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Lateglacial and Late Holocene environmental and vegetational change in Salada Mediana, central Ebro Basin, Spain

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Abstract

The Salada Mediana lacustrine sequence, central Ebro Basin, Spain (41°30′10″N, 0°44′W, 350 m a.s.l.) provides an example of the potential and limitations of saline lake records as palaeoclimate proxies in the semi-arid Mediterranean region. Sedimentary facies analyses, chemical stratigraphy, stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) of authigenic carbonates, $\delta^{13}C$ values of bulk organic matter and pollen analyses from sediment cores provide paleohydrological and vegetation change reconstructions for the Lateglacial and Late Holocene in the central Ebro basin. A preliminary chronology is based on ^{210}Pb and ^{14}C AMS dates. The lacustrine sequence is composed of three sedimentary Sections. The Lower Section was deposited in a permanent saline to brackish lake. This stage represents the most humid period in the record and it was accompanied by the expansion of temperate trees (particularly *Corylus*). The Middle Section was deposited in an ephemeral playa-lake complex. Frequent subaerial exposure conditions favour the colonisation of the playa lake floor by *Chenopodiaceae* during a low water table period. This interval reflects the most arid conditions in the Salada Mediana record, including the current environment. A secondary temperate tree expansion occurred after the maximum aridity period. Aquatic plants and cyanobacterial mats spread in the lake during periods of raised water tables.This paleohydrological and vegetational evolution attests to large changes in effective moisture during the Lateglacial in the semi-arid northeastern Spain. The abundance of *Corylus* during the Lateglacial indicates that refugia for temperate trees were located along the Ebro valley during the Last Glacial Maximum. The Holocene sediments in the Salada Mediana records have been eroded, and the Upper Section represents deposition during the last few centuries. © 2000 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

The uniqueness of the Mediterranean regions on the Iberian Peninsula during the Last Glacial Cycle (LGC) in relation to both northern Europe and eastern Mediterranean regions has been well documented with pollen–climate response surface methodologies (Watts, 1986; Huntley and Prentice, 1988, 1993; Roberts and Wright, 1993; Cheddadi et al., 1997; Prentice et al., 1998), and preliminary results of lake-level changes (Guiot et al., 1993; Harrison and Digerfeldt, 1993; Harrison et al., 1993, 1996; Yu and Harrison, 1995). Most pollen- and lake-level records indicate that vegetational and hydrological changes in the region were responses more to effective moisture than to temperature fluctuations (Pons and Reille, 1988; Huntley and Prentice, 1993; Street-Perrott and Perrott, 1993; Davis, 1994; Valero-Garcés et al., 1998; Pantaleón-Cano et al., 1999). Increasingly better Lateglacial and Holocene records from the Iberian Peninsula reveal greater climate variability and more arid–humid transitions than previously documented (Huntley, 1988; Harrison et al., 1993; Huntley and Prentice, 1993; Davis, 1994; Pérez-Obiol and Julià, 1994; Lamb et al., 1995; Allen et al., 1996; Peñalba et al., 1997; Valero-Garcés et al., 1998; Giralt et al., 1999 in press).

An influence of North Atlantic climate during the Lateglacial and the Holocene has been illustrated by

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several pollen records from northwestern Iberia (Turner and Hannon, 1988; Guiot et al., 1993; de Beaulieu et al., 1994; Peñalba, 1994; van der Knaap and van Leeuwen, 1995; Allen et al., 1996; Peñalba et al., 1997), the Pyrenees (Jalut et al., 1992; Montserrat, 1992), and eastern Iberia (Pérez-Obiol and Julià, 1994; Wansard, 1996; Valero-Garcés et al., 1998). However, the timing and nature of the main climatic events in Mediterranean Iberia has also a connection with northern Africa (Ballouche et al., 1986; Pons and Reille, 1988; Lamb et al., 1989, 1995; Prentice et al., 1998; Valero-Garcés et al., 1998). The occurrence of a number of abrupt and rapid arid/humid transitions during the Holocene, clearly indicates that other mechanisms besides orbital forcing have controlled the location and intensity of the Azores high and the associated Mediterranean rainfall belt (Overpeck, 1989; Gasse et al., 1990; Harrison et al., 1996; Valero-Garcés et al., 1998).

To better understand the contradictions and to reconstruct a coherent history of the effective moisture for the region during the last Glacial cycle, new records from hydrologically sensitive regions in Iberia are needed. Most palaeorecord sites in Spain are located in high mountains or in coastal areas. Few sites are from low-elevation areas in interior Spain (Davis, 1994; Taylor et al., 1998; Dorado-Valiño et al., 1999), and most of them cover only short timescales. There are no available lacustrine records for the Lateglacial in the lowland regions of interior Iberia.

Potential sites for lacustrine palaeorecords outside the coastal and mountain areas exist. The semi-arid climate, and the presence of large endorheic regions have favoured the development of a large number of small saline lakes in Spain (Comín and Alonso, 1988; Pueyo-Mur and De la Peña, 1991). The reduced thickness of sediment accumulated in these basins, the presence of numerous hiati, and the complexity of evaporite deposition and early diagenetic processes have discouraged the study of these lacustrine basins as palaeoenvironmental and palaeoclimate records. Sediments accumulated in groundwater-fed, discharge playas that experience large fluctuations in water level, chemical composition and salinity are however potentially sensitive indicators of changes in the hydrologic budget. Several studies have shown the potential of these records in Iberia (Pueyo-Mur, 1979; Davis, 1994; Schütt, 1998a, b; Giralt et al., 1999; Valero-Garcés et al., 2000a). In this paper we apply palaeohydrologically sensitive lacustrine indicators (sedimentary facies, chemical, and stable isotope stratigraphy) and pollen analyses to a playa lake, Salada Mediana, located in the central Ebro Basin, NE Spain. A preliminary AMS ^{14}C- and ^{210}Pb-based chronology allows us to investigate several hypotheses for Lateglacial and Late Holocene palaeohydrological and vegetation evolution in the continental lowlands of northeastern Spain.

2. The climate of the central Ebro Basin

The central Ebro Basin is the most northern area of truly semi-arid climate in Europe. The climate is Mediterranean with a strong continental influence characterised by very hot summers, cold and dry winters, and low rainfall (300–350 mm yr^{-1}) due to the rainshadow effect of the Iberian Range (Capel Molina, 1981; García-Vera, 1996). Average values at Zaragoza airport, the closest weather station to Salada Mediana, are 320 mm of annual rainfall, 1194 mm of evapotranspiration, and 24.2 and 6.4°C average temperatures in July and January, the warmest and coldest months, respectively (Faci-González and Martínez-Cob, 1991). Below-freezing night-time temperatures are common in winter. Thermal stratification in winter causes long periods of fog and cold temperatures in the lowlands, which strongly limits vegetation growth. The presence of a strong, dry, and prevalent NW wind also contributes to an annual water deficit, especially during the 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). In the central Ebro valley, spring and autumn precipitation accounts for more than 70% of total annual rainfall; May is the wettest month (40.8 mm) and July the driest (16.8 mm). Depressions associated with the jet stream only affect central and eastern Iberia in spring and autumn when the jet stream is moving northward or southward, respectively. In winter, the jet stream steers depressions towards the straight of Gibraltar, but the size of the Iberian Peninsula is sufficient to form a winter anticyclone, which reduces precipitation still further. The mid-winter period is particularly important for groundwater recharge because this is the time when low temperatures restrict evapotranspiration (García-Vera, 1996).

3. Geographic location

The semi-arid climate has favoured the development of a large number of small saline lakes in the endorheic areas of the Iberian Peninsula. Four closed-drainage areas contain most of these ephemeral and shallow lakes: the central Ebro Basin, the northern Castilla, La Mancha, and the Guadalquivir basin (Comín and Alonso, 1988; Pueyo-Mur and De la Peña, 1991).

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. The long history of human occupation in the area has contributed to the transformation of the landscape since the Neolithic (Davis, 1994; Gutiérrez-Elorza and Peña-Monné, 1998). This unique ecosystem is characterised by the presence of a number of endemic species and

