cuenca del Ebro durante el Pleistoceno superior y Holoceno. Instituto Pirenaico de Ecología-CSIC, Zaragoza: 210 pp.

González-Sampériz, P., Sopena, M. C., 2002. Recent Holocene palaeoenvironmental evolution in the Central Ebro Basin (NE Spain). Quaternary International, 93-94, 177-190.

González-Sampériz, P., Valero-Garcés, B., Carrión García, J. S., 2004. Was the Ebro valley a refugium for temperate trees? Anales de Biología 26, 13-20.

González-Sampériz, P., Valero-Garcés, B., Carrión, J. S., Peña-Monné, J. L., García-Ruiz, J. M., Martí-Bono, C. 2005 Glacial and Lateglacial vegetation in Northeastern Spain: new data and a review. Quaternary International 140-141, 4-20

González-Sampériz, P., Valero-Garcés, B. L., Moreno, A., Jalut, G., García-Ruiz, J. M., Martí-Bono, C., Delgado-Huertas, A., Navas, A., Otto, T., Dedoubat J.J., 2006. Climate variability in the Spanish Pyrenees for the last 30,000 yr: El Portalet peatbog sequence. Quaternary Research, in press.

Grootes, P., Stuiver, M., 1997. Oxygen 18/16 variability in Greenland snow and ice with 10^3-to 10^5-year time resolution. Journal of Geophysical Research 102, 26455-26470.

Gutiérrez-Elorza, M., Peña-Monné, J. L. 1998. Geomorphology and late Holocene climatic change in northeastern Spain. Geomorpholoy, 23, 205-217.

Gutiérrez-Elorza, M; Desir, G., Gutiérrez-Santolalla, F., 2002. Yardangs in the semiarid central sector of the Ebro Depression (NE Spain). Geomorphology 44: 155-170.

Harrison, S. P., Digerfeldt, G,. 1993. European lakes as palaeohydrological and palaeoclimate indicators. Quaternary Science Reviews 12, 233-248.

Harrison, S. P., Prentice, I. C., Guiot, J., 1993. Climatic controls on Holocene lake-level change in Europe. Climate Dynamics 8, 189-200.

Harrison, S. P., Yu, G., Tarasov, P. E., 1996. The Holocenelake levels record from Eurasia. Quaternary Research 45, 138-159.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Xiaosu, D., 2001. Climate Change 2001: The Scientific Basis. IPCC. Cambridge University Press, 944 pp.

Ibáñez, M.J., 1975. El endorreismo aragonés. Cuadernos de Aragón n° 8-9. Institución Fernando el Católico-CSIC. Zaragoza, 31-44.

IGME., 1971. Geologic Map of Spain 1:200000. Huesca nº 23. Instituto Geológico y Minero de España, Madrid.

López-García, P., 1986. Estudio palinológico del Holoceno español a través del análisis de yacimientos arqueológicos. Trabajos de Prehistoria 43, 143-158.

Mata, M. P., Pérez, A., López-Aguayo, F., 1988. Mineralogía del perfil de "La Muela", Terciario del sector central de la depresión del Ebro (provincia de Zaragoza). Estudios Geológicos 44, 135-143.

Montserrat, J., 1992. Evolución glaciar y postglaciar del clima y la vegetación en la vertiente sur del Pirineo: estudio palinológico. Monografías del Instituto Pirenaico de Ecología-CSIC, Zaragoza, 147 pp.

Moore, P; Webb, J. A., Collinson, A., 1991. An illustrated guide to pollen analysis. London. Hodder and Stroughton. 216 pp.

Moreno, A., Valero-Garcés, B. L., González-Sampériz, P., Navas, A., Machín, J., Delgado-Huertas, A., 2004. El registro paleoambiental y paleoclimático de las saladas de la Playa y la Salineta (Zona Central de la Depresión del Ebro). Geotemas 6, 137-140.

Peinado-Lorca, M., Rivas-Martínez, S. (Eds)., 1987. La vegetación de España. Colección Aula Abierta, 515 pp.

Peña-Monné, J. L., Chueca, J., Julián, A., Echeverría, M. T., 1996. Reconstrucciones paleoambientales en el sector central de la Depresión del Ebro a partir de rellenos de valle y conos aluviales. In: Pérez Alberti, A. (Ed.), Dinámica y evolución de los medios Cuaternarios. Santiago de Compostela, 291-307.

Pérez-Obiol, R., Roure, J. M. 1990. Aportaciones palinológicas para la interpretación de la evolución reciente del paisaje vegetal de los Monegros. Actas VII Simposio APLE (1988). Granada, 485-491.

Prentice, I. C., Guiot, J., Harrison, S. P., 1992. Mediterranean vegetation, lake levels and palaeoclimate at the Last Glacial Maximum. Nature 360, 658-660.

Prentice, I. C., Harrison, S. P., Jolly, D., Guiot, J., 1998. The climate and biomes of Europe at 6000 yr BP: comparison of model simulations and pollen-based reconstructions. Quaternary Science Reviews 17, 659-668.

Pueyo-Mur, J. J., 1979. La precipitación evaporítica actual en las lagunas saladas del área Bujaraloz, Sástago, Caspe, Alcañiz y Calanda (provincias de Zaragoza y Teruel). Revista Institución Investigaciones Geológicas Diputación Provincial de Barcelona 33, 5 - 56.

Pueyo-Mur, J. J., Inglès-Urpinell, M., 1987. Substrate mineralogy, pore brine composition, and diagenetic proceses in the playa lakes of los Monegros and Bajo Aragón, Spain. In: Rodríguez-Clemente, R., Tardy, Y. (Eds.), Geochemistry and Mineral Formation in the Earth Surface. CSIC-CNRS, Granada., pp. 351–372.

