

Paleohydrological fluctuations and steppe vegetation during the last glacial maximum in the central Ebro valley (NE Spain)

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Abstract

Combined analysis of sedimentary facies, geochemistry and pollen from lake sediment records, and sedimentological and palynological studies from slope deposits allow the characterization of vegetation and lake level status during the Last Glacial (LGM) in the central Ebro valley (NE Spain). These records show the presence of phases of increased effective moisture, while regional vegetation was dominated by steppe species. The longest lake record comes from La Salineta, one of the saline lakes in the Los Monegros area; the other lake sequence comes from a sinkhole in the Gállego River floodplain. The slope deposit from Valmadrid is the only periglacial deposit found in the central Ebro valley. Our data indicate that, at least for some intervals during full glacial times, when cold steppe vegetation dominated the region, some lakes experienced more positive water balance than today, and run-off was also high. The data 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. Increased flow from the Pyrenean rivers during the early deglaciation could also have played a significant role in the paleohydrological cycle in the central Ebro valley. However, La Salineta records also show evidence for arid periods during glacial times, indicating the complex evolution of hydrology and moisture availability in the central Ebro valley during the LGM.

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1. Introduction

Evidence for higher-than-present lake levels and steppe vegetation during the millennia around the Last Glacial Maximum has been described in several records from the northern Mediterranean, particularly the central and eastern regions (Prentice et al., 1992; Roberts and Wright, 1993; Yu and Harrison, 1995). The apparent conflict between the semi-arid conditions indicated by pollen assemblages, and the increased effective moisture indicated by lake-level reconstructions has been solved by postulating changes in rainfall seasonality as the main factor controlling moisture

availability and vegetation. The drying effect of the cold North Atlantic Ocean during glacial times could have been counteracted by a summer-dry and winter-wet regime and an increase in storm frequency under a southward-shifted jet stream (Prentice et al., 1992). In the eastern Mediterranean there is also evidence for high lake levels in Lake Lisan (the precursor of the Dead Sea) (Stein et al., 1997). Besides, in Soreq Cave (Israel), a substantial growth of speleothems occurred during the 25–17 kyr BP period, in contrast to many studies that show zero to very little growth in northern Europe during glacial times (Bar-Matthews and Ayalon, 1997).

The evidence for high lake levels in some of these records from the eastern Mediterranean (Lakes Ioannina and Xinias in Greece, for example) has been challenged recently, and it has been suggested that both pollen and lake level records indicate dry climate

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conditions during the LGM in this part of the Mediterranean (Tzedakis, 1994; Digerfeldt et al., 2000). In most Mediterranean regions there is a shortage of reliable paleohydrological and vegetational reconstructions, and accurate radiocarbon dates, and at present, regional climate reconstructions are heterogeneous and sometimes contradictory. There is a need for more data to allow the reconstruction of glacial climate in the Mediterranean. To contribute to this goal, we describe in this paper several palaeoecological records from northeastern Spain spanning the glacial period.

Commonly, glacial pollen spectra from Spanish sites are characterized by taxa typical of steppe, e.g. *Artemisia*, grasses, Chenopodiaceae, Asteraceae and *Ephedra distachya* (Navarrés site in eastern Spain: Carrión and van Geel, 1999; Padul site and Carihuella cave in southern Spain: Pons and Reille, 1988; Carrión et al., 1998; Banyoles in northeastern Spain: Pérez-Obiol and Julia, 1994 and Sileslake, Carrión, 2002) in common with full-glacial floras from other European records (Huntley et al., 1999; Allen et al., 1999). In Banyoles, in what is now part of the humid Mediterranean climate zone, the *Artemisia* steppe vegetation during the LGM reflects cold and arid conditions (Pérez-Obiol and Julia, 1994), although the presence of relatively deeper lacustrine facies and a sharp negative $\delta^{18}\text{O}$ excursion in the authigenic carbonate isotope record suggest increased water levels in the lake (Valero-Garcés et al., 1998). In the Mediterranean climate zones of the Iberian Peninsula, available effective moisture has been a major factor controlling vegetational and environmental changes during the Lateglacial and Holocene (Huntley, 1988; Huntley and Prentice, 1993). This is particularly true in semi-arid regions like the central Ebro valley, the most northerly area of truly semi-arid climate in Europe. Environmental, vegetational, cultural and climate conditions in the Central Ebro valley during glacial times are unknown due to the lack of paleorecords covering that period. Archaeological sites ascribed to Lateglacial times (Magdalenian) occur in the Pre-Pyrenees, in the Iberian Range and in strategic sites as natural corridors between the Spanish Central Plateau and the Ebro Basin, or close to thermal areas (Utrilla and Rodanés, 1997). The absence of Lateglacial archaeological sites in the Ebro Basin has been traditionally explained as a combination of the low impact on the landscape of the hunters-gatherers and the disappearance of sites by erosion and burial. The discovery of inactive Quaternary *yardangs* (erosional landforms produced by wind action) in Los Monegros area (Gutiérrez-Elorza et al., 2002) indicates the occurrence of periods with extremely arid climate, minimal soil and vegetation and prevalent one-directional winds. Although there are numerous lacustrine records in the Spanish Central Pyrenees (Montserrat Martí, 1992; Jalut et al., 1992), and in the

Ebro valley (Davis, 1994; Burjachs-Casas et al., 1996; Valero-Garcés et al., 2000a-c), most of them only cover the Late and post-glacial history of the region. Basal AMS ^{14}C dates from glacial lakes associated with moraines in the Gállego river headwaters indicate that the upper Gállego River was already deglaciated during the global Last Glacial Maximum (18–20 kyr) (González-Sampériz et al., 2001; García-Ruiz et al., 2003), and that mountain vegetation was a cold steppe. Lake sequences from the abundant saline lakes in the Ebro basin could potentially provide long records including glacial stages. Several studies have shown the potential and limitation of lacustrine records in the Ebro Basin for paleoclimate reconstructions (Davis, 1994; Burjachs-Casas et al., 1996; Schütt, 1998; Valero-Garcés et al., 2000a-c). Paleoenvironmental and paleoclimatic interpretation of these records is complicated by the presence of numerous hiatus caused by deflation and erosive processes, the complexity of evaporite deposition and diagenesis, and the lack of preservation of some important biological proxies such as diatoms (J.M. Reed, pers. comm.).