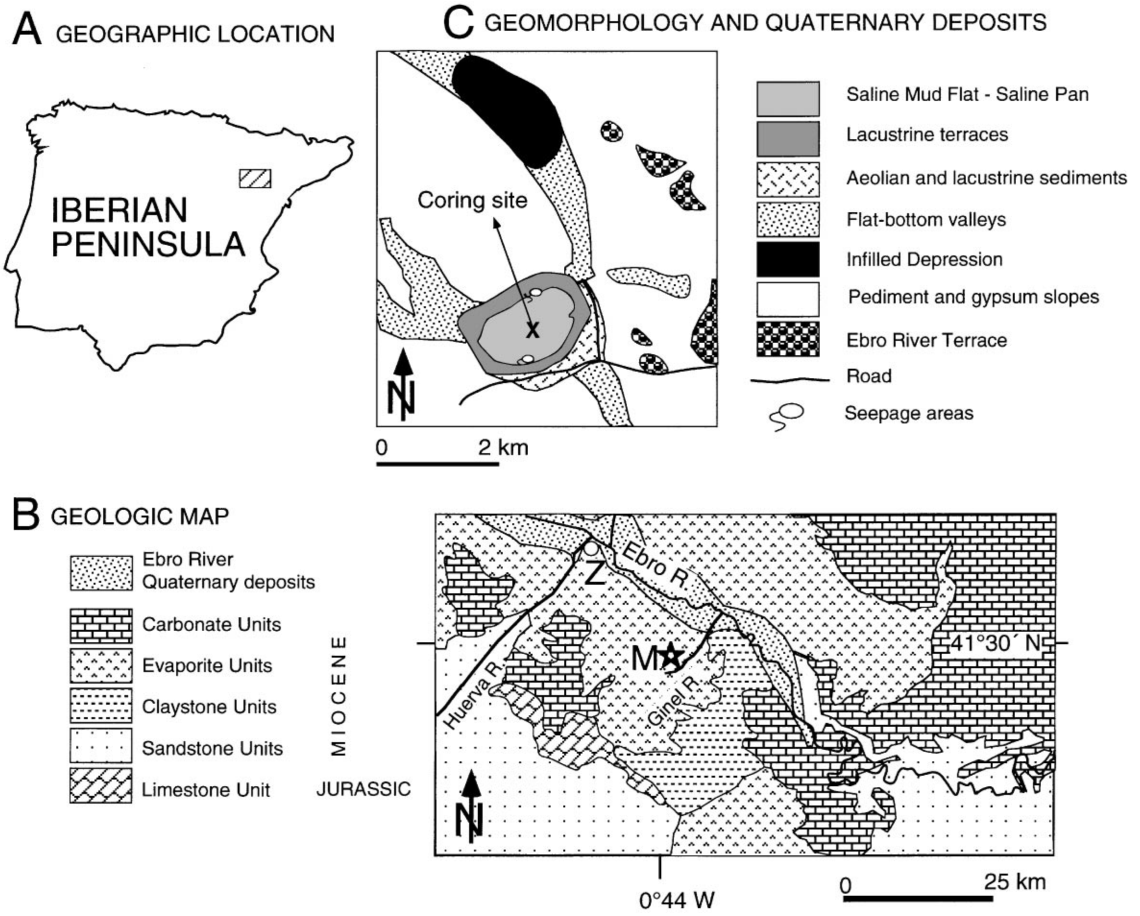

Fig. 1. (A) Geographic location. (B) Location of Salada Mediana in the Central Ebro basin, Iberian Peninsula, and Geologic map of the surroundings. Z = Zaragoza, M = Salada Mediana. (C) Geomorphologic map and location of the coring site.

others typical from northern Africa and the cold steppes of central Eurasia. Small relict forests are dominated by *Pinus halepensis, Quercus coccifera,* and *Juniperus*. Around the Salada Mediana area, and in the lowlands of the central Ebro basin, the mountain taxon *Juniperus thurifera* survives the extreme conditions and the winter thermal inversion. At higher altitudes (400–700 m a.s.l.), with less extreme conditions, a Mediterranean pine and oak (*Quercus ilex rotundifolia*) forest with a dense shrubland develops. The margins of the saline lakes are dominated by halophytic plant communities, e.g. *Salicornia* and other taxa of the *Suaedetum brevifoliae* association (Braun-Blanquet and Bolòs, 1957).

Most lake depressions in the central Ebro Basin occur in groups, particularly on the central plateau of Los Monegros (about 100, 16 of them flooded every year) and in the Bajo Aragón area (Pueyo-Mur and De la Peña, 1991; García-Vera, 1996). The brines are of a (Cl^-)–(SO_4^{2-})–(Na^+)–(Mg^{2+}) type and undergo strong seasonal oscillations in concentration because of groundwater input, evaporation and progressive salt precipitation. The genesis of the depressions has been related to dissolution of the underlying Tertiary evaporites, preferential water circulation through faults, differential erosion, and surface deflation (Pueyo-Mur, 1979; Pueyo-Mur and De la Peña, 1991; Benito et al., 1998; Sánchez-Navarro et al., 1998). In the Zaragoza area, these depressions were formed during the Upper Pleistocene as evidenced by the presence of *Elephas meridionalis* (van Zuidam, 1980).

The Salada Mediana playa lake (Latitude: 41°30′10″N, Longitude: 0°44′W, 350 m a.s.l.) is a small (main axis about 325 m × 500 m; surface area: 14 ha), seasonal (Z_{max}: 50–0 cm) playa lake, located 20 km southeast of Zaragoza, on the Miocene Zaragoza Formation (Fig. 1). The Salada Mediana waters are of a (SO_4^{2-})–(Cl^-)–(Na^+)–(Mg^{2+}) type, with low carbonate and calcium contents, and high Mg/Ca ratios. The salinity and composition of the brine vary greatly during the year (Valero-Garcés et al., 2000a). The playa lake is fed by rainfall, runoff and groundwater. Modern accumulation in Salada Mediana is dominated by chemical precipitation of sulphates (gypsum, mirabilite, thenardite, bloedite), chlorides, and carbonates (dolomite, high-magnesium calcite, calcite).

4. Methods

Two long cores (165 cm long) were retrieved with a modified 5 cm diameter Livingstone corer in the centre of the lake in August 1996. A short core (45 cm long) was taken in 1997 and sampled in the field at 1 cm intervals for ^{210}Pb analyses. Sedimentary facies were identified based on colour, lithology, and sedimentological structures. One long sediment core was split, photographed, described, and sampled every 1 cm for organic matter and carbonate content, and every 5 cm for other analyses. Organic matter contents were determined by loss-on-ignition analyses, and carbonate content was measured with a calcimeter. The long and short cores were correlated using organic matter and carbonate contents and sedimentary facies. Sediment mineralogy was determined by a Siemens D-500 diffractometer; percentages of the different mineral species were calculated using relative reflectance factors and are semi-quantitative. Clay minerals were identified on oriented samples ($< 2\ \mu$m), dried at room temperature, and treated with ethylene glycol. Carbon and sulphur elemental analyses were performed with a Perkin-Elmer 260 Analyser. Bulk sediment samples were digested with a heated mixture of HCl and HNO_3 acids (3 : 1 ratio), filtered, and analysed for major (Ca, Mg), minor (Al, Sr, Na, Fe, Mn) and trace element (B and Li) composition with a JY 98 Inductively Coupled Plasma spectrometer. Potassium content was measured with a Perkin Elmer/Coleman 51-Ca photometer. Pollen samples integrate 1.5 cm thick intervals. The pollen was extracted in 18 samples by the classic chemical method modified, without acetolysis, and concentrated using Thoulet (Dupré, 1992). *Lycopodium* spores were added to the samples to calculate the pollen concentration (Stockmarr, 1971). The chronology is constrained by ^{210}Pb dating of the short core, and 6 AMS ^{14}C dates from pollen concentrates. The concentrates were obtained following the same chemical method with HF, HCl, KOH, and Thoulet and they are composed of pollen grains, and some charcoal and other unidentified organic matter particles in small amounts. Oxygen and carbon isotopic compositions were measured on bulk-sediment samples following standard procedures, and the isotopic values are reported in the conventional delta notation relative to the PDB standard. Most samples were composed of only one carbonate phase (stoichiometric, well-ordered, non-ferroan dolomite). For samples with a mixed calcite and dolomite mineralogy, a double extraction at 25 and 50°C was performed. The δ^{13}C values of organic matter were measured after carbonate removal with HCl 1 : 1. Isotopic compositions of cyanobacterial mats and halophytic plants were also analysed. Analytical precision was better than 0.1‰ for δ^{18}O and δ^{13}C in carbonates and organic matter.

5. Results

5.1. Sedimentology and geochemistry

The 150 cm long sediment sequence overlying the Miocene gypsum is composed of massive to vaguely banded grey muds with some thin gypsum layers intercalated at the bottom, and topped by laminated black sediments (Fig. 2). The sediments are fine-grained ($< 20\ \mu$m), and mainly composed of gypsum, dolomite, illite, quartz, and organic matter, with variable amounts of salts (mirabilite, thenardite, and bloedite). A detailed description of facies and geochemical composition of the sediments is provided elsewhere (Valero-Garcés et al., 2000a). Three sedimentary sections are identified based on sedimentary structures, facies and mineralogy. The Lower Section (150–107 cm) is composed of massive, grey, dolomite- and gypsum-rich muds with abundant gypsum (as laminae and isolated crystals) and intervals richer in organic matter content and with the highest carbonate contents of the whole core. The interval 121–107 cm depth has the lowest carbonate, organic matter and clay mineral content, and the highest gypsum content. The overlying Middle Section (107–19 cm) is composed of massive to banded (up to several cm thick) grey, greenish and reddish muds without gypsum laminae and crusts. The section is characterised by low and relatively constant carbonate content, and higher organic matter. The contact between the Lower and Middle Sections is marked by abrupt changes in sediment composition and sedimentary structures as evidence of an unconformity. The sediments from the lower half (107–70 cm) are green-grey and dark-grey, and with higher organic matter content. They change gradually upcore to grey-red sediments with low organic matter contents (70–19 cm). There are two intervals with abundant isolated gypsum crystals (107–92 and 40–30 cm depth), and two intervals with higher clay mineral content (80–60 and 30–19 cm depth). Sulphates (thenardite and bloedite) are more abundant in the upper half of the Middle Section. The limit between the Middle and Upper Sections has been located following mineralogical criteria at the first appearance of calcite in the core. The Upper Section (19–0 cm) is characterised by the occurrence of calcite, higher content of the more soluble sulphates (mirabilite, thenardite, and bloedite), and the dark-grey, banded (19–9 cm) to black, laminated (9–0 cm) nature of the sediments.