Quirantes, J., 1978. Estudio sedimentológico y estratigráfico del Terciario continental de los Monegros. Instituto Fernando el Católico, Zaragoza.

Ramírez, J.L., 1997. Mapa geológico de España a escala 1:50000, Gelsa (n. 413). ITGE, Madrid.

Reed, J. M., Stevenson, T., Juggins, S., 2001. A multi-proxy record of Holocene climatic change in southwestern Spain: the Laguna de Medina, Cádiz. The Holocene 11, 707-719.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G., Manning, S., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., Weyhenmeyer, C. E., 2004. IntCal04. Terrestrial Radiocarbon Age Calibration, 0-26 Cal Kyr B.P. Radiocarbon 46, 1029-1058.

Roc, A. C., Sánchez-Goñi, M. F., Pérez, A., Alfonso, S., Jouanneau, J. M., Sánchez, J. A., 2002. Relación entre la evolución sedimentaria de la laguna de Gallocanta (Cordillera Ibérica, NE de España) y la historia de la vegetación de su cuenca durante el Cuaternario Reciente. Journal of Iberian Geology 28, 243-262.

Roca, J. R., Julià, R., 1997. Lae Glacial and Holocene climatic changes and desertification expansion based on biota content in the Salines séquense, Southeastern Spain. Geobios 30, 823-830.

Rodó, X., Baert, E., Comín, F. A., 1997. Variations in seasonal rainfall in Southern Europe during the present century: relationships with the North Atlantic Oscillation and the El Niño-Southern Oscillation. Climate Dynamics 13, 275-284.

Rodó, X., Giralt, S., Burjachs, F., Comin, F. A., Tenorio, R. G., Julià, R., 2002. High-resolution saline lake sediments as enhanced tools for relating proxy paleolake records to recent climatic data series. Sedimentary Geology 148, 203-220.

Samper-Calvete, F. J., García-Vera M. A., 1998. Inverse modeling of groundwater flow in the semiarid evaporitic closed basin of Los Monegros, Spain. Hydrogeology Journal 6, 33-49.

Sánchez-Navarro, J. A., Pérez, A., Coloma, P., Martínez-Gil, F. J., 1998. Combined effects of groundwater and eolian processes in the formation of the northernmost closed saline depression of Europe. North-East Spain, Hydrological Processes 12, 813-820.

Schütt, B., 1998. Reconstructions of Holocene paleoenvironments in the endorheic basin of Laguna de Gallocanta, Central Spain by investigation of mineralogical and geochemical characters from lacustrine sediments. Journal of Paleolimnology 20, 217-234.

Stevenson, A., 2000. The Holocene forest history of the Montes Universales, Teruel, Spain. Holocene 10, 603-610.

Stevenson, A.; Macklin, M.; Benavente, J.; Navarro, C.; Passmore, D., Davis, B. A. S., 1991. Cambios ambientales durante el Holoceno en el Valle del Ebro: sus implicaciones arqueológicas. Cuaternario y Geomorfología 5 ,149-164.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13, 614-621.

Sumner, G., Homar, V., Ramis, C., 2001. Precipitation seasonality in Eastern and Southern coastal Spain. International Journal of Climatology 21, 219-247.

Taylor, D. M., Pedley, H. M., Davies, P., Wright, M. W., 1998. Pollen and mollusc records for environmental change in central Spain during the mid- and late Holocene. The Holocene 8, 605-612.

Tilo, M.A., 1992 Conjuntos líticos de superficie de los Monegros oscenses. In: Utrilla, P. (Ed.), Aragón/Litoral Mediterráneo. Intercambios culturales durante la Prehistoria. Institución Fernando el Católico. Zaragoza, 153-166.

Utrilla, P., Rodanés, J.M., 1997. La actuación del hombre sobre el paisaje durante la Prehistoria en el Valle Medio del Ebro. In: García-Ruiz, J.M., López García, P. (Eds.), Acción humana y desertificación en ambientes mediterráneos. Instituto Pirenaico de Ecología-CSIC. Zaragoza, 61-98.

Valero-Garcés, B. L., Zeroual, E., Kelts, K., 1998. Arid phases in the western Mediterranean region during the last glacial cycle reconstructed from lacustrine records. In : Benito,G., Baker, V.R., Gregory, K.J. (Eds.), Paleohydrology and Environmental Change. (.), pp. 67-80.

Valero-Garcés, B.L., González-Sampériz, P., Delgado-Huertas, A., Navas, A., Machín, J., Kelts, K., 2000a. Late Glacial paleohydrology and vegetational change in Salada Mediana, Central Ebro Basin, Spain. Quaternary International 73/74, 29-46.

Valero-Garcés, B. L., Navas, A., Machin, J., Stevenson, T., Davis, B. A. S., 2000b. Responses of a saline lake ecosystems in semi-arid regions to irrigation and climate variability. The history of Salada Chiprana, Central Ebro Basin, Spain. Ambio 26, 344-350.

Valero-Garcés, B. L., Delgado-Huertas, A., Navas, A., Machín, J., González-Sampériz, P., Kelts, K., 2000c. Quaternary palaeohydrological evolution of a playa lake: Salada Mediana, central Ebro Basin, Spain. Sedimentology 47, 1135-1156.