In this paper, we present palynological, sedimentological and geochemical data from two lake records and one slope deposit in the Central Ebro valley that include sedimentary units deposited during glacial times (18–30 kyr) and we integrate them with available glacial paleorecords from the Ebro Basin. The longest lake record comes from La Salineta, one of the saline lakes in the Los Monegros area. The other lake sequence comes from a sinkhole in the Gállego river floodplain, close to the town of San Juan de Mozarrifar. The slope deposit from Valmadrid is the only periglacial deposit found in the central Ebro valley. These sedimentary sequences from the Ebro Basin cannot provide “high resolution” records due to the specific nature of the depositional environments. On the other hand, the lack of diatoms, ostracods, and other biological remains in the sediments reduce significantly the potential for multi-proxy research, in systems that have proven to be very complex (Valero-Garcés et al., 2000a, b). However, because of the lack of available high-quality data, these records provide almost the only paleoclimate and paleoenvironmental reconstructions for glacial times in the Ebro Basin.

2. Geographic and climate setting of the central Ebro valley

The spatial variability of the climate across Spain is extreme compared to most other parts of the Mediterranean, particularly in rainfall distribution due to the Iberian topography and other geographic factors (Martin-Vidé and Gómez, 1999). This heterogeneity at the sub-regional scale has to be considered when interpreting the regional paleoclimate signal derived

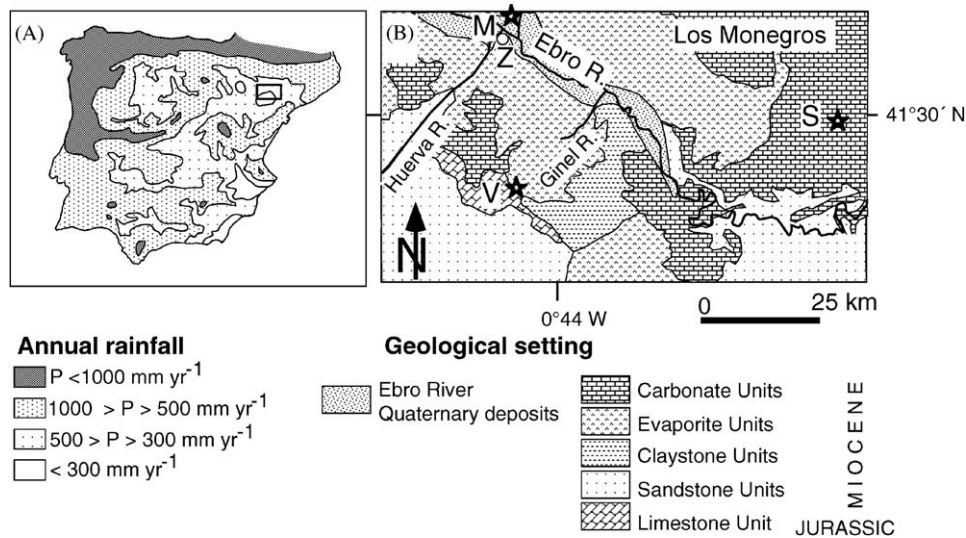


Fig. 1. Geographic location of the study sites in the Los Monegros region, Central Ebro valley. (A) Under modern climatic conditions, the region receives less than 300 mm per annum of precipitation. (B) Geological location of the three sites: La Salineta lake (S), the San Juan de Mozarrifar sequence (M) and the Valmadrid slope deposit (V). Z = Zaragoza.

from the records. The climate in the Central Ebro valley is continental Mediterranean with very hot summers, cold, dry winters, and low annual rainfall (average 300–350 mm yr⁻¹, Capel-Molina (1981)) (Fig. 1A). The high insolation and evapotranspiration (1000–1500 mm yr⁻¹), and the prevalence of strong dry NW winds also contribute to a water deficit throughout the year, especially during the summer. Rainfall is distributed irregularly, although spring and autumn precipitation accounts for more than 70% of the total annual rainfall. The central Ebro valley is a steppe, mostly dedicated to agriculture, with some small areas dominated by *Pinus halepensis*, *Quercus coccifera*, *Juniperus thurifera* and *Juniperus sabina* (Blanco et al., 1997).

The Central Ebro valley contains many shallow, saline lake basins, particularly in the central plateau of Los Monegros and in the Bajo Aragón area (Pueyo-Mur, 1979; Fig. 1B). The brines are of (Cl⁻)-(SO₄²⁻)-(Na⁺)-(Mg²⁺) 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 Tertiary evaporite substrate, preferential water circulation through fault lines, differential erosion, and surface deflation (Pueyo-Mur, 1979; Benito et al., 1998; Sanchez-Navarro et al., 1998). Three sedimentary lacustrine units and 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). Most of the lakes are located in the Intermediate unit, and only a few (La Salineta among others) occur in the Upper lacustrine unit, north of the main Los Monegros endorheic system. La Salineta lake is located 1.5 km south of the town of Bujaraloz at an

altitude of 325 m a.s.l. The present lake is a seasonal playa lake that holds water longer than most of the other lakes. Water chemistry is dominated by sodium-chloride and salinities can reach values up to 200 g l⁻¹. A thick, soft and wet halite crust covers the surface during the summer. Groundwater is typically of magnesium-sulfate or calcium-sulfate type with an average TDS of 5 g l⁻¹. Stable isotope data (García-Vera, 1996) suggest that groundwater, rainwater, and run-off (estimated as less than 10% of the rainfall) are the main water input to the lakes (Samper-Calvete and García-Vera, 1998). Groundwater recharge (ca. 20–45 mm yr⁻¹) takes place at the interfluvies and highlands. Hydrological modelling suggests that the upper aquifer discharges one third of the total recharge (5822 m³ yr⁻¹) into La Salineta Lake, and that the lower aquifer contributes 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 area) lies within a much larger paleolake, whose deposits have been eroded and form cliffs up to 4 m high surrounding the present lake. The cliffs are well developed at the windward southeastern end of the basin. The paleolake 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 sections, remains of a small cliff (1 m high) mark the boundary of the maximum extent of the lake. Natural vegetation is very restricted locally due to the dominance of winter wheat farming in the catchment. Halophytes dominate the shoreline and algal mats cover the lake bottom and are more visible when the halite crust re-dissolves with the autumn rains.

The San Juan de Mozarrifar Sequence is located close to the city of Zaragoza (220 m a.s.l., 41°44'35" N, 0°51'50" W), in the Quaternary floodplain and terrace deposits of the Gállego River, a tributary of the Ebro river. The fluvial deposition of the Gállego River in this area has been strongly influenced during the Late Quaternary by subsidence and collapse processes affecting the underlying Miocene gypsum and evaporite substrate (Benito et al., 1998). As a consequence, the Gállego terrace system is complex, with large thickenings of the fluvial deposits, large-scale deformation structures and smaller topographic depressions, some of them still active (Benito et al., 1998). Due to the incision of the Gállego river channel by flooding in 1996, several paleo-depressions were revealed in the floodplain area close to the town of San Juan de Mozarrifar. One of them allowed a detailed study of the three-dimensional geometry and the nature of the deposits.