Dolomite is the only carbonate phase occurring in the Lower and Middle Sections. Although only one dolomite phase was identified by XRD techniques, the presence of both, detrital and authigenic dolomites is likely. The occurrence of dolomite in a restricted number of surface playa lake sediments in the Ebro Basin (Mingarro et al., 1981) suggests that dolomite-bearing formations are only local suppliers of detrital dolomite and not regional

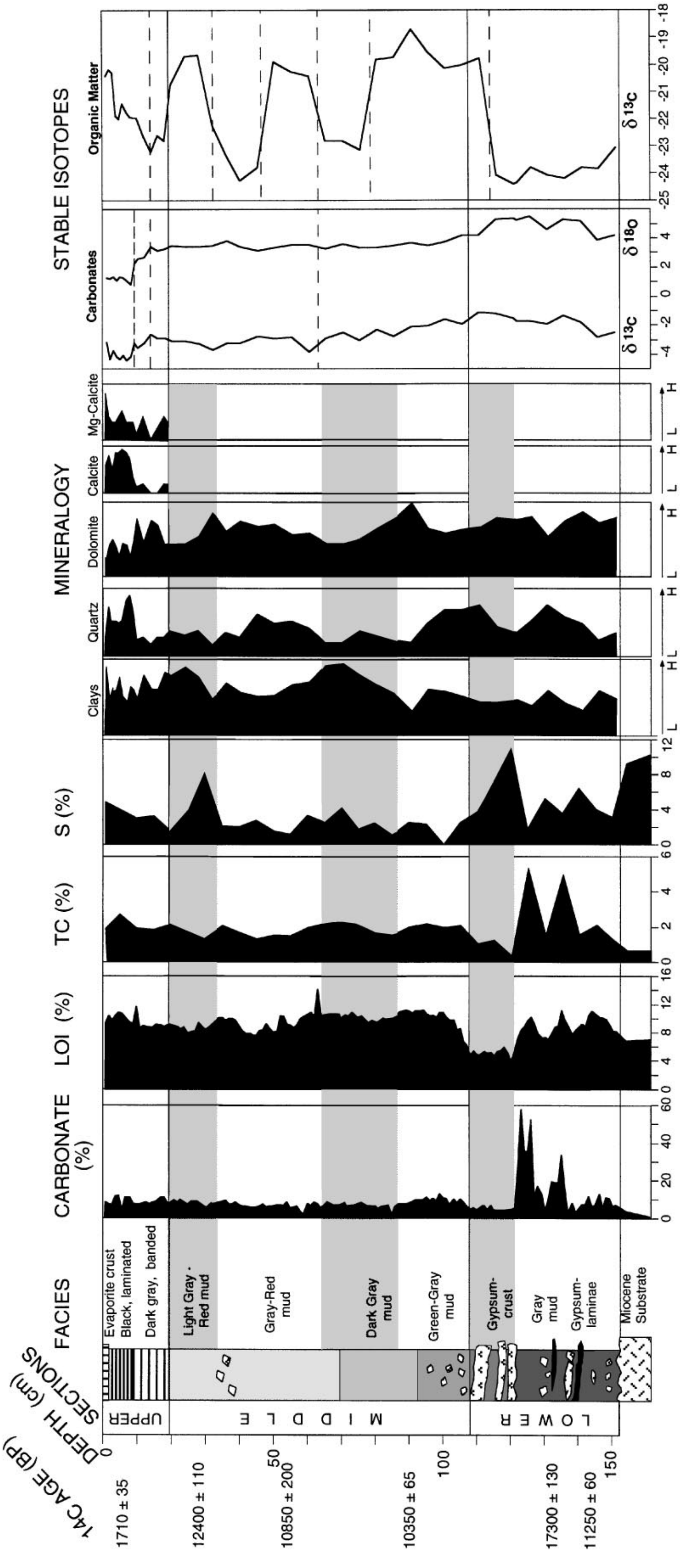

Fig. 2. Sedimentary facies, sediment composition (LOI: loss on ignition, TC: total carbon, S: total sulphur), semiquantitative mineralogy (L: low, H: high content), and stable isotope composition of the Salada Mediana core. The shadow intervals indicate the main arid periods based on sedimentology, lithology and mineralogy. Dashed lines mark the main transitions in stable isotopic composition of dolomite and bulk organic matter.

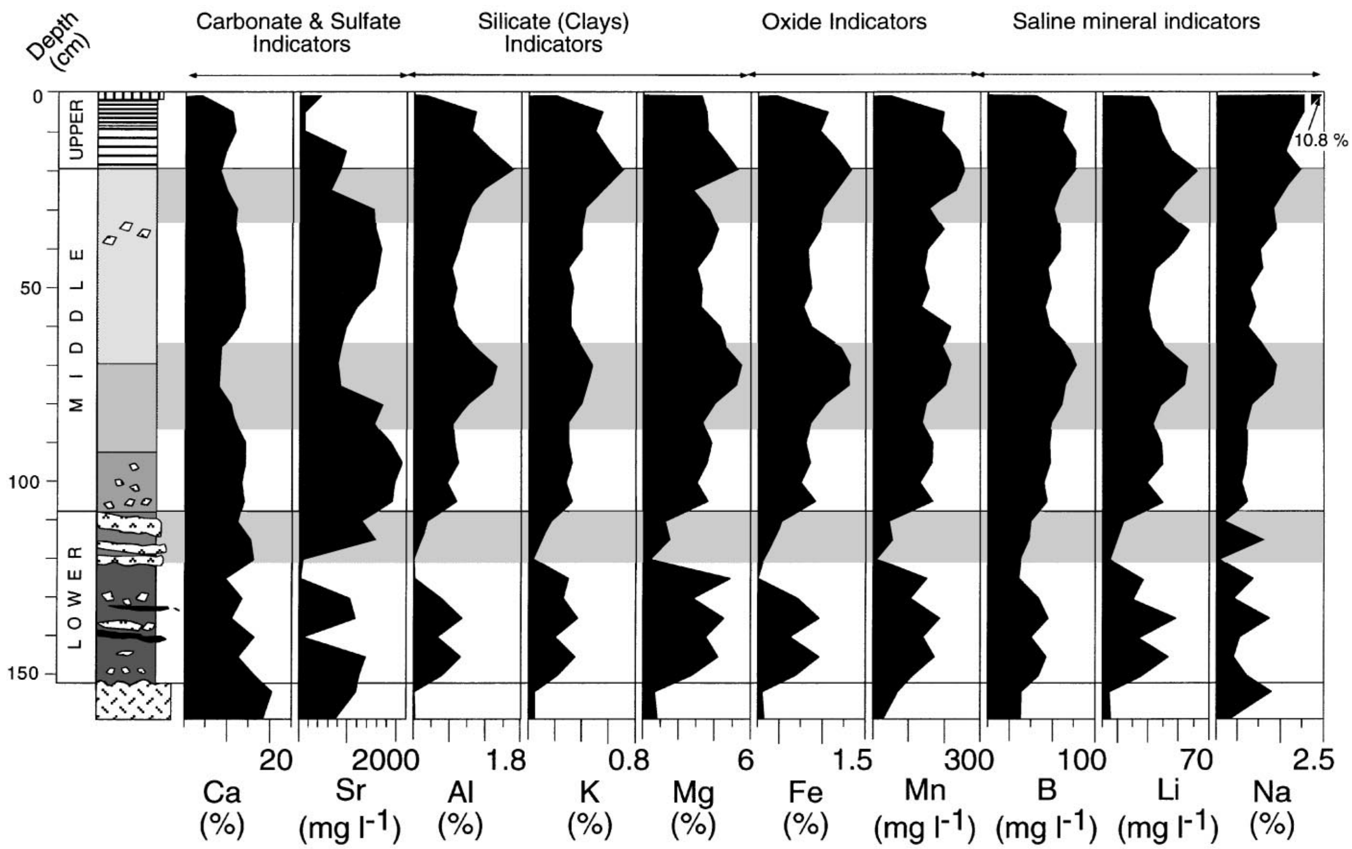

Fig. 3. Chemical composition of the Salada Mediana core. The shadow intervals with higher contents in elements derived from silicate (Al, K, Mg), oxide (Fe, Mn) and saline (B, Li, Na) minerals define the main arid periods in the Middle Section. The shadow interval at the top of the Lower Section corresponds to the gypsum-rich interval also identified as an arid period.

sources for the Ebro valley. The dolomite-bearing formations in the Salada Mediana watershed are the Miocene Zaragoza Formation, the Quaternary lacustrine and aeolian deposits, and the saline soils. They likely contribute some aeolian dolomite to the lacustrine sediments. Isotopic and sedimentological data indicate that calcite and dolomite form in the modern environment and also during deposition of the Upper Section (Valero-Garcés et al., 2000a). Environmental conditions in the Lower Sections were also conducive to dolomite formation. In summary, although there are possible sources of detrital (aeolian) dolomite, we assume that most dolomite in Salada Mediana formed from lacustrine or interstitial waters.