Valero-Garcés, B.L, González-Sampériz, P., Navas, A., Machín, J., Delgado-Huertas, Peña-Monne, J.L., Sancho-Marcén, C., Stevenson, T., Davis, B. A. S., 2004. Paleohydrological fluctutations and steppe vegetation during the last glacial maximum in the Central Ebro valley (N.E. Spain). Quaternary International 122, 43-55.

van Zuidam, R.A., 1980. Un levantamiento geomorfológico de la región de Zaragoza. Geographicalia 6, 103-134.

Vandergoes, M. J., Prior, C. A., 2003. AMS dating of pollen concentrates - a methodological study of Late Quaternary sediments from South Westland, New Zeland. Radiocarbon 45, 479-491.

Yu, G., Harrison, S.P., 1995. Lake status record from Europe: Data base documentation. NOAA Paleoclimatology Publication Series Report 3, Boulder, pp 451.

FIGURES

Figure 1. A) Location of the Central Ebro Basin in the Northeastern Iberian Peninsula. Gray shaded areas indicate the topography. B) Closer view of the regional geological map with the location of La Playa and La Salineta records and previous studies in playa-lake systems of Monegros area.

The numbers 1-11 correspond to previous studies in playa-lakes from the Central Ebro Basin: 1- Gallocanta, 2- Salada Mediana, 3- Hoya del Castillo, 4- Chiprana, 5- Salada Pequeña, 6- La Estanca, 7- El Rebollón, 8- El Camerón, 9- La Playa, 10- La Salineta, 11- La Clota.

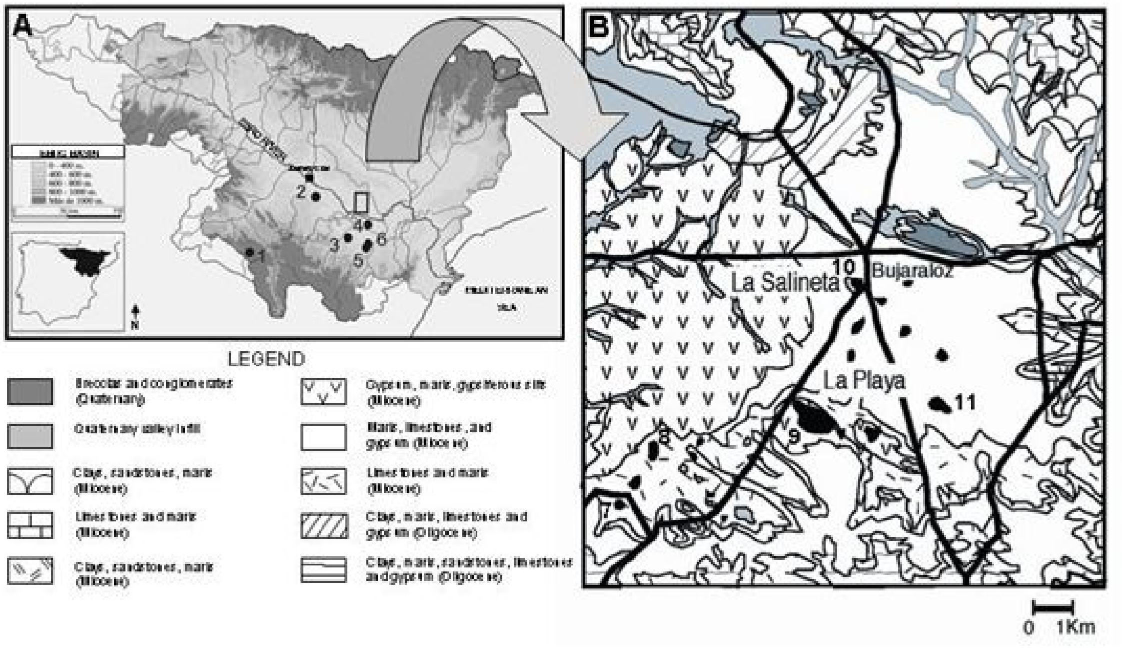
Figure 2. La Playa depth profiles of sedimentary facies, grain-size, mineralogy, carbon content and main elemental composition. The three sedimentary sequences and the facies legend are shown. Shaded bars mark the levels with increased aeolian input. Chronological reconstruction and correlation with pollen zones are indicated.

Figure 3. La Salineta depth profiles of sedimentary facies, grain-size, stable isotopes, mineralogy, inorganic carbon content and main elemental composition. The three sedimentary sequences and the facies legend are shown. Shaded bars mark the levels with increased aeolian input. Chronological reconstruction and correlation with pollen zones are indicated.

Figure 4. Depth profiles of *Artemisia,* as the main component of steppe taxa, halophytes and aquatic plants from La Playa and La Salineta records. Halophytic group is composed by Chenopodiaceae in La Playa record and by Chenopodiaceae and Plumbaginaceae in La Salineta record. Aquatic group is composed by *Ruppia, Myriophyllum* and *Potamogeton* in both records.

Figure 5. Pollen diagram from La Playa record. Chronological reconstruction and correlation with sedimentological units are indicated.

Figure 6. Pollen diagram from La Salineta record. Chronological reconstruction and correlation with sedimentological units are indicated.