The Torrecilla de Valmadrid scree (570 m a.s.l., 41°26'49" N, 0°53'42" W) is the only stratified slope deposit known in the central Ebro basin. In the Pyrenees and Iberian Range stratified slope scree is common (García-Ruiz et al., 2001) and is widely considered indicative of the lower limit of the periglacial belt and a reflection of relict morphoclimatic cold conditions. The Torrecilla de Valmadrid scree is located about 25 km south of Zaragoza in a narrow E–W trending gorge incised in a Jurassic paleo-relief. The cliff height is about 100 m from 676 m a.s.l. at the top to 570 m a.s.l. at the bottom of the gorge and it is composed of alternating matrix-supported beds and coarser, clast-supported layers.

3. Methodology

An outcrop with paleolake sediments located in the southeastern cliff of La Salineta and a core collected below the cliff with a Hiller corer (320 m a.s.l., 41°28'55" N, 0°09'30" W) were described and sampled every 10 cm in 1991 (Davis, 1994). The total length of this section (labeled as La Salineta Section) was 465 cm long (0–360 cm from the open section, 360–465 cm from the core). The analyses performed included pollen, charcoal, microfossils and geochemistry, and the results are described in detail elsewhere (Davis, 1994). A new 8 m long core (labeled as La Salineta Core) was drilled in the cliff close to the previous section. It provides the longest lacustrine record available in the central Ebro valley. The core reached the substrate composed of Miocene Limestone. The sediment core was split, described, and sampled for organic matter, mineralogy, geochemistry, stable isotope, and pollen analyses following methods described elsewhere (Valero-Garcés et al., 2000b). Sedimentological and geochemical analyses provided the basis for facies identification and unit definition in

the core. No terrestrial organic remains for dating were found in the core, and the chronology is constrained by bulk organic matter AMS ¹⁴C dates. The San Juan de Mozarrifar lacustrine sequence and the Valmadrid slope deposits were measured and described in the field and sampled for pollen studies and radiocarbon dating.

4. Results

4.1. Chronology

Reliable chronologies for saline lake sequences in the Ebro basin have been hindered by the scarcity of terrestrial macrofossils for radiocarbon dating (Davis, 1994; Burjachs-Casas et al., 1996; Schütt, 1998; Valero-Garcés et al., 2000b). The presence of tree remains in the San Juan de Mozarrifar sequence is unique. A minimum conventional radiocarbon age of 28,000 ¹⁴C yr BP was obtained from a conifer trunk in this sequence (Table 1).

Organic macroremains were very scarce in both La Salineta Section (Davis, 1994) and La Salineta Core studied in this paper. *Chenopodiaceae* seeds from the upper 20 cm of the 465 cm long La Salineta section (Davis, 1994) gave a modern AMS age probably caused by soil contamination, and consequently the chronology of this section is unknown. The presence of *Fagus* towards the base of the section and above 350 cm suggests a Late Holocene age. Pollen of *Fagus* does not occur until 3.0 kyr in other sites in the Ebro Basin like Salada Pequeña, and it is not found at any of the early Holocene sites in the Ebro Basin (Davis, 1994). The earliest *Fagus* occurrences on the Spanish Pyrenees are dated around 5 kyr (Montserrat Martí, 1992), although in the Northern Meseta, the Iberian Range and the eastern Pyrenees, *Fagus* pollen grains have been recorded at about 7–8 kyr BP (Franco-Múgica et al., 2001).

The upper 2 m of La Salineta Core are affected by farming and modern edaphic processes and, consequently, were not sampled for AMS radiocarbon dating because carbon contamination was likely. The only macroremains found in the core were located at 184–186 cm depth and provided a modern radiocarbon age. Since the organic matter content was also very low, bulk samples were treated as palynological samples to concentrate organic particles and were microscopically checked for the composition of the remaining organic fraction. Pollen grains were very scarce and the organic fraction was mostly composed of micro-charcoal particles. An internally consistent chronological framework has been developed for the lower sedimentary units based on three AMS ¹⁴C dates ranging from 18,790 ± 500 ¹⁴C yr BP to 23,900 ± 140 ¹⁴C yr BP (Table 1). Four more dates from the upper units show reversals and the validity of these dates must

Table 1
Absolute radiocarbon dates (non-calibrated) from La Salineta, Valmadrid and San Juan de Mozarrifar sequences

Laboratory	Site	Depth	ID #	Sample	d 13C	Fraction modern	Error	Age 14C year BP	Age error (yr)
INSTAAR	La Salineta	184–186	NSRL-10417	Organic macrorest	–25.0 (Estim.)	1.1838	0.0037	Modern	
INSTAAR	La Salineta	209–211	NSRL-12149	Organic microrests	–24.5	0.19752	0.0021	13,050	85
INSTAAR	La Salineta	329–331	NSRL-12150	Organic microrests	–26.4	0.38161	0.0027	7740	55
ARIZONA	La Salineta	382–384	AA51325	Organic microrests	–26.4	0.1760	0.0036	13,950	160
INSTAAR	La Salineta	429–431	NSRL-12151	Organic microrests	–24.3	0.27407	0.0019	10,400	55
ARIZONA	La Salineta	501–504	AA51326	Organic microrests	–26.4	0.0965	0.0060	18,790	500
Woods Hole	La Salineta	567–570	OS-22526	Organic microrests	–19.18	0.072	0.0011	21,100	120
Woods Hole	La Salineta	822–825	OS-22527	Organic microrests	–22.92	0.0512	0.0009	23,900	140
INSTAAR	Valmadrid	Base	NSRL-12148	Pollen concentrate	–25.0 (Estim.)	0.11934	0.0013	17,100	85
Zurich University	Mozarrifar	Base 3B	UZ-1778	Conifer tree fragment				28,000	

be discussed, particularly in relation to hard-water effects and contamination by old carbon and modern edaphic processes. Although it cannot be completely ruled out, hard-water effects are unlikely in these samples, since they seem to be mostly composed of charcoal and the aquatic amorphous organic fraction is mostly destroyed during the treatment. The microscope assessment indicated that the unidentified particulate organic matter was very scarce, and the samples are mostly composed of charcoal. Contamination with old carbon brought by aeolian activity could be the reason for the two samples (209–211 and 382–384 cm depth) with older ages ($13,050 \pm 85$ ^{14}C yr BP and $13,950 \pm 160$ ^{14}C yr BP) compared with the underlying samples. Taking all the dates into account, the upper units seem to span from Lateglacial to early Holocene times, although a more detailed chronology remains uncertain. The internal consistence of the AMS dates from the lower units support that they comprise the last glacial maximum.