Fig. 3 shows the main chemical proxies for Salada Mediana sediments. The calcium curve primarily reflects the gypsum content, and secondarily, the carbonate content. In the Lower Section, it shows a decreasing trend in the lower part, and peak values in the gypsum-rich interval that parallel the sulphur content trends. The carbonate-rich intervals are not reflected in the Ca content, indicating that dolomite is a subordinate source of calcium. The relatively Ca-poor intervals in the Middle Section (80–60 and 30–19 cm depth) correlate with lower gypsum and dolomite, and higher clay mineral contents. Strontium follows a similar pattern like calcium, with lower values in the Lower Section and in the clay-rich intervals of the Middle Section. Lower Sr values in the Upper Section are consistent with the decrease in the dolomite content and the increase in calcite. The chemical elements associated to clays (Al, K, and Mg), oxides (Fe, Mn) and saline minerals (Na, Li, and B) show similar patterns: (i) moderate and fluctuating values in the Lower Section, (ii) a sharp decline in the gypsum-rich interval (121–107 cm depth), (iii) two increasing trends in the Middle Section with peak values in the intervals 80–60 and 30–19 cm depth separated by a sharp decline at around 60 cm depth, and (iv) a decreasing trend in the Upper Section. A large increase in sodium in the uppermost sample (10.8%) reflects the presence of halite, mirabilite and thenardite in the crust that covered the bottom of the lake.

5.2. The isotope record

A large range (almost 5‰) and high values (between 0.8 and 5.47‰) characterise the $\delta^{18}O$ record for the Salada Mediana dolomite samples (Fig. 2). The heaviest oxygen compositions (> 5‰) occur in the Lower Section. Following a negative shift above the gypsum-rich interval (1.2‰), values decrease to 3.5‰ during the lower half of the Middle Section. Isotopic values remained similar with slight decreases through the upper part of the Middle Section and the transition to the Upper Section. Two rapid negative shifts of about 1.2‰ occurred at 12 cm and at the base of the black, laminated sediments (9 cm depth). The top sediments (9–0 cm depth) are characterised by the lowest isotopic values.

The Lower Section also has the heaviest $\delta^{13}C_{dol.}$ (dolomite) compositions. The transition to the Middle Section correlates with the onset of a decreasing $\delta^{13}C_{dol.}$ trend that continues into the lower half of the Middle Section. Similar to the $\delta^{18}O$ record, the values show little variability in the upper half of the Middle Section. A large negative shift (1.4‰) occurs at 12 cm depth, preceding a 4 cm interval of rapid $\delta^{13}C_{dol.}$ decrease and the lightest values in the core (− 4.41‰).

The $\delta^{13}C_{org.}$ (bulk organic matter) curve (Fig. 2) shows two distinct populations: (i) samples with $\delta^{13}C_{org.}$ values between − 25 and − 22‰, and (ii) samples with $\delta^{13}C_{org.}$ values between − 22 and − 19‰. The absence of parallel trends with $\delta^{13}C_{dol.}$ values suggests that changes in the particulate organic matter and not in the dissolved inorganic carbon are the main factors in the isotope composition of the bulk organic matter. Under current conditions, cyanobacterial mats are the main carbon producers in the saline pan, while halophytic vegetation dominates the saline mudflats. These two main organic carbon sources have distinctive $\delta^{13}C$ values: cyanobacterial mats have considerably heavier values (between − 12.8 and − 11.2‰ PDB) than terrestrial halophytic plants (between − 20 and − 24‰ PDB). Supplies of both aquatic and terrestrial organic matter to the sediments are important for the Salada Mediana carbon budget. Changes in the surface extent of saline pan/saline mudflat environments will have a large impact on the relative proportion of these constituents incorporated into the sediments.

5.3. Pollen

Pollen results are presented in Fig. 4. The large percentage of arboreal pollen is striking, considering that the modern vegetation is devoid of trees. Besides a dominating *Pinus*, other trees present are *Juniperus* and *Quercus ilex-coccifera type*. Modern pollen rain data, however, also show a large percentage (up to 50%) of *Pinus*, which indicates that most has been transported from the Pine forest in the Alcubierre Sierra and other small forest patches in the Ebro Basin. The pollen record of Salada Mediana reflects three different vegetational communities: (i) a regional pollen influx from the surrounding steppe and mountain environments (*Juniperus, Pinus, Quercus ilex-coccifera type*), (ii) the terrestrial (*Chenopodiaceae*) and aquatic (*Myriophyllum, Ruppia*) vegetation in the Salada Mediana itself, and (iii) the evolution of gallery forests — mostly composed of *Corylus* and other deciduous trees — along the Ginel and Ebro rivers, and some smaller creeks. Based on variations of the most important ecological taxa we have identified from the bottom to the top four pollen zones.

5.3.1. Zone IV (150–107 cm)

This zone correlates with the Lower sedimentary Section. Maxima of *Corylus* and minima of *Chenopodiaceae* suggest a significant presence of trees in areas close to the lake, most likely in the streams feeding the lake, or in the nearby valleys of the Ginel and the Ebro rivers. These *Corylus* communities could also include some other deciduous trees (*Alnus, Salix, Quercus faginea-pubescens type, Fraxinus*). In the pollen diagram, the *Oleaceae* column includes the genus *Phillyrea, Fraxinus,* and *Olea*. The presence of some thermophilous taxa (*Pistacia, Myrtus*, and particularly *Ceratonia*) — today absent in the areas nearby Salada Mediana (Viñuales and Vericad, 1996) — indicates warmer temperatures or minimum winter temperatures not as extreme as today. The presence of fern spores and freshwater aquatic plants (particularly *Myriophyllum*) defines a period of freshwater conditions in the lake that correlates with the maximum *Corylus* development. *Poaceae* and *Liliaceae* are the most significant grasses in this period. At a regional scale, the vegetation would be an open Mediterranean forest, dominated by *Pinus, Quercus ilex rotundifolia, Quercus coccifera*, and *Juniperus*. The upper part of pollen zone IV corresponds to the gypsum-rich interval and is characterised by decreasing percentages of *Corylus* and other deciduous trees, a slight increase in *Chenopodiaceae*, and the disappearance of *Myriophyllum*. The increase in *Oleaceae* could indicate the substitution of *Corylus* by *Fraxinus* as the main component of the gallery forest. The pollen concentrations are among the highest, although the number of taxa is smaller than in other zones.

5.3.2. Zone III (107–70 cm)

It correlates with the lower half of the Middle Section. The pollen spectra are characterised by the highest *Chenopodiaceae* percentages (up to 25% of total, up to 50% without pine), consistent with a frequently dry Salada Mediana. The relative increase in *Juniperus* and *Quercus ilex type*, correlating with the *Corylus* demise at the base of this unit could indicate an expansion of regional Mediterranean and steppe environments, and the decrease of the gallery forest along the rivers. However, because of the relatively small surface of the Salada Mediana, the large amounts of *Chenopodiaceae* could mask the arboreal pollen rain. Therefore, the decrease in temperate trees forests could be smaller than suggested by the pollen diagram. The upper part of this pollen zone has very low percentages of aquatic plants, a decrease of *Poaceae*, the