A
B
2
3
4
5
6
1
N
LEGEND
Breccias and conglomerates (Quaternary)
Quaternary valley infill
Clays, sandstones, marls (Miocene)
Limestones and marls (Miocene)
Clays, sandstones, marls (Miocene)
Gypsum, marls, gypsiferous silts (Miocene)
Marls, limestones, and gypsum (Miocene)
Limestones and marls (Miocene)
Clays, marls, limestones and gypsum (Oligocene)
Clays, marls, sandstones, limestones and gypsum (Oligocene)
La Salineta
10
Bujaraloz
La Playa
11
8
9
0
1Km

1

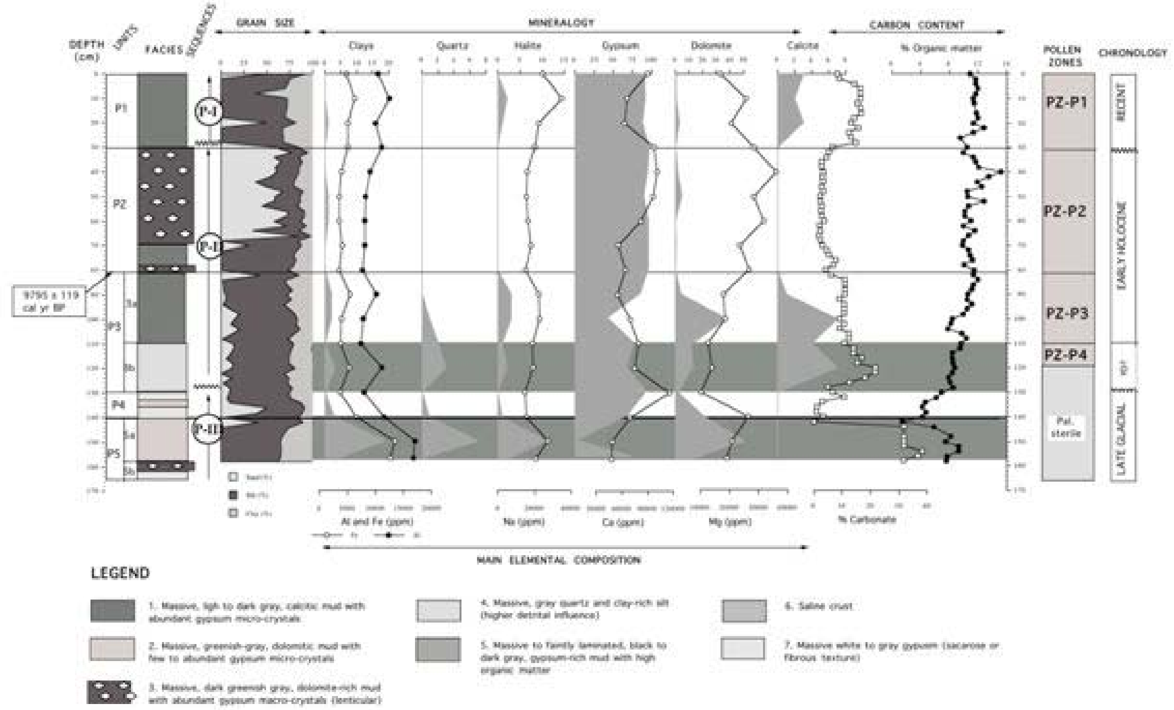

DEPTH (cm)
UNITS
FACIES
SEQUENCES
GRAIN SIZE
MINERALOGY
Clays
Quartz
Halite
Gypsum
Dolomite
Calcite
CARBON CONTENT
% Organic matter
POLLEN ZONES
CHRONOLOGY
P1
P2
P3
3a
3b
P4
P5
5a
5b
P-I
P-II
9795 ± 119 cal yr BP
PZ-P1
PZ-P2
PZ-P3
PZ-P4
Pal. sterile
RECENT
EARLY HOLOCENE
LATE GLACIAL
Al and Fe (ppm)
Na (ppm)
Ca (ppm)
Mg (ppm)
% Carbonate
MAIN ELEMENTAL COMPOSITION
LEGEND
1. Massive, ligh to dark gray, calcitic mud with abundant gypsum micro-crystals
2. Massive, greenish-gray, dolomitic mud with few to abundant gypsum micro-crystals
3. Massive, dark greenish gray, dolomite-rich mud with abundant gypsum macro-crystals (lenticular)
4. Massive, gray quartz and clay-rich silt (higher detrital influence)
5. Massive to faintly laminated, black to dark gray, gypsum-rich mud with high organic matter
6. Saline crust
7. Massive white to gray gypsum (sacarose or fibrous texture)