Pollen concentrates have provided enough material for AMS dating in organic-poor deposits in several sites from the Pyrenees and the Ebro Basin (Valero-Garcés et al., 2000a, b; García-Ruiz et al., 2001) and this technique was used to date the scree deposits of Valmadrid. The pollen concentrates were obtained following the same chemical method used to prepare palynological samples. Two paired samples were prepared at each level to study the palynological composition, and check for other possible organic contaminants. The presence of small amounts of thermophilous pollen types is considered a long-distance signal from refugia in the Ebro valley (Valero-Garcés et al., 2000a, b). The fact that pollen grains are evenly preserved and equally susceptible to stain within each particular sample, and the absence of apparent reworking point to internal consistence of pollen spectra in terms of both taphonomy and chronology. The ^{14}C AMS date from the pollen concentrate at the base of the scree was $17,100 \pm 85$ ^{14}C yr BP (Table 1).

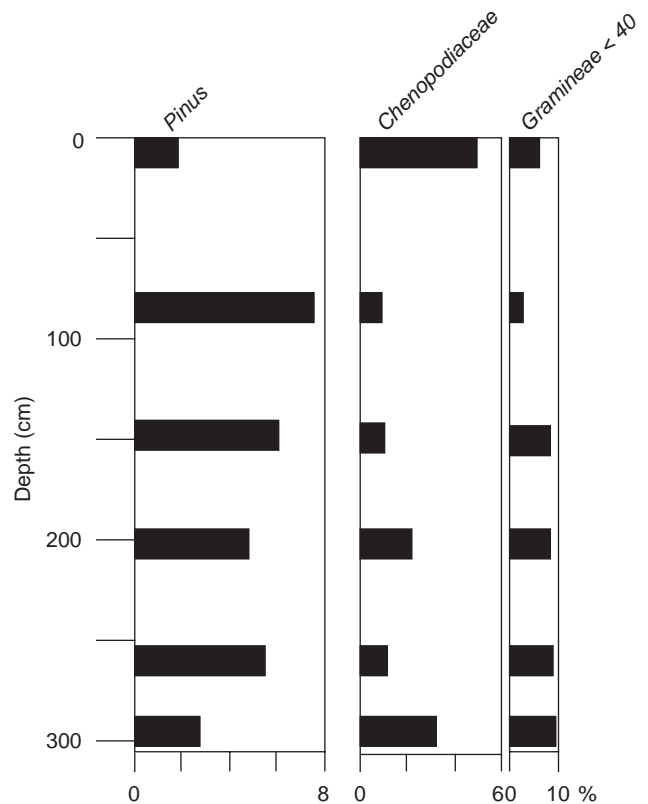


Fig. 2. Main pollen taxa (in %) from the upper 3 m of La Salineta core sequence. Samples below 3 m were sterile.

4.2. La Salineta

4.2.1. Pollen record

A detailed description of the 4.65 m long La Salineta Section can be found in Davis (1994). The pollen record suggests seasonal playa-lake environments and a change in the regional vegetation from *Pinus* and *Quercus ilex* type woodland and grass steppe to a *Pinus* and *Juniperus* woodland. Pollen preservation in the 8 m long La Salineta Core was bad, and below 3 m depth, the samples were sterile (Fig. 2). Arboreal pollen is

dominated by *Pinus*, while *Chenopodiaceae* oscillations may reflect changes in lake surface. The presence of four large *Gramineae* grains also indicates likely anthropogenic influence.

4.2.2. Sedimentary and geochemical record

Five sedimentary units have been defined in the La Salineta core based on sedimentological, lithological and geochemical criteria (Fig. 3). In this paper we only deal with the lower Units 5, 4 and 3. Depositional environments for saline lake sediments can be identified integrating a variety of criteria (see Valero-Garcés et al., 2000a, c, for details): increased dolomite content commonly reflects higher Mg/Ca ratios in more concentrated waters; occurrence of microcrystalline gypsum laminae suggests periods of higher sulfate concentration; higher organic matter contents indicate higher biological productivity and better conditions for preservation (less oxidizing). Calcium concentrations reflect both carbonate and gypsum contents. Higher carbonate contents in Unit 5 and 1 correlate with higher calcium contents. However, the high calcium contents of Unit 3 do not correlate with high carbonate values, and more likely reflect higher gypsum contents.

Unit 5 is composed of dark greenish gray, massive to faintly banded calcitic and gypsum-rich muds with some cm-long limestone clasts from the Miocene substrate. The high carbonate and relatively high organic matter contents, and the presence of calcite as the only carbonate mineral in Unit 5B suggest a short period of less concentrated lake waters and higher organic productivity immediately after the genesis of the lake basin. This interpretation is consistent with higher rainfall conducive to increased karstic activity. Decreasing carbonate content and appearance of dolomite mark a rapid transition during Unit 5A to progressively more concentrated waters and more frequent desiccation periods. Unit 4 is composed of massive, dolomitic mud with abundant gypsum crusts. More abundant gypsum, occurrence of dolomite as the only carbonate phase, low organic matter and carbonate contents, and high Mn, Fe and K concentrations are interpreted as deposition in ephemeral saline lake environments during unit 4. The trend to increasing carbonate (dolomite) and organic matter content at the top of unit 4 could reflect more frequent flooding episodes in the lake.

The large change in sediment composition defined by the onset of Unit 3 is likely to reflect a sedimentary hiatus. Unit 3 is characterized by the increased presence