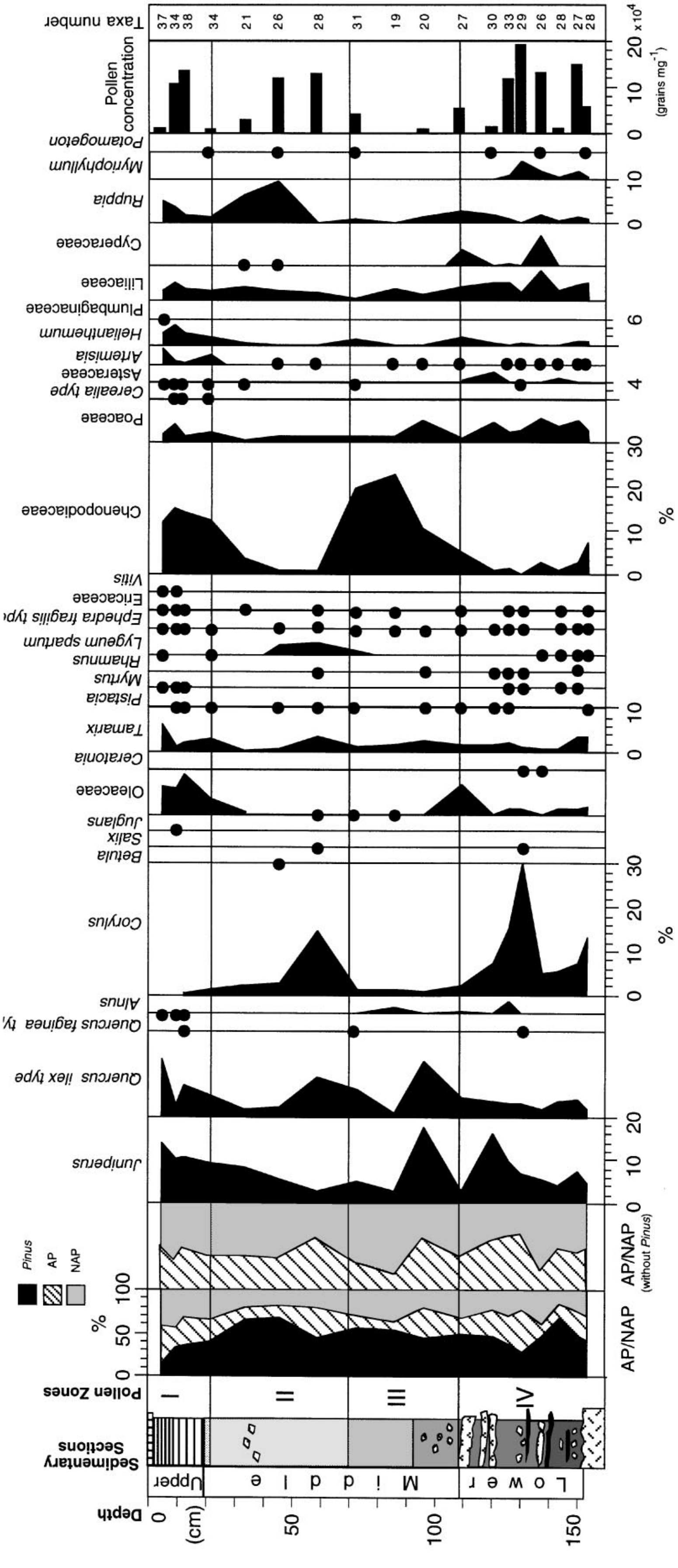

Fig. 4. Salada Mediana pollen diagram with most representative taxa. Dots indicate pollen percentage lower than 1%.

highest *Chenopodiaceae* content, and lower taxa variability, suggesting even more frequent desiccation stages in the Salada Mediana. All these indicators identify pollen zone III as the most arid period in Salada Mediana. Intervals of low pollen concentration as those at the top of this zone correspond to periods of reduced vegetation when the dominant taxa are non-arboreal (Pantaleón-Cano et al., 1996, 1999). Some of the thermophilous taxa (*Pistacia, Myrtus, Ceratonia*) disappear, likely as a result of increasing intensity of summer droughts.

5.3.3. *Zone II (70–22 cm)*

An increase in arboreal pollen, particularly *Pinus* but also *Corylus*, and *Quercus ilex type*, and a sharp decrease in *Chenopodiaceae* mark the lower boundary of this zone that corresponds to the upper part of the Middle sedimentary Section. The peak in *Corylus* indicates the recovery of some deciduous forest patches after their demise in the previous zone. The highest percentages of *Ruppia* suggest that the Salada rarely dried out. The upper part of this zone shows again a decrease in trees (*Pinus, Corylus*) and aquatic plants (*Ruppia*), and an increase in *Chenopodiaceae* and *Artemisia* indicating generally more arid conditions, and frequent desiccation events in the lake.

5.3.4. *Zone I (22–0 cm)*

This unit is characterised by the appearance of anthropogenic indicators (*Cerealia type, Vitis, Asteroideae, Cichorioideae, Centaurea, Artemisia, Plantago, Malvaceae, Urticaceae, Brassicaceae*, *Asphodelus*, etc.). The high *Oleaceae* percentages could include, besides *Fraxinus* and *Phillyrea*, cultivated *Olea europaea*. Harsh climate and poor soils however stopped olive cultivation in the Mediana area in more recent times. Although arboreal — and particularly pine — pollen content decreases, there is no clear evidence of deforestation during this period. Most tree and shrub taxa remain with similar percentages at the top of the Middle Section and the lower part of the Upper Section, implying that regional tree cover did not significantly change. High percentages of *Chenopodiaceae* and the low content of *Ruppia* suggest arid conditions similar to modern. The upper part correlates with the black, laminated sediments and it is characterised by the lowest pine values, but a relative increase in other arboreal taxa.

5.4. *Chronology*

Reliable chronologies for saline lake sequences in Iberia have been hindered by the scarcity of terrestrial macrofossils for radiocarbon dating (Davis, 1994; Burjachs-Casas et al., 1996; Schütt, 1998a, b; Giralt et al., 1999; Valero-Garcés et al., 2000b). Our preliminary chronological model for Salada Mediana is based on six AMS ^{14}C dates from pollen concentrates (long core), and a ^{210}Pb chronology for the uppermost sediments from the short core (Tables 1 and 2, Fig. 5). The ^{210}Pb content in the upper sediments is very low, and unsupported ^{210}Pb is only found in the top 4 cm (Table 2). The unsupported ^{210}Pb flux of 0.14 pCi cm^{-2} yr^{-1} is relatively low compared to north temperate mid-continental regions. Similar low values occur in another saline lake in the Ebro Basin (Salada Chiprana: Valero-Garcés et al., 2000b), and they are coherent with low regional atmospheric fluxes of ^{210}Pb as expected in an arid region. Supported ^{210}Pb is almost constant, and activities in the upper 4 cm show a monotonic decline with depth (Fig. 5A). If we use the constant flux: constant sedimentation model (Olsson, 1986), we obtain a mean accumulation rate of 0.06 g cm^{-2} yr^{-1}, which gives an age of c. 100 yr at 4 cm (Fig. 5B). All other proxy records (sedimentological, isotopic, geochemical) give evidence of similar environmental conditions and absence of sedimentary hiati during deposition of the top (0–9 cm), black, laminated sediments (Figs. 2 and 3). Extrapolation of the ^{210}Pb-derived mean sedimentation rate would give a basal date for the laminated interval of c. 1820 AD.

The large discrepancy between the ^{210}Pb-derived age (1860 AD calendar years at 5.5 cm) and the youngest AMS ^{14}C date (1710 ± 35 BP at 4.5–5.5 cm) (Fig. 5C) suggests either the presence of a sedimentary hiatus or

Table 1
^{14}C AMS dates of Salada Mediana sediment core

Depth (cm)	Material	Weight (mg)	^{14}C age (yr BP)	Error (yr BP)	Fraction modern	δ^{13}C PDB (measured) (‰)	Lab number
Long core (this study)							
4.5–5.5	Pollen concentrate	27.23	1710	35	0.8078 ± 0.0037	− 23.13	OS-16717
28–29.5	Pollen concentrate	0.97	12,400	110	0.2134 ± 0.0029	− 25.4	NSRL-10586
50–51	Pollen concentrate	3.3	10,850	200	0.25942 ± 0.00654	− 25.06	OS-14932
89.5–91	Pollen concentrate	0.64	10,350	65	0.2756 ± 0.0023	− 23.6	OS-22658
132.5–135	Pollen concentrate	0.94	17,300	130	0.1159 ± 0.0019	− 25.0	NSRL-10588
146.5–148	Pollen concentrate	0.89	11,250	60	0.2468 ± 0.0019	− 25.4	NSRL-10589
Long core (Pérez et al., 1998)							
130	Bulk organic matter		12,700				

Table 2
^{210}Pb analyses of the upper part of the Mediana short core

Interval (cm)	Cum. dry mass (g cm^{-2})	Unsup. activity (pCi g^{-1})	Error (± s.d.)	Age (base interval) (yr)	Error (± s.d.)	Date AD	Sediment Accum. (g cm^{-2} yr^{-1})	Error (± s.d.)
0–1	1.08404	1.9365	0.1448	19.56	9.37	1978	0.0552	0.01097
1–2	2.2928	1.197	0.143	47.57	19.37	1950	0.0433	0.01728
2–3	3.6022	0.3629	0.1307	67.12	33.52	1931	0.067	0.05496
3–4	4.8715	0.3179	0.078	107.02	113.5	1891	0.0318	0.06445

Supported ^{210}Pb: 0.5698 ± 0.0737 pCi g^{-1}

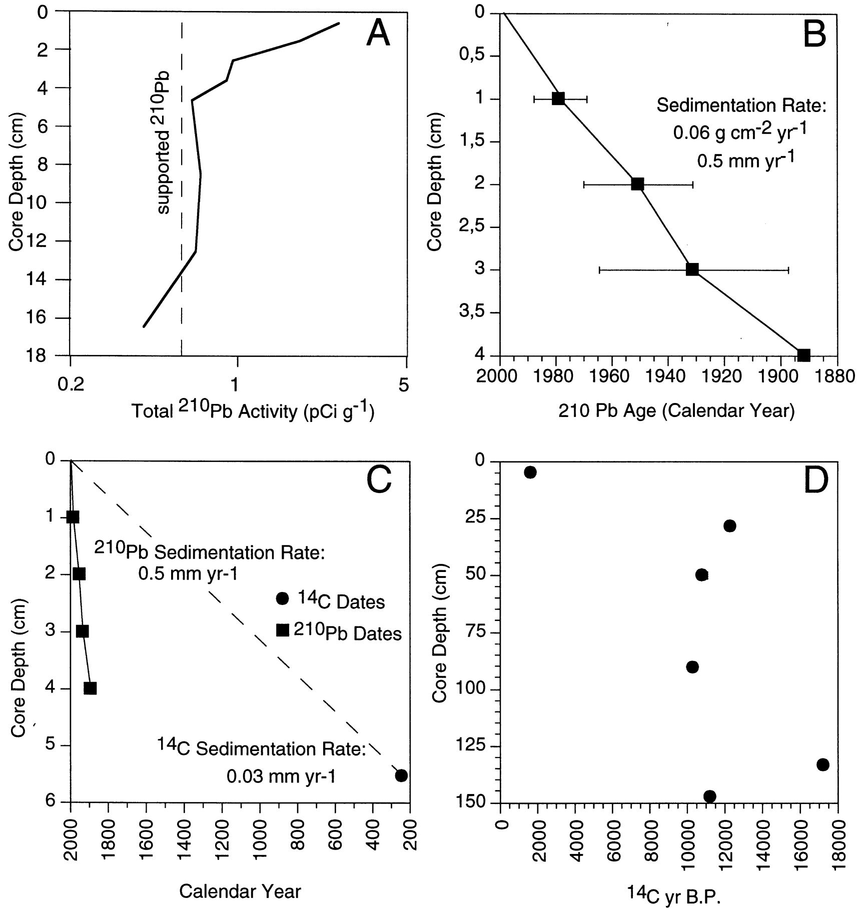

Fig. 5. Chronological framework for the Salada Mediana sequence. (A) Total ^{210}Pb activity in the Upper Section. (B) Average sedimentation rate and age (constant rate of supply model). (C) Comparison between the ^{210}Pb and ^{14}C dates for the upper 6 cm of sediments. (D) Age–depth relationship for the AMS ^{14}C dates.