FIGURE 2

2

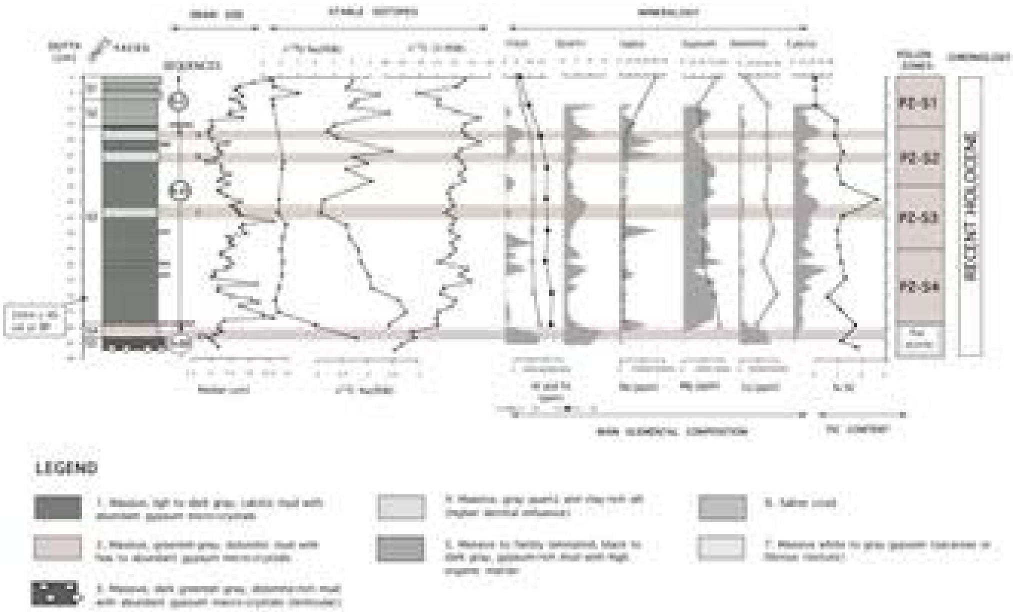
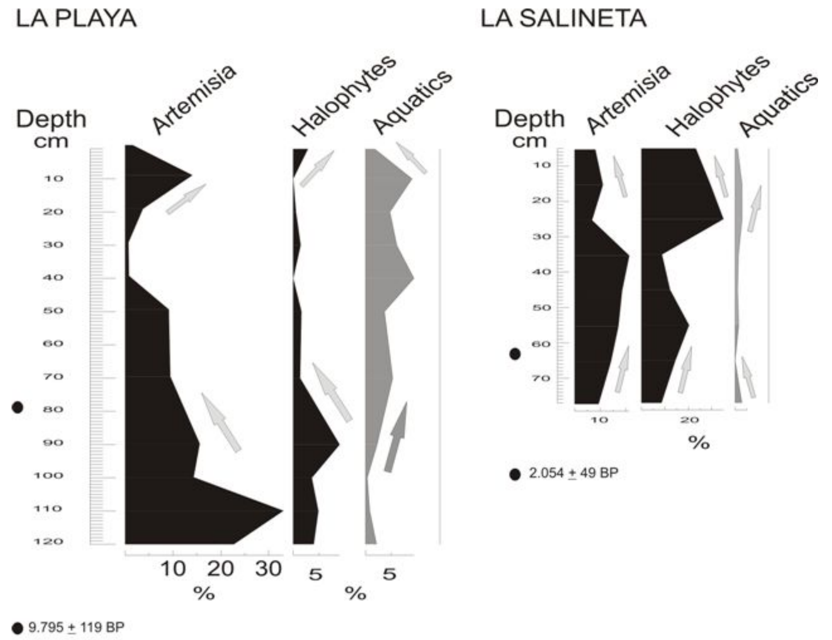
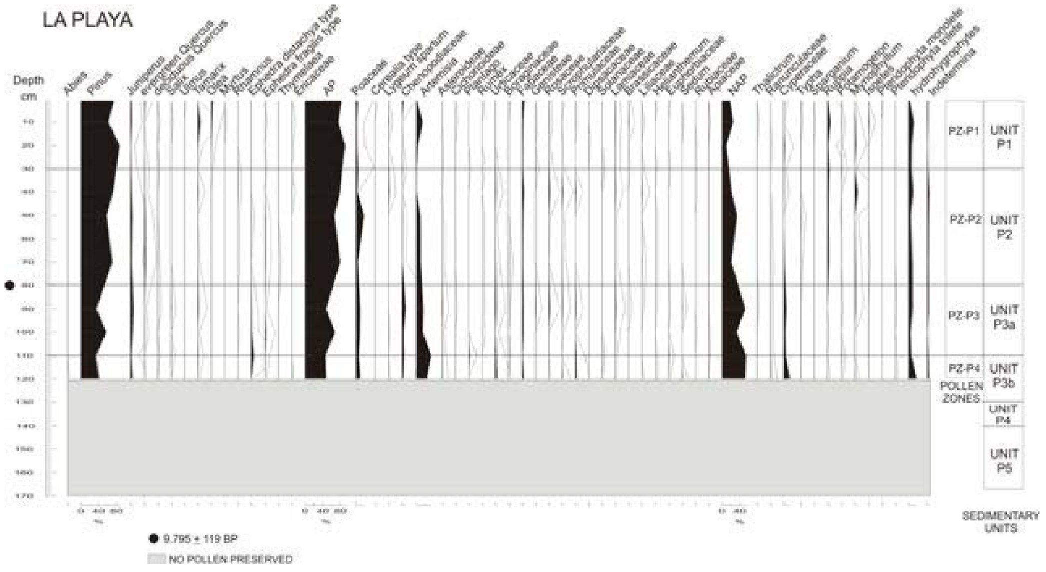

STABLE ISOTOPES
MINERALOGY
SEQUENCES
PZ-S1
PZ-S2
PZ-S3
PZ-S4
RECENT HOLOCENE
LEGEND

FIGURE 3



Halophytes + Steppe (*Artemisia*) // Aquatics fluctuation: water balance evolution