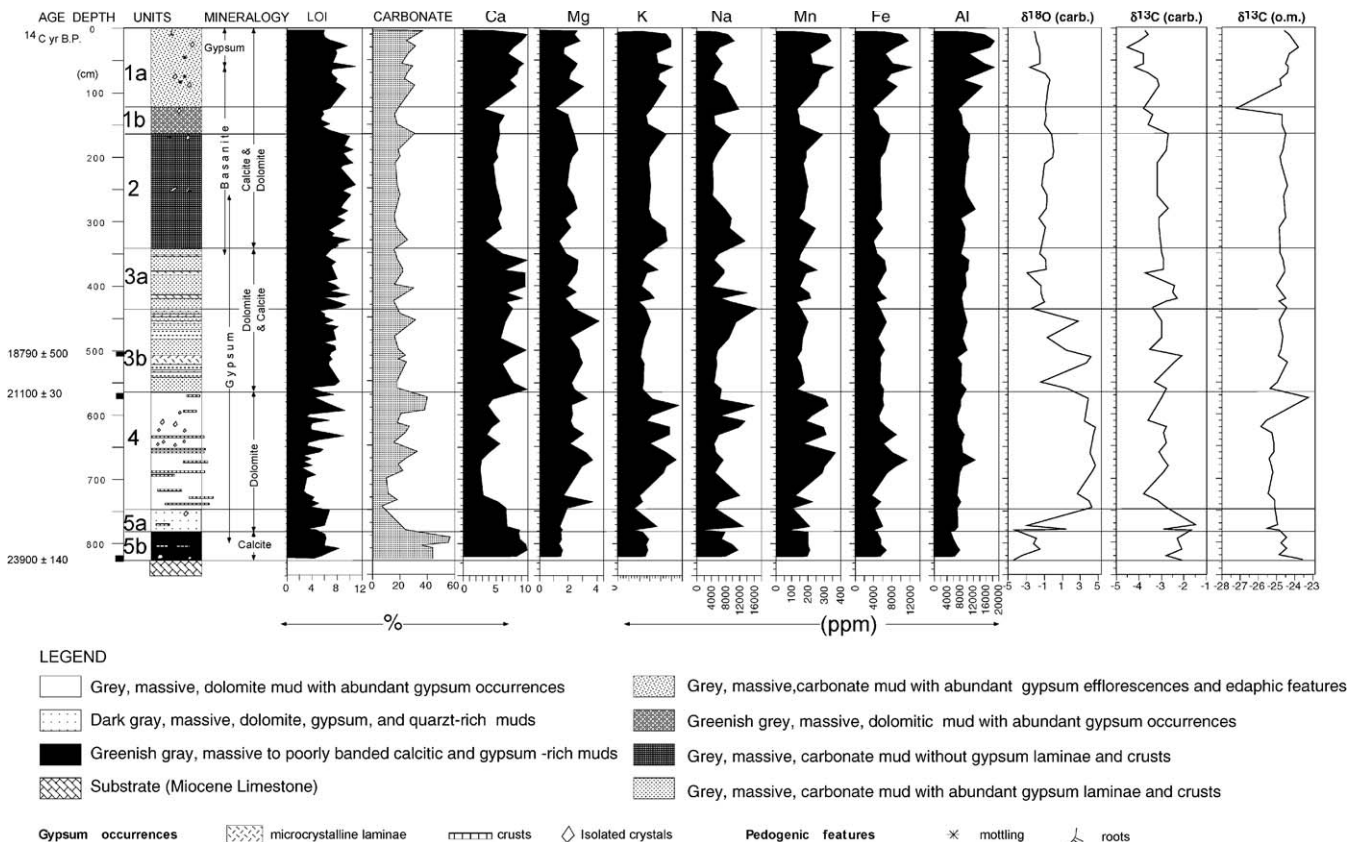


Fig. 3. La Salineta sedimentological, mineralogical, geochemical and isotopic record. LOI: loss on ignition. The stable isotope ($\delta^{18}\text{O}_{\text{carb}}$ and $\delta^{13}\text{C}_{\text{carb}}$) values are from bulk carbonate samples. The $\delta^{13}\text{C}_{\text{(o.m.)}}$ values are from bulk organic matter samples.

of gypsum laminae composed of microcrystals, the occurrence of both calcite and dolomite, and higher organic matter content. The values of some salinity indicators (Na, K) are relatively smaller in the lower part (sub-unit 3B), peak in the middle part, and decrease again towards the top (sub-unit 3A). A relatively more positive water balance and lower water salinity is inferred for this unit, which is interpreted as deposited in a semi-permanent saline lake with periods of increased water concentration (gypsum deposition).

4.2.3. Stable isotope record

A large range (between -5‰ and $+5\text{‰}$ PDB) characterizes the $\delta^{18}\text{O}$ curve for La Salineta carbonate samples (Figs. 3 and 4). The lowest oxygen compositions (between -5‰ and -3‰) occur in unit 5. Isotope values increase at the base of unit 4 and remain high ($+3\text{‰}$ to $+5\text{‰}$) to the top of this unit. Unit 3 is characterized by a marked negative excursion at the base, and relatively higher and more variable values in sub-unit 3B, with two main positive excursions (500–530 cm and at around 450 cm). A sharp transition occurs between sub-units 3A and 3B. The isotope values in the upper units 3A, 2 and 1 are relatively lower (between 0‰ and -3‰) and more constant.

The $\delta^{13}\text{C}_{\text{carbonate}}$ record shows three distinctive intervals. Unit 5 has the heaviest $\delta^{13}\text{C}_{\text{carbonate}}$ compositions. The values in the overlying Units 4, 3, and 2 show a small range (-4‰ to -3‰), and they decrease slightly at the top of the core (Unit 1). Covariance between oxygen and carbon isotope values is not significant if all the values are considered (Fig. 4). Covariant patterns are clearer in Unit 4 and within the group of high $\delta^{18}\text{O}$ values in Unit 3B. A similar behavior in other saline lakes suggests that covariance increases during less positive water balance episodes (Talbot, 1990; Valero-Garcés et al., 2000a). Sedimentological and geochemical proxies also identified these intervals as periods of deposition in ephemeral saline lake environments with more concentrated waters.

Most $\delta^{13}\text{C}_{\text{org}}$ (bulk organic matter) values are smaller than -24‰ suggesting a dominance of terrestrial over lacustrine carbon sources. The lowest value occurs at the base of Unit 1A (-27.2‰), and the highest (-23.2‰) at the top of unit 4. In other saline lakes in the Ebro basin (Salada Mediana; Valero-Garcés et al., 2000a, b), cyanobacterial mats have considerably heavier values (between -12.8‰ and -11.2‰ PDB) than terrestrial halophytic plants (between -24 to -26‰ PDB). The $\delta^{13}\text{C}_{\text{org}}$ curve (Fig. 3, $\delta^{13}\text{C}(\text{o.m.})$) shows three main intervals: (i) high and relatively constant values ($> -25\text{‰}$) in Unit 5B that slightly decrease in Unit 4; (ii) constant and relatively higher values in Units 3, 2 and 1B; and, (iii) increasing and then decreasing ($40\text{--}0\text{ cm}$) values in Unit 1A.

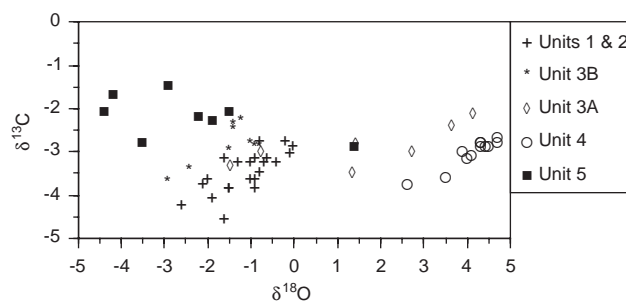


Fig. 4. Scatter cross plot of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ stable isotope values of the main units in La Salineta record. Covariance between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ is significant in units interpreted as deposited under more negative water balance.