a reservoir effect of about 1600 yr. A mixed origin (terrestrial and lacustrine) for the pollen dated in the upper sample — suggested by the relatively heavier δ^{13}C value (− 23.13‰ PDB, Table 1) — could be responsible for such a reservoir effect.

Five AMS ^{14}C dates on pollen concentrates are available for the Middle and Lower Sections of the Mediana core (Table 1, Fig. 5). Another core studied by Pérez et al. (1998) gave a basal date of 12,700 ^{14}C yr BP for a bulk organic matter sample (Table 1). The AMS dates seem to confirm that most of the Lower and Middle Sections of the Mediana sequence represent the Lateglacial. A combination of several factors may account for the age inversions, particularly a hardwater effect and contamination by old detrital carbon. The presence of lacustrine organic matter remains and aquatic plant pollen in the pollen concentrates could produce a hardwater effect during the Lateglacial. The microscope checks of pollen concentrates indicate that the presence of unidentified particulate organic matter is very small. In addition to that, the $\delta^{13}C$ values (around $-25‰$ PDB) do not indicate any significant presence of lacustrine organic matter in the dated samples. However, a reservoir effect cannot be ruled out completely in some samples. Geyh et al. (1998) have shown that the reservoir effect is not constant with time for a specific lake, and it is mainly a function of the volume/surface ratio, and consequently depends on water depth. They documented how in hydrologically closed lakes the reservoir effect may change several thousands of years over a short period. The date of 17,300 ± 130 ^{14}C yr BP at 132–135.5 cm depth could be affected by a large reservoir effect due to the presence of relatively large amounts of aquatic pollen (*Myriophyllum*) in the sample. Even though the pollen and the sedimentological data do not suggest significant reworking in these levels, there could be some contamination with older organic material. In spite of the chronological uncertainties, this preliminary chronological framework suggests the presence of a Lateglacial sequence (Lower and Middle sedimentary Sections) and a historic sequence (Upper Section) in the Salada Mediana core with a long hiatus in between.

6. Interpretation and discussion

6.1. Paleohydrological and vegetational change in Mediana

Fig. 6 summarises the palaeolimnological and vegetational evolution of Salada Mediana. The development of a karstic depression in the Miocene gypsum substratum led to the origin of a permanent saline lake. The characteristic features of the Lower Section (alternating high carbonate muds and gypsum laminae) suggest deposition in a sulphate–carbonate lake system with alternating brackish (carbonate-dominated) and hypersaline (gypsum-dominated) stages (Hardie et al., 1978; Smoot and Lowestein, 1991). The intervals with abundant large gypsum crystals and clusters — particularly at 121–107 cm depth — are interpreted as periods when brine concentrations led to formation of diagenetic gypsum, perhaps when the lake desiccated.

The $\delta^{18}O$ curve cannot be interpreted as a function of simple evaporation from a closed system that would be related to salinity. The $\delta^{18}O$ of precipitating carbonates

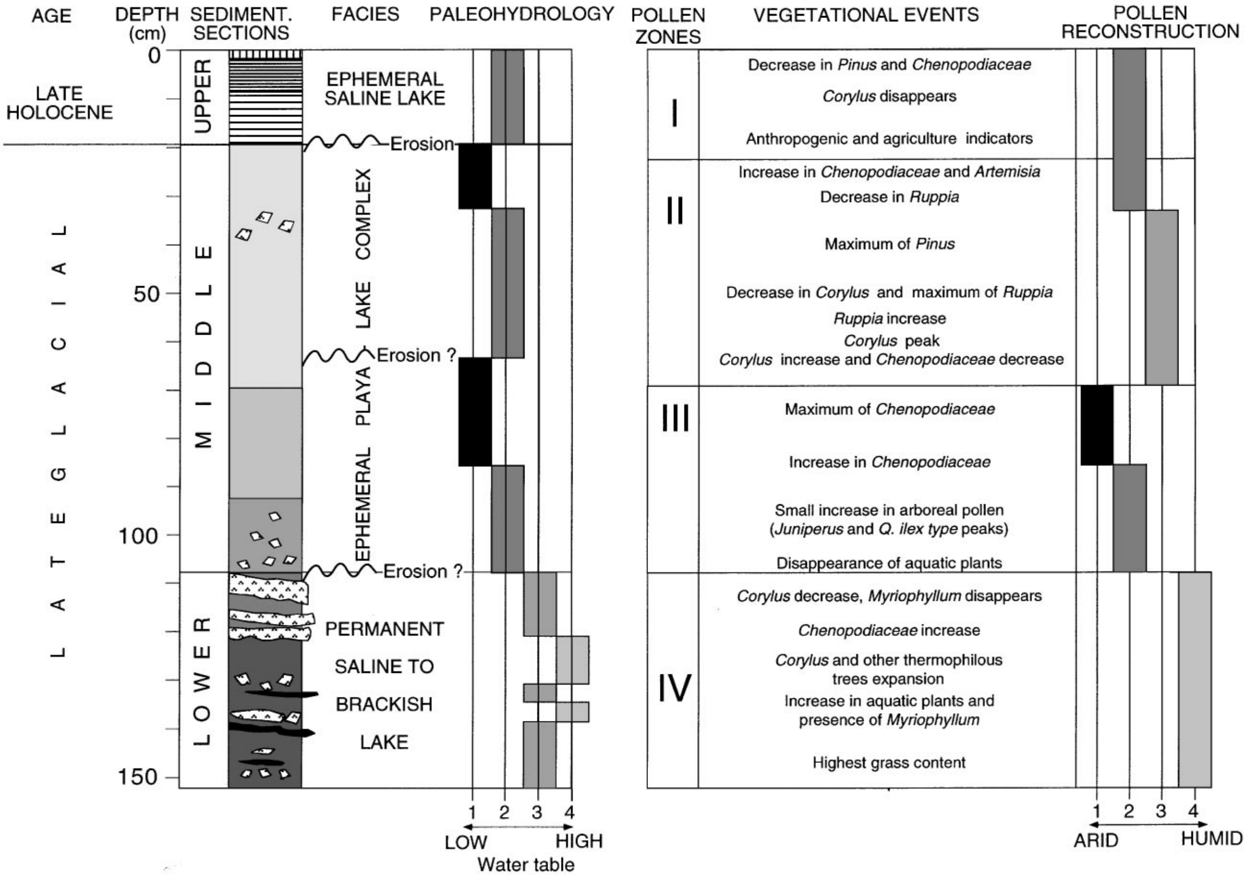

Fig. 6. Paleohydrological evolution and vegetational history of Salada Mediana. The paleohydrological evolution is based on sedimentological, geochemical and isotopic proxies. The numbers indicate the dominant depositional subenvironment: 1. saline mudflats, 2. saline pan–ephemeral shallow saline lake, 3. permanent saline lake, 4. permanent brackish lake. The main vegetational events and the effective moisture reconstruction are based on pollen data.

depends on both the temperature of formation, and the isotopic composition of the water (Siegenthaler and Eicher, 1986; Talbot, 1990; Chivas et al., 1993). Carbon isotopic ratios of bulk organic matter and carbonate track sediment organic matter sources, lake paleoproductivity, changes in vegetation and catchment hydrology, and variations in the dissolved inorganic carbon (DIC) pool, controlled by input and biological processes, mainly respiration and photosynthesis (Hakansson, 1985; Talbot and Kelts, 1990; Aravena et al., 1992; Meyers, 1994).

Geochemical indicators — the lowest values of boron, and relatively low values of lithium and strontium — and palynological evidence — abundance of *Corylus*, and presence of *Myriophyllum sp.* — identify the carbonate-rich intervals in the Lower Section (135–123 cm) as the freshest stage in the whole sequence. More negative $\delta^{13}C_{org.}$ values in the Lower Section are also consistent with a deeper brackish lake without cyanobacterial mats. They correlate with high arboreal pollen concentrations, implying a more vegetated watershed. The high $\delta^{18}O$ values in the Lower Section, and the strong isotope covariance between carbon and oxygen isotope values point to hydrologically closed conditions, long residence time, and isotopically evolved waters (Talbot, 1990; Li and Ku, 1997). Isotopically heavy, but relatively low-salinity lake waters could also result from either changes in the moisture sources or seasonality (more summer precipitation). At a regional scale, the vegetation would be an open Mediterranean forest, dominated by *Pinus,* non-deciduous *Quercus* and *Juniperus*. The gypsum-rich interval does not show a significant decrease in *Juniperus* and *Quercus*, suggesting that the regional forest did not greatly change during this hydrological crisis.