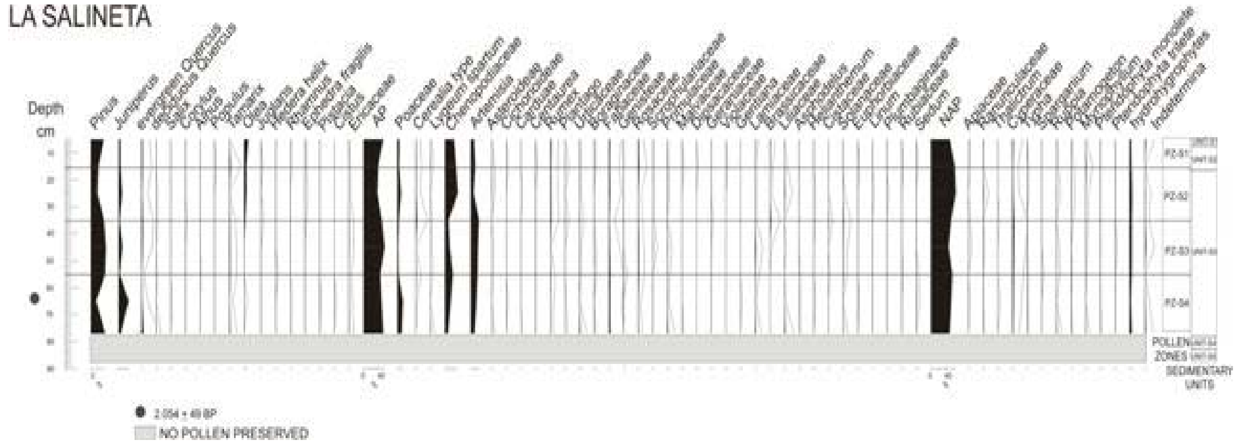


Table 1 – a) Radiocarbon dating of La Playa and La Salineta cores. AA = Arizona Dating Facility (AMS dating). See text for explanation about calibration procedures; b) Radiocarbon dates obtained in the other studies from saline lakes of the Central Ebro Basin. See Fig. 1 for the lakes location.

a)

Lake	Lab code	Depth	Material	^{14}C age (yr BP)	Age error (yr)	Calibrated age (cal yr BP) ( )
La Playa	AA54259	80 cm	Pollen concentrate	8773	73	9676 - 9914
La Playa	~	140 cm	Pollen concentrate	Not enough organic material		
La Playa	~	160 cm	Pollen concentrate	Not enough organic material		
La Salineta	AA60923	65-67 cm	Pollen concentrate	2081	38	1966 - 2131

b)

Lake	Core depth	Sample	^{14}C age	Reference
Salada Mediana	1,65 m	5 cm	1710 BP	Valero-Garcés et al., 2000a
		28 cm	12,400 BP	
		50 cm	10,850 BP	
		90 cm	10,350 BP	
		133 cm	17,300 BP	
		147 cm	11,250 BP	
La Salineta	4,65 m	--------	------------	Davis 1994
	8 m	209 cm	1305 BP	Valero-Garcés et al., 2004
		329 cm	7740 BP	
		382 cm	13,950 BP	
		429 cm	10,400 BP	
		501 cm	18,790 BP	
		567 cm	21,100 BP	
		822 cm	23,900 BP	
Guallar	2 m	60 cm	7 485 BP	Davis, 1994
Chiprana	2 m	50 cm	315 BP	Stevenson et al., 1991
		75 cm	420 BP	
		192 cm	5725 BP	
		150 cm	3410 BP	Valero-Garcés et al., 2000b
Salada Pequeña	4 m	40 cm	340 BP	Stevenson et al., 1991
		102 cm	1225 BP	
		164 cm	2325 BP	
		186 cm	2230 BP	
		236 cm	2675 BP	
La Estanca	1,93 m	162 cm	430 BP	Davis, 1994
		182 cm	470 BP	
Hoya del Castillo	5 m	175 cm	5275 BP	Davis, 1994
		280 cm	7325 BP	
		410 cm	8855 BP	
Gallocanta	0,22 m	----------	----------	Davis, 1994
	1,10 m	60 cm	840 BP	Burjachs et al., 1996
		95 cm	12,230 BP	
	1,37 m	----------	----------	Roc et al., 2002

Table 2. Sedimentary facies in La Playa and La Salineta cores.

Facies	**Facies description**
Gypsum-rich carbonatic mud facies	
Facies 1: Massive, light to dark gray, calcitic mud	Dm-thick layers, where carbonate values reach up to 20% (mostly, calcite). Gypsum micro-crystals are abundant, more in La Salineta core. OM: 10%.
Facies 2: Massive, greenish-gray, dolomitic mud	Cm to dm-thick layers where dolomite is the dominant carbonate. Siliciclastic silty-clayed particles (quartz, clay minerals) are also abundant.
Facies 3: Massive, dark greenish gray, dolomite-rich mud	Cm to dm-thick layers where dolomite dominates the carbonatic fraction (mainly in La Salineta core). Gypsum appears as coarse crystals (up to 75% of sandy material in La Playa core) with frequent lenticular habit.
Siliciclastic silt facies	
Facies 4: Massive, gray siliciclastic silt	Cm-thick layers (marked from "*a*" to "*c*" in La Salineta core) characterized by abundant siliciclastic minerals (quartz and clay minerals) and dolomite in comparison to gypsum or halite. Al and Fe content are relatively high. OM: <10%.
Organic facies	
Facies 5: Massive to faintly laminated, black to dark gray, organic-rich mud	Cm-thick layers (only present in La Salineta core) with mm-thick lamination towards the top, with high amount of organic matter (>10%). Sediments are mainly composed by gypsum, calcite and halite.
Evaporite facies/Microcrystalline laminae	
Facies 6: Massive, white evaporite crust	Cm thick layers that represent the present-day evaporite crust, containing halite, bloedite and mirabilite.
Facies 7: Massive, white to gray gypsum-rich layers	Cm-thick gypsum layers (only present in La Playa core) with very low carbonatic or organic matter content (OM: <6%). Gypsum is present as micro-crystals with a sacarose texture or as layers of fibrous crystals.