4.3. San Juan de Mozarrifar record

Five main units have been identified in the San Juan de Mozarrifar sequence (Fig. 5). The basal Unit 1, composed of fluvial gravels, has an exposed thickness of 3 m. Unit 2 (1.2 m thick) is composed of sands with some ferruginous thin layers, root structures and tree-trunks remains. It is topped by a paleosol horizon with a ferruginous crust. Deposition of this unit occurred in a fluvial environment with long periods of subaerial exposure when edaphic processes took place. The sediment layers show a paleo-depositional slope, common in depositional environments with a slow subsidence synchronous with the infilling of the depression. Pollen samples from this unit were sterile, probably because pollen grains were oxidized. Unit 3 (3.9 m thick) is composed of two subunits: (i) sub-unit 3A: 1.1 m of dark gray and black, laminated organic-rich and carbonate-rich silts with abundant gastropods, root structures and “in situ” conifer tree trunks and roots. One of these tree roots has been dated as $> 28,000$ ^{14}C yr BP (Table 1); (ii) sub-unit 3B: 2.80 m of black, finely laminated, organic-rich, carbonate muds. Unit 3 represents deposition in a depression generated in the floodplain due to subsidence and collapse of the underlying evaporites. After a period characterized by shallow waters with frequent subaerial exposure and colonization by trees (sub-unit 3A), a permanent, relatively deeper lake was formed and finely laminated sediments were deposited. The finely laminated layers are carbonate-rich sediments with abundant detrital particles and organic remains. Unit 4 is composed of massive silts and it lies unconformably over the previous unit. Unit 4 has also been partially eroded by the deposition of gravel and sands of higher Gállego River terraces (Unit 5), dated as Holocene by the presence of *Elephas* tusks.

Pollen samples from Unit 3 show prevailing non-arboreal pollen with *Pinus* as main tree ($< 25\%$) which indicates an open regional landscape dominated by steppe vegetation (*Chenopodiaceae*, *Ephedra*, *Artemisia*). The high

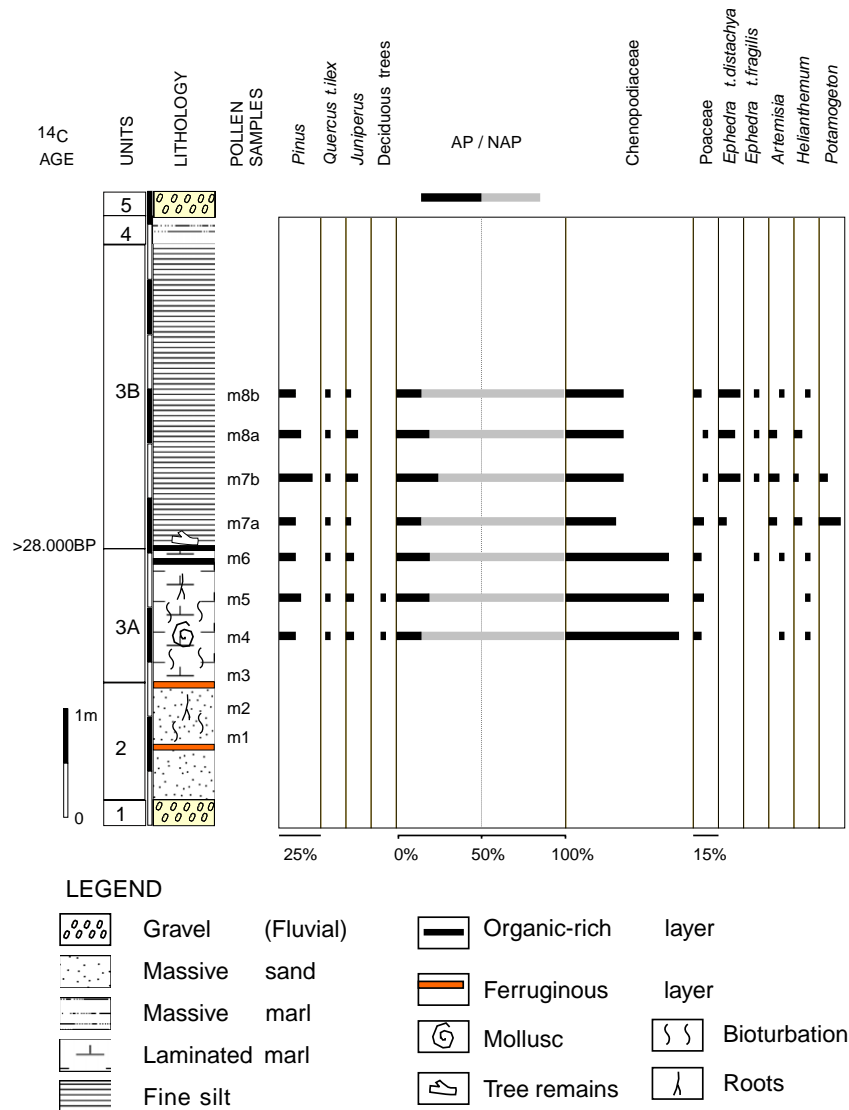


Fig. 5. San Juan de Mozarrifar sedimentological and palynological record. Dots indicate pollen percentage lower than 2%.

Chenopodiaceae content in sub-unit 3A suggests periods of subaerial exposure and colonization of the floodplains and the lakeshores by grasses. Pollen assemblages in sub-unit 3B show some decrease in *Chenopodiaceae*, a minor increase in *Ephedra distachya* type, *Ephedra fragilis* type, *Artemisia* and *Helianthemum* and a larger increase in aquatics (*Potamogeton*). All these features indicate more permanent water bodies, as was interpreted from the sedimentological record. An increase in water availability would have turned the sinkholes and dolines in the large Gállego floodplain from seasonally flooded, during deposition of sub-unit 3A, to permanently aquatic, during deposition of sub-unit 3B. The presence of pollen from temperate trees—some of them currently absent in the Central Ebro valley such as *Corylus*, *Alnus* and *Salix*—suggests the existence of a small riparian forest in the Gállego and Ebro rivers (Sanchez-Goñi and Hannon, 1999; Valero-Garcés et al, 2000b).

The San Juan de Mozarrifar sequence is one example of the many sinkholes that occurred in the area, reaching up to 12 paleo-depressions per km². Although only this sequence has been dated, geomorphological data suggest their genesis was temporarily restricted to discrete periods. Higher evaporite dissolution and subsidence rates are related to periods of increased river discharge (Benito et al., 1998). Although the dating of this sequence is not accurate, it provides an example of the occurrence of periods of increased river flow in the Pyrenean rivers at times of “full-glacial” conditions in northern Europe.