The vaguely banded nature of the sediments, relatively high organic matter and low carbonate contents in the lower half of the Middle Section (107–92) cm) are congruent with ephemeral shallow saline lake–saline pan environments. The upcore increasing trends (92–65 cm) in clay mineral content (illite), and saline element indicators in the Middle Section are interpreted as a reflection of the progressive dominance of desiccation (saline mudflat) versus flooded (saline pan) stages. The clay-rich intervals could result from efflorescent crust development and deposition of small amounts of wind-blown material in small depressions when the water table was below the sediment surface. Intervals of higher sulphate contents are also interpreted as increasingly arid conditions, more conducive to gypsum formation. The intervals of lower Na, B and Li contents correspond to periods of increasing water balance in the lake.

Average lake levels in Salada Mediana were lower during the Middle Section than during the humid period that inaugurated sedimentation in the lake (Lower Section). After the arid period reflected in the gypsum-rich interval, an increase in water balance allowed the development of a playa-lake with a saline pan colonised by bacterial–algal mats, and surrounded by saline mudflats with halophytic vegetation. We propose an increase in lacustrine bacterial and algal organic matter input during the saline lake periods as the cause of positive $\delta^{13}C_{org.}$ excursions during the Middle Section. The two lower positive excursions (110–80 and 65–50 depth intervals) correspond to facies with lower clay content and lower values of silicate, oxide (Al, Fe and K), and saline (B, Li and Na) mineral indicators, and higher content of calcium and strontium. All these proxies suggest an increased water balance in the Salada with frequent flooded stages. The increase in boron, lithium, sodium, and clay contents, the abundance of *Chenopodiaceae* pollen, and a sharp decrease in $\delta^{13}C_{org.}$ values during the 80–65 cm depth interval indicate the progressive dominance of desiccation (saline mudflat) versus flooded (saline pan) stages. Following this arid interval, the perennial saline pan environments dominated again in Salada Mediana (65–30 cm depth interval). Increased water balance produced a decrease in sodium, boron and lithium content in the sediments and a sharp decrease in *Chenopodiaceae*. A synchronous short expansion of *Corylus* and *Quercus ilex type* also indicates more humid conditions and, perhaps, a climatic amelioration. Increasingly arid conditions resulted in a decrease of *Corylus* and *Quercus ilex type* and a progressive increase in *Juniperus* and *Pinus*. The chemical enrichment of the Salada sediments during this interval indicates frequent periods of subaerial exposure. However, during the flooded episodes, *Ruppia* dominated the aquatic vegetation in the Salada Mediana, as indicated by the maximum values in the pollen diagram. The negative $\delta^{13}C_{org.}$ excursion (50–30 cm interval), synchronous to the *Ruppia* peak, also suggests that cyanobacterial mats did not dominate the flooded areas of the lake. The sediments from the top of the Middle Section (30–19 cm depth interval) show peak values of chemical indicators of aridity, higher clay content, and more abundant isolated gypsum crystals and aggregates which indicate the dominance of mudflats. These expanded environments would be colonised by *Chenopodiaceae*, which shows an increase during this interval. Bacterial mats were likely the main organic producers during the reduced flooded episodes (saline pan subenvironments), as indicated by the *Ruppia* decrease and the sharp positive $\delta^{13}C_{org.}$ excursion at the top of the Middle Section.

The dolomite isotope compositions do not show the limnological and hydrological fluctuations deduced by other proxies in the Middle Section. The $\delta^{13}C$ and $\delta^{18}O$ values slightly decreased during the lower half, and remained constant during the upper half. Other factors, besides evaporative concentration of lake waters, have to be involved. Steady-state isotopic processes, increase in the relative groundwater ratio, changes in moisture source, and reduced summer evaporation could have played significant roles. Isotopically lighter waters can be consistent with increased salinity if lake levels are so low that annual floods reset the system. This scenario is coherent with the shallow saline lake environments interpreted for the Middle Section.

According to our ^{210}Pb dating framework, the Upper Section only comprises the most recent Holocene. The absence of early Holocene and mid-Holocene deposits in the Mediana sequence indicates desiccation and deflation. Numerous arid periods have been documented in the Ebro basin during the Holocene (Burillo et al., 1985; Stevenson et al., 1991; Davis, 1994; Macklin et al., 1994; Wansard et al., 1996, 1999; Gutiérrez-Elorza and Peña-Monné, 1998). Sedimentary hiati could be located at the base of this section (22 and 19 cm depth), between the gray, banded and black, laminated sediments (9 cm depth) or elsewhere. If there were no hiati within the Upper Section, accumulation would have resumed in Salada Mediana a few centuries ago (c. 16th century, according to the ^{210}Pb-inferred sedimentation rates) during another period of increased water balance. The large increase in *Oleaceae*, and the occurrence of *Cerealia type* also suggest that deposition resumed during historical times. If there were some hiati, the Upper Section could represent a much longer period of deposition during the late Holocene.

Pollen spectra show evidence for anthropogenic impacts on vegetation and agricultural land use. The presence of calcite indicates a significant change in brine composition (lower Mg/Ca ratio) that could be a reflection of lower salinity. Preservation of fine lamination and increase in quartz content also suggest deposition in an ephemeral saline lake or a saline pan with longer periods of flooding and a generally less negative water balance. However, the abundance of Na-sulphates and relatively high values of chemical salinity indicators (sodium, boron) attest more concentrated brines, probably as a consequence of residual brine enrichment. The changes in mineralogy and chemical concentrations of the sediments predate a large negative shift in the isotopic composition. The large negative shift of δ^{18}O values could be related to an increase in the water balance (higher effective moisture) or a change in rainfall seasonality or moisture source. It correlates with another large $\delta^{13}C_{dol.}$ shift which indicates an abrupt increase in the isotopically light carbon source that could be related to increased groundwater input. Precipitation of calcite, and lighter δ^{18}O values are coherent with an increase in the water balance during deposition of the Upper Section, although the brine was rather concentrated, and sodium-rich. Dissolution of previously precipitated salts would explain higher chemical concentrations in isotopically lighter waters.

The negative $\delta^{13}C_{org.}$ excursion at the base of the Upper Section (19–12 cm interval) is smaller than the previous ones, but it correlates with high *Chenopodiaceae*, low *Ruppia* pollen percentages, and high chemical concentrations. Synchronously with the large shift in dolomite isotope values at 12 cm depth, the $\delta^{13}C_{org.}$ values increase, as a response to the development of bacterial mats in the saline pan.

In summary, the Salada Mediana sedimentary sequence documents a basal depositional cycle in a sulphate–carbonate saline lake (Lower Section) that ended with a period of desiccation, and likely basin floor deflation. Subsequent deposition took place in a playa-lake system dominated by saline pan and saline mudflat subenvironments (Middle Section). Two periods of lowered water table with saline mudflat subenvironment expansion, and deflation occurred at the middle and top of the Section. A raised water table in more recent times caused deposition of laminated, calcite-bearing, and black sediments (Upper Section).

6.2. The *Corylus* refugia

The presence of significant percentages of *Corylus* pollen in Lateglacial sediments is a striking feature of the Salada Mediana record. Modern *Corylus* is restricted to the Eurosiberian climatic region and in the continental Mediterranean region it occupies only shallow gorges in the NW Ebro valley and is absent in the central Ebro valley (Blanco et al., 1997). Further east (Catalonia, NE Spain), *Corylus* occurs in mixed Mediterranean forests in humid areas between 200 and 900 m altitude. In modern mixed forests, pollen percentages of up to 25% indicate that *Corylus* is a significant taxon (Huntley and Birks, 1983). High percentages of *Corylus* in pollen zones IV and II imply the presence of mixed forests in the Ebro and Ginel valleys during the Lateglacial, and suggest much higher precipitation than today.

In southern Spain, Stevenson (1985) documented the presence of a temperate forest of *Corylus* and *Betula* on the Guadalquivir plain, synchronous to the deposition of peat bands in the El Asperillo site (Huelva province). He proposed a general lowering of vegetation belts during the cooler and wetter lateglacial period (around 13,000 ^{14}C yr BP) to explain the presence of an oceanic species like *Corylus*, absent in the region in modern times. Peñalba (1994) showed that most tree taxa (*Quercus, Corylus, Alnus, Pinus*) were distributed widely during pre-Holocene times in the northern Iberian peninsula as patchy refugia at intermediate elevations. From these refugia species spread at different times depending on climatic and ecological conditions. These refugia are proposed for the low and middle elevations of the Iberian Mountains and the coastal areas (Turner and Hannon, 1988; Peñalba, 1994). The *Corylus* peaks in Pollen zones IV and II could reflect expansion from their refugia in the Ebro valley during periods of climatic amelioration. The expansion pattern of this tree in Spain during the

Holocene remains unclear with several potential glacial refugia (Blanco et al., 1997; Sánchez-Goñi and Hannon, 1999). Along the northern and southern slopes of the Pyrenees, *Corylus* spread around 9500 BP (Jalut et al., 1992; Montserrat, 1992) but later, at about 8000 BP in most northern–central Spanish sites (Peñalba, 1994; Sánchez-Goñi and Hannon, 1999). Several sites in northwestern Spain (Allen et al., 1996) and in the Iberian Range (Sánchez-Goñi and Hannon, 1999) provide evidence for an early *Corylus* expansion c. 9000 BP followed by the spread of other thermophilous trees. The evidence for *Corylus* colonisation earlier in northern and higher altitude sites of the NW Iberian Range suggests a *Corylus* refugia in the NW Ebro basin, north of the Iberian Range (Sánchez-Goñi and Hannon, 1999).