Table 3 – Location, chronology and main pollen data from the previous studies in playa lake systems from the Central Ebro Basin. (Hol. = Holocene). (? = without dates)

Name	Location	Coordenates	Core depth	Chronology	Pollen data		References
					Vegetation cover	Hydrological conditions	
Salada Mediana	Mediana (Zaragoza)	350 m a.s.l. 41º30'10"N 0º44'W	165 cm	Recent Hol.	AP decrease. Steppe taxa (*Helianthemum, Artemisia*) & ruderals increase. Presence of *Cerealia, Vitis, Juglans*. *Olea* expansion	Chenopodiaceae dominance. Low values of aquatics (only *Ruppia*)	Valero-Garcés et al., 2000a
				Lateglacial	Conifers dominance (*Pinus-Juniperus*). Abundance of *Corylus*, & evergreen *Quercus* (refuge area)	Aquatics (mainly *Myriophyllum*) increase, in opposition to Chenopodiaceae. Moisture fluctuation	
La Playa	Bujaraloz (Zaragoza)	340 m a.s.l. 41º25'00"N 0º11'10"W	110 cm	Holocene ?	*Pinus* dominance, relatively high proportions of evergreen *Quercus* and mesophytes (*Corylus*?). *Cerealia, Vitis* & *Olea* cultives. Ruderals	Chenopodiaceae fluctuations but in less proportions. Without aquatic taxa	Pérez-Obiol and Roure, 1990
			230 cm	Holocene ?	*Pinus-Juniperus* fluctuations in AP local dominance. Steppe taxa, ruderals, presence of *Olea* & *Cerealia*	*Ruppia* presence. Chenopodiaceae fluctuations indicating moisture fluctuations	Stevenson et al., 1991
			162 cm	Recent Hol.	Decrease of AP (pine deforestation). *Artemisia* & ruderals increase. *Cerealia* cultive and *Olea* expansion	Relatively high values & taxonomic variety of aquatics, mainly *Ruppia*. Quenopods, low values. Fluctuations	Moreno et al., 2004 and this study
				Early Hol.	Increase in AP (*Pinus* dominance, presence of *Juniperus* and evergreen *Quercus*). Minimum of steppe taxa	Highest proportions of aquatics (mainly *Myriophyllum*). Lowest values of quenopods. More humid conditions	
				Lateglacial?	Steppe taxa (*Artemisia, Ephedra distachya, Plantago* & Urticaceae) highest values. AP less than 40% (*Pinus*, *Abies* present)	Aridity. Low values of aquatic taxa. Chenopodiaceae present, not dominant	
La Salineta	Bujaraloz (Zaragoza)	325 m a.s.l. 41°28’55’’N, 0°09’30’’W	465 cm (outcrop)	Holocene ?	*Pinus* dominance (junipers and evergreen oaks present). Relatively high values of *Artemisia*. Possible *Cerealia* and increase of *Olea* at the top.	Chenopodiaceae fluctuations (peaks between 10 and 50%). Seasonal playa-lake environment	Davis, 1994
			87 cm	Recent Hol.	Coniferous dominant in reduced AP. Steppe taxa and ruderals. *Olea* expansion	Chenopodiaceae-aquatics fluctuations. Seasonal-playa lake.	this study
La Clota	Bujaraloz (Zaragoza)	347 m a.s.l. 41º24'25"N 0º6'18"W	90 cm	Holocene ?	*Pinus* dominance in AP. *Artemisia* and Compositae relatively high values. Presence of *Cerealia* and *Olea*. Low pollen preservation & taxa diversity	Very high percentages of Chenopodiaceae. Dominance of spectra. No aquatic plants recorded. Aridity	Pérez-Obiol and Roure, 1990
El Rebollón	Bujaraloz (Zaragoza)	320 m a.s.l. 41º22'30"N 0º18'21"W	30 cm	Holocene ?	Pinus dominance. Important presence of evergreen *Quercus*. High values of *Olea* and *Cerealia*. Steppe taxa & ruderals.	Very high proportions of Chenopodiaceae. No aquatic plants recorded. Aridity & human impact	Pérez-Obiol and Roure, 1990