4.4. Torrecilla de Valmadrid slope deposits

The Torrecilla de Valmadrid stratified deposits occur in both northern and southern slopes of the cliff. Screens are composed of alternating matrix-supported beds and

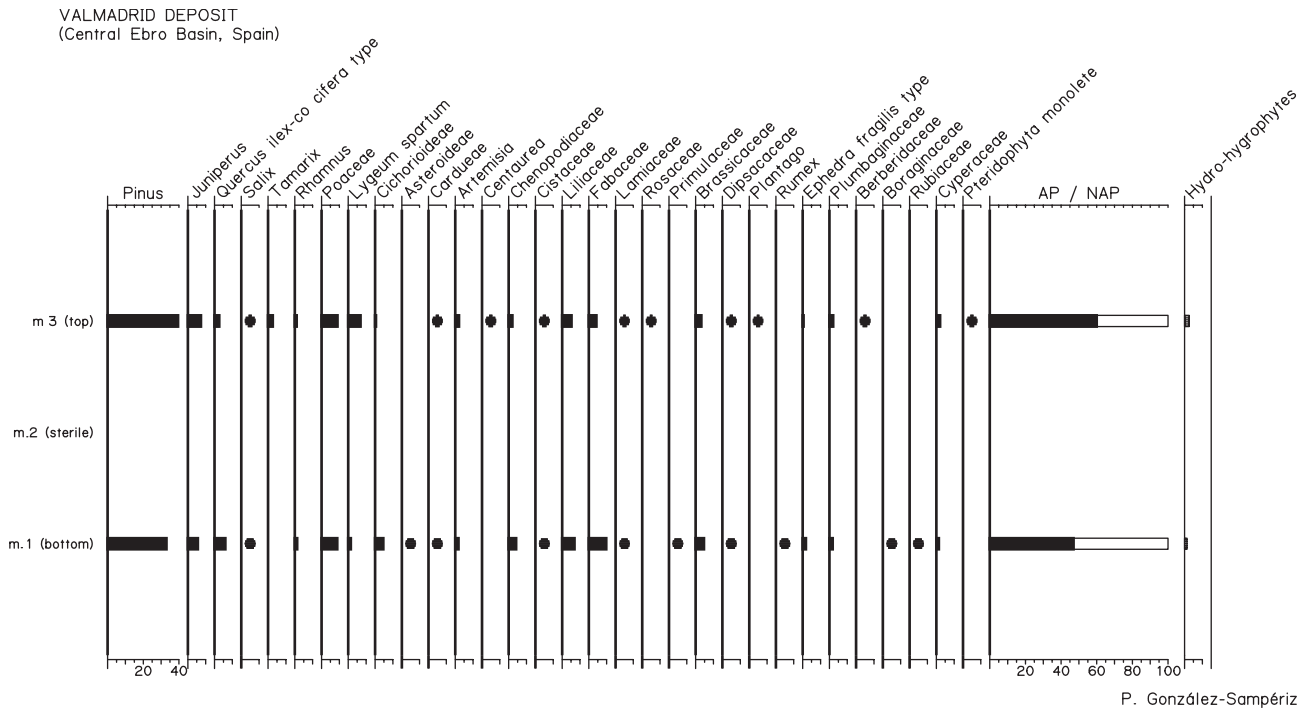


Fig. 6. Pollen assemblages from the Torrecilla de Valmadríd stratified slope deposits. Dots indicate presence lower than 2%.

coarser, clast-supported layers with clasts of up to 8.5 cm long. The origin of these deposits is related to the presence of appropriate cliff lithology (carbonate), the occurrence of freeze-thaw cycles that generate the clasts, and the existence of several slope processes such as debris flow activity, creep and wash erosion and intense freezing conditions that resulted in the documented grain-size distribution (García-Ruiz et al., 2001). One of the three pollen samples was sterile and the uppermost contains clear evidence for contamination by modern pollen (Fig. 6) (Not included in the diagram). The pollen assemblage in the lower sample is mostly composed of *Pinus* and grasses (about 50%). Although *Pinus* is the dominant tree, other taxa such as *Juniperus*, *Quercus ilex-coccifera* type, *Rhamnus*, *Salix* are present. Grasses are dominated by *Poaceae*, *Fabaceae* and other steppic taxa such as *Artemisia*, *Chenopodiaceae*, *Lygeum spartium* and *Ephedra fragilis* type, all plausibly indicative of aridity. This pollen spectrum reflects open vegetation, not very different from that at current landscape.

One AMS ^{14}C date of a pollen concentrate provides an age of $17,100 \pm 85$ ^{14}C yr BP for the onset of the scree formation. The presence of Mediterranean taxa seems incompatible with cold conditions needed for scree formation. However, an increase in continentality and seasonality could explain the presence of periglacial activity during the very cold winters and the occurrence of thermophilous taxa during the relatively warmer summers, particularly in some more protected, southern slopes.

5. Discussion and conclusion

Combined sedimentary facies, geochemical analyses and pollen spectra from lake sediment records, and sedimentological and palynological studies from slope deposits allow the vegetation and lake level status during glacial times in the central Ebro valley to be characterized. The interpretation of the mineral and geochemical records in shallow lakes dominated by groundwater flow is complex because of the different responses of the depositional system to rapid hydrological changes (Reed et al. 2001; Valero-Garcés et al., 2000a-c). A rise in the water table may cause an increase in salinity due to re-dissolution of previously precipitated salts, and consequently, discrepancies in the isotope-, mineralogy- or pollen-based reconstructions. These could explain some of the disparities between mineralogical and pollen-based interpretations found in some Spanish records (Reed et al. 2001; Valero-Garcés et al., 2000a).

The studied records show the presence of some phases of increased effective moisture while vegetation was dominated by steppe taxa. The genesis of sinkholes in the central Ebro basin is related to increased dissolution of the evaporite and carbonate substrate (Benito et al., 1998). Some depressions in the Ebro valley originated during the Lower and Middle Pleistocene. However, geomorphologic criteria indicate that many depressions also formed during the Upper Pleistocene (van Zuidam, 1980). Periods of increased evaporite dissolution and karstic activity are likely to reflect higher effective

moisture and run-off in the central Ebro valley. A period of increased river flow prior to 28 kyr would be responsible for the genesis of large sinkholes in the Gállego river floodplain like the San Juan de Mozarrifar. Although absolute dates for deglaciation in the Gállego Upper valley are absent, basal dates from glacial lakes (González-Sampériz et al., 2001) indicate that the maximum glacier extent in the Pyrenees occurred earlier than the global LGM, when the Scandinavian Ice Sheet and most glaciers in northern Europe reached their maximum. The onset of deglaciation in the Gállego prior to 30 kyr (García-Ruiz et al., 2003) could have caused an increased river flow responsible for increased evaporite dissolution and sinkhole genesis in the lower reaches of the river crossing the Tertiary evaporite formations. Pérez-Obiol and Julia (1994) interpreted peaks in mesothermophilous taxa in Banyoles as an evidence for an interstadial event between 30,000 and 27,000 yr BP in Mediterranean Spain. However, Carrión et al. (1998) do not find any expansion of *Quercus* in the Carihuela Cave (Granada, Spain) during the inter-Pleniglacial zones and they consider that the *Quercus* expansion in Banyoles is not more prominent than other peaks in the middle Würm at Padul (Pons and Reille, 1988). The ascription of these small peaks in mesothermophilous taxa to major warming events is still debatable.