The presence of *Corylus* in Salada Mediana during the Lateglacial implies survival during the Last Glacial Maximum in refugia for temperate trees along the Ebro valley. The initial expansion of *Corylus* in northern Spain would have been in areas with more oceanic climatic conditions (northern slopes of the Iberian Range), or migrating along Ebro river tributaries with favourable soil moisture conditions.

6.3. Effective moisture fluctuations in iberia

In the Mediterranean regions of the Iberian Peninsula, vegetational and hydrological changes for the Last Glacial Cycle have responded more to effective moisture than to temperature fluctuations (Pons and Reille, 1988; Huntley and Prentice, 1993; Pantaleón-Cano et al., 1999). Paleoenvironmental research in Iberia has been dominated by pollen studies from peat bogs, either in high mountain areas or along the coast, where some of the effective moisture crisis may have not been as pronounced as in semi-arid areas. Besides, there are few detailed and adequately dated records for the Last Glacial Cycle of the Iberian Peninsula. Many of the available records cover relatively short timescales (Davis, 1994; Franco-Múgica et al., 1998; Taylor et al., 1998), and only a few extend into the Lateglacial: Pyrenees (Jalut et al., 1992; Montserrat, 1992); Padul (Florschütz et al., 1971; Pons and Reille, 1988); southern Spain (Stevenson, 1985); Olot (Pérez-Obiol, 1988); Banyoles (Pérez-Obiol and Julià, 1994; Wansard, 1996; Valero-Garcés et al., 1998); Sanabria area (Allen et al., 1996; Julià et al., 1996); eastern Spain (Carrión and Dupré, 1996); Salines (Giralt et al., 1999); nortwestern Iberian Range (Peñalba, 1994; Peñalba et al., 1997; Sánchez-Goñi and Hannon, 1999), and southern Spain (Pantaleón-Cano et al., 1999). All of these records document several humid and arid periods since the Last Glacial Maximum (LGM). Some sequences point to a period of increased effective moisture in the Iberian Peninsula after the LGM. Deep-water sedimentary facies and a large negative $\delta^{18}O$ excursion in Banyoles suggest that immediately after the LGM — dated as 22,890 $\pm$ 310 ^{14}C yr BP and 18,000 U/Th yr BP — there was a period of increased effective moisture in northeastern Spain (Valero-Garcés et al., 1998). In two records from Almeria province (SE Spain), Pantaleón-Cano et al. (1999) identify a warmer and more humid period between 18,000 and 15,000 ^{14}C yr BP.

The presence of stadials and interstadials in the Lateglacial Iberian sequences is also well known. In northwestern Spain (Allen et al., 1996), pollen-based paleoclimate reconstructions indicate a dry and cool climate with strong seasonality, during the 14,600–12,400 ^{14}C yr BP period and the Younger Dryas (10,700–9800 ^{14}C yr BP), and moister conditions, with increased summer precipitation, during the Lateglacial interstadial (12,400–10,500 ^{14}C yr BP). In Serra da Estrela (Portugal), woodland expansion was delayed suggesting an increase in winter precipitation in the Atlantic side of Iberia during the Lateglacial interstadial (van der Knaap and van Leeuwen, 1995). Further south, in Padul, *Quercus* proliferated between 13,000 and 11,000 ^{14}C yr BP (Pons and Reille, 1988). The development of peat within the coastal sand dune environments in Huelva (southern Spain) is thought to correspond to the lateglacial period (around 13,000 ^{14}C yr BP) and represent a cooler and wetter episode that also caused the expansion of a temperate forest with *Betula* and *Corylus* (Stevenson, 1985). Peñalba et al. (1997) propose a reduced winter precipitation during the Younger Dryas episode in Quintanar de la Sierra. In Banyoles and Salines, periods of increased rainfall and/or temperature identified by mineralogy, pollen and ostracod assemblages and geochemistry (Roca and Julià, 1997; Julià et al., 1998; Wansard et al., 1998) are correlated with the Bølling-Allerød and Preboreal periods. The Oldest Dryas and Younger Dryas are marked at both sites by low lake levels and decrease in mesic trees indicating a cold and dry climate. Increased water balance in Banyoles during the Bølling-Allerød and the Early Holocene was also interpreted from isotope geochemistry data (Valero-Garcés et al., 1998). In Gallocanta, a large saline lake in the Ebro Basin, Burjachs et al. (1996) ascribed the basal unit to a humid period preliminary dated at 12,230 $\pm$ 70 ^{14}C yr BP, although they considered that the presence of *Fagus* pollen could imply a much younger age.

The Salada Mediana sequence also shows large effective moisture fluctuations. According to the current chronological framework for Salada Mediana, the Upper Section corresponds to the Late Holocene, most likely to the last few centuries (16th–20th centuries). The Lower and Middle Sections would correspond to the Lateglacial, and they are composed of phases of relatively higher effective moisture (150–120, 107–90, 65–50 cm depth intervals) followed by phases of increasing aridity (120–107, 90–65, 50–19 cm depth intervals). The ascription of the detected humid and arid intervals in Salada Mediana to the known stadial and interstadial during the

Lateglacial or to the Preboreal humid phase remains inconclusive because of the lack of detailed chronological control.

The rise in lake level detected in Salada Mediana during the last few centuries has been documented in other saline lakes in the Ebro Basin as well. A progressive increase of the lake level in Salada Chiprana began c. 600 yr ago (the 14th century) and correlates with the implementation of irrigation (Valero-Garcés et al., 2000b). Several studies in Laguna Gallocanta document increased lake levels during recent times (Davis, 1994; Burjachs et al., 1996; Schütt, 1998a). Dendroclimatic reconstructions for the Central Ebro valley (Creus et al., 1996) show high climatic variability (rainfall and temperature) since the 13th century, following a relatively low variability for the Medieval Warm Period. Increased precipitation and lower evaporation caused by reduced temperatures could account for a general watertable rise in the central Ebro valley during the 15th–16th centuries.

Wetter conditions in Mediterranean Iberia may result from different circulation regimes as a result of different global forcing (glacial or insolation changes) (Harrison et al., 1993, 1996; Huntley and Prentice, 1993; Kutzbach et al., 1993): (i) a southward displacement of the westerlies leading to an increase in winter precipitation; (ii) a northward extension of the African monsoon during intervals of higher-than-present summer insolation, and weakening of the influence of the subtropical anticyclonic circulation over the Mediterranean, (iii) a local monsoon-like phenomenon, generated by the extensive land areas of the Iberian Peninsula, that favour the development of low-pressure areas over the Mediterranean and increase cyclonic rainfall and storms in summer. Although the first mechanism seems more plausible for Lateglacial times, the other two would explain an increase in summer precipitation and a reduction of the water stress for sensitive trees such as *Corylus*. Recent increases in lake levels seem to coincide with the end of the Medieval Warm Period (900–1300 AD) (Pfister et al., 1998). Davis (1994) proposed that this humid episode throughout the Ebro basin is linked to an increase in winter precipitation similar to conditions during Iberian-Roman times.

7. Conclusions

The Salada Mediana record provides an example of the potential and limitations of saline lake sequences for paleoclimate proxies in semi-arid Mediterranean regions. In such depositional systems, the facies succession is mainly governed by fluctuations in water balance, brine composition, salinity, and aeolian processes. Sedimentary facies analyses, geochemistry, stable isotopes (δ^{18}O and δ^{13}C) of authigenic carbonates, $\delta^{13}C_{org.}$ values, and pollen stratigraphy from sediment cores provide a reconstruction for paleohydrology and vegetation change in the central Ebro Basin. The Salada Mediana sedimentary sequence starts with a basal depositional cycle in a permanent saline to brackish lake (Lower Section) that ended with a period of desiccation, and probably deflation. The overlying sediment package (Middle and Upper Sections) represents a playa-lake complex dominated by saline pan and saline mudflat subenvironments. Periods of higher water tables are characterised by saline pan facies and periods of lowered water tables by a saline mudflat subenvironment expansion and deflation.

Although dating uncertainties persist due to hiati, age reversals, and unknown reservoir effects, the proxy records from Salada Mediana provide some reasonable hypotheses for Lateglacial and Late Holocene paleohydrological and vegetational evolution. The presence of *Corylus* in Mediana indicates that suitable refugial zones for temperate trees occurred during the Last Glacial Maximum along the Ebro valley. An absence of early Holocene and mid-Holocene deposits in the Mediana sequence indicates deflation during arid Holocene periods. Similar to other sites in the Ebro Basin, the Salada Mediana record shows increased effective moisture during the last few centuries.

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