El Camerón	Bujaraloz (Zaragoza)	330 m a.s.l. 41º24"00"N 0º17'15"W	20 cm	Holocene ?	Low AP values (*Pinus* and presence of *Quercus* & *Olea*). Steppe dominance (*Artemisia*, Cichorioideae, *Ephedra…*)	Very high percentages of Chenopodiaceae. No aquatic plants. Intense aridity	Pérez-Obiol and Roure, 1990
Laguna Guallar	Bujaraloz (Zaragoza)	336 m a.s.l. 41º24’30’’N, 0º13’40’’W	200 cm	Early Hol.	Increase in coniferous forest (pines-junipers) & oaks formations. Presence of mesophytes. Decrease in steppe.	Low values of quenopods. High proportions of *Ruppia*. *Carpinus* identification could be *Myriophyllum*	Davis, 1994
				Lateglacial ?	Steppe taxa (*Artemisia & Ephedra distachya*) highest values. AP between 20-50% (*Pinus-Juniperus*)	Aridity. Very low values of aquatic taxa (only presence of *Ruppia*). Chenopodiaceae present, not dominant	
Chiprana	Chiprana (Zaragoza)	150 m a.s.l. 41°14’30’N, 0°10’50”W	200 cm	Recent Hol.	Decrease in pines. High expansion of *Olea*. Presence of junipers and oaks. Steppe taxa & ruderals. Possible *Cerealia*.	High but intermittent values of *Ruppia*. Relatively high propotions of Chenopodiaceae with fluctuations	Davis, 1994
				Middle Hol.	Local forest (AP, 85-90%) with *Pinus* dominance, *Quercus ilex-coccifera* (10%) and *Juniperus* (5%)	Very low or inexistent Chenopodiaceae values. No aquatic taxa preserved but *Carpinus* type could be *Myriophyllum*	
Salada Pequeña	Alcañiz (Teruel)	350 m a.s.l. 41º02’40’’N, 0º13’10’’W	400 cm	Recent Hol.	AP 50%. (*Pinus* dominance, junipers & evergreen oaks, *Olea* expansion). Steppe taxa, ruderals. *Cerealia*? *Juglans*	High Chenopodiaceae values / moderate *Ruppia* proportions fluctuation. Ephemeral shallow saline lake. Aridity.	Stevenson et al., 1991
La Estanca	Alcañiz (Teruel)	342 m a.s.l. 0º10'57’’N, 41º3'54"W	193 cm	Recent Hol.	*Pinus-Juniperus-Quercus ilex-coccifera* formations. High expansion of *Olea*. Steppe taxa & ruderals. Possible *Cerealia*.	Highest proportions of quenopods at the base. Fluctuation with abundant- varied aquatic component towards the top	Davis, 1994
Hoya del Castillo	Híjar (Teruel)	260 m a.s.l. 41º28’55’’N, 0º09’30’’W	500 cm	Middle Hol.	Pinus dominance (80% of total spectra). Presence of junipers & evergreen oaks. Low percentages of steppe taxa.	Chenopodiaceae fluctuation (low values). Presence of *Ruppia*	Davis, 1994
				Early Hol.	Forest formations (*Pinus-Juniperus-Quercus ilex* type). Presence of mesophytes. Low values of steppe taxa.	Highest proportions of *Ruppia*, in fluctuations with Chenopodiaceae	
				Lateglacial ?	Highest proportions of *Ephedra distachya* type & *Artemisia*. Low values of AP (only pines and junipers)	Highest percentages of Chenopodiaceae. No presence of aquatic taxa.	
Gallocanta	Zaragoza Teruel	1000 m a.s.l. 40º58’30’’N, 1º30’10’’W	22 cm	Recent Hol. ?	*Pinus* dominance. Junipers, evergreen oaks & *Olea* relatively high values. No steppe taxa. Cultives (*Cerealia* type & *Juglans*)	Chenopodiaceae low proportions fluctuates with high values of *Ruppia*	Davis, 1994
			110 cm	Recent Hol.	*Pinus* dominance. Junipers & oaks relatively high values. Expansion of *Olea*. Low steppe taxa values. *Cerealia, Secale & Vitis* presence. Ruderals	Highest but relatively low values (20%) of quenopods fluctuate with highest proportions of *Potamogeton* and *Ruppia* & the presence of *Myriophyllum*.	Burjachs et al., 1996
				Lateglacial	*Pinus* dominance (90%). Steppe taxa	No Chenopodiaceae. Aquatics presence	
			137 cm	Recent Hol.	*Pinus* dominance. Oaks important &. *Olea* expansion. Cereal crops. Ruderals	Low values of quenopods. Hygrophytes but no aquatic plants recorded.	Roc, 2003

Table 4. Chronological synthesis of climate conditions in the Central Ebro Basin since the Lateglacial. Palaeoclimate information is obtained from the playa-lake sites indicated in the table (underlined names are the playa-lakes located in the Monegros region; note that none is available for the Middle Holocene).

PERIODS	Vegetation cover	Hydrological situation	Climate conditions	Playa-lake Sites
Recent Holocene	*Pinus* dominance in AP but decrease by human activities. Open cover with steppe formations, increase in ruderals, cereal crops, *Vitis* and *Juglans* presence and expansion of *Olea.*	Chenopodiaceae fluctuations indicate a seasonal unstable water depth. *Ruppia* (the most saline water tolerant aquatic taxa recorded) is always present with relatively high values in some moments. Seasonally slightly higher water levels.	Arid or semi-arid climate. Intense anthropogenic activities, with periods of positive water balance in playa-lakes	Mediana, La Playa, La Salineta, Laguna Guallar, La Clota, El Rebollón, El Camerón, Chiprana, Salada Pequeña, La Estanca, Gallocanta
Middle Holocene	*Pinus* dominance in bad preserved pollen spectra. *Juniperus* and evergreen *Quercus* decrease. Retreat of the vegetation cover.	Very low percentages of aquatic taxa (only *Ruppia* as saline waters tolerant). Chenopodiaceae increase and always present. Ephemeral shallow saline lakes during long periods and very important aeolian erosion.	Aridity intensification and Human impact (fire events, deforestation, agriculture, pastoralism). Increase of erosion (deflation) and consequent sedimentary *hiatus*.	Chiprana, Hoya del Castillo
Early Holocene	Expansion of coniferous forest (*Pinus, Juniperus*), and evergreen *Quercus* formations. Reduction of steppe taxa (*Artemisia, Ephedra*).	General low values of Chenopodiaceae. High proportions of aquatic plants (still *Myriophyllum, Potamogeton* and *Ruppia* in minor percentages). Higher groundwater levels.	Positive water balance and increase in forest formations caused by cool temperatures and / or higher precipitation.	La Playa, La Salineta Core-Section, Laguna Guallar, Hoya del Castillo
Lateglacial	Complex mosaic: coniferous patches (*Pinus* dominance, *Juniperus* presence), mesophytes and thermophytes refuges areas (*Corylus* & evergreen *Quercus*), and steppe formations (*Artemisia, Ephedra,* other heliophytes)	Alternation between shallow and deep lake levels. Phases of increased effective moisture (relatively high percentages of *Myriophyllum* presence of *Potamogeton* and *Ruppia* in low values). Arid periods with dry lake surface (Chenopodiaceae fluctuation) and intense deflation.	Fluctuation of arid - wetter periods as a reflection of the arid - cold and wet - warm global phases. Moister edaphic conditions due to increased flow from the Pyrenean rivers (deglaciation processes).	Mediana, La Playa, La Salineta Core-Section, Laguna Guallar, Hoya del Castillo, Gallocanta