La Salineta Lake also originated during glacial times (prior to $23,900 \pm 140$ ^{14}C yr BP) due to karstification of the underlying Miocene limestone. The base of La Salineta (Unit 5) reflects the highest effective moisture period of the whole sequence. Hydrological modelling indicates that because of the low-permeability of the substrate La Salineta closed-basin is very sensitive to changes in groundwater recharge (Samper-Calvete and García-Vera, 1998). Under the modern hydrological regime, an increase in groundwater recharge from 20 to 50 mm yr^{-1} would increase the discharge to the lakes to equal the estimated maximum evaporative capacity and would cause a remarkable rise in the water table. Changes in the precipitation: evaporation ratio would also have a large impact on the water balance. This period of relatively freshwater conditions (Unit 5) was followed by another of increased chemical concentration of the lake waters (Unit 4). Unit 4 represents one of the lowest effective moisture period in the whole record, and according to the preliminary chronology, also corresponds to full glacial conditions (prior to 21 kyr).

There are several lines of evidence that the Mediterranean was wetter than northern Europe during full glacial times. Using the best analogues approach, Peyron et al. (1998) reconstructed LGM climate of Europe from pollen data. South of the Pyrenees-Alps, temperatures of the coldest month were $-15 \pm 5^\circ\text{C}$ and annual mean temperature was $-10 \pm 5^\circ\text{C}$; the available moisture index and annual precipitation were lower than

present (-20% and $-600 \pm 200 \text{ mm}$, respectively). The reconstructions show that the Mediterranean region was relatively wetter than northern Europe during the LGM. A succession of temperate and cold environments in the Iberian Peninsula during a part of the last glacial period (50–30 kyr) has been interpreted from pollen spectra from marine cores off-shore Portugal (Sanchez-Goñi et al., 2000). Available terrestrial records fail to resolve the impact of these fluctuations in vegetation and moisture balances. However, many terrestrial records document several humid and arid periods since the LGM. Other Iberian records also suggest periods of increased effective moisture during glacial times. Deep-water sedimentary facies and a large negative $\delta^{18}\text{O}$ excursion in the Banyoles record indicates 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 north-eastern Spain (Valero-Garcés et al., 1998). La Salineta and Salada Mediana (Valero-Garcés et al., 2000a, b) provide the only available Lateglacial lacustrine records for the Ebro valley. In Mediana, two periods of increased effective moisture, identified by higher lake levels and temperate tree expansion (particularly *Corylus*), occurred after 18 kyr. Palynological evidence for a cold climate in the Central Ebro valley during glacial times (around 18 kyr) comes from the Valmadrid slope deposits.

High lake levels in Mediterranean regions during glacial times could also have occurred due to cold winters and cool, cloudy summers that greatly reduce potential evapotranspiration (COHMAP Members, 1988). However, a simple reduction of evapotranspiration tends to reduce drought stress on vegetation as well as increasing run-off. The apparent contradiction between the complex mosaic vegetation in the Ebro basin during glacial times (30–18 kyr) synchronous with periods of increased run-off in the Pyrenean rivers and more positive water balance in the central plateau of Los Monegros is possibly caused by the sensitivity of lake levels and vegetation to different components of the water balance. Although it is still conjectural, vegetation in Mediterranean environments seem to tend to equilibrium such that evapotranspiration during the wet periods (winters) conserves enough water to survive through dry periods (summer) (Prentice et al., 1992). Lake levels in shallow lakes dominated by surface aquifers are particularly sensitive to changes in run-off from the catchment. A soil water-balance model (Prentice et al., 1992) showed that combining winter cooling with a redistribution of the same total annual precipitation (increase in winter and decrease in summer) and potential evapotranspiration can increase run-off at the expense of soil moisture causing an increase in percolation and lake levels and a reduction in vegetation cover.

GCM experiments indicate that temperatures in the Mediterranean region were $5\text{--}10^\circ\text{C}$ lower than present

in winter due to strong westerlies from the cold North Atlantic, and only 1–3°C lower in summer because of local heating and weaker westerlies (Kutzbach et al., 1993). Harrison et al. (1996) explained the LGM climate by the development of anticyclonic circulation over the Scandinavian Ice Sheet, and a southward displacement of the westerly jet. Most models show a year-round strengthening of the jet stream, and increased winter precipitation along the jet stream close to the latitude of the Mediterranean. High paleoproductivity during the LGM in the Alborán Sea also indicates stronger westerlies in the Western Mediterranean (Bárcena et al., 2001). The marine records from the Alborán Sea also show a moister episode from 18.5 to 17.3 kyr BP. Relatively warmer sea-surface temperatures for the time around the LGM have been interpreted in the marine offshore core SO75-6KL, Portugal, based on dinoflagellate cysts (Boessenkool et al., 2001). As the jet stream retreated northward, the source of additional winter precipitation was removed and annual precipitation remained low because of the cold North Atlantic; lake levels in the eastern Mediterranean fell to a minimum during Lateglacial times. In Iberia, the Lateglacial effective moisture fluctuations have been linked to a southwards displacement of the Atlantic oceanic polar front, the Azores high and the Mediterranean winter belt (Harrison et al., 1996; Gasse, 2000). The hydrological response in Iberia to these fluctuations is unknown due to the lack of well-dated and detailed lake level reconstructions.

The paleoenvironmental reconstructions from these three records from NE Spain show the occurrence of periods of increased effective moisture and run-off in the central Ebro valley during glacial times, when vegetation was a complex mosaic landscape. The data are coherent with the hypothesis that, at least for some periods, the ice-age climate of the western Mediterranean was characterized by cold winters, relative intense winter precipitation and summer droughts. Increased flow from the Pyrenean rivers during the early deglaciation could also play a significant role in the paleohydrological conditions in the central Ebro valley. However, La Salineta records also show the occurrence of arid periods during glacial times, indicating a complex picture of hydrological and moisture evolution in the central Ebro valley during the LGM. To solve the controversies of the glacial climate in the Mediterranean region during glacial times, a network of well-dated records analyzed with a variety of paleohydrological proxies is needed.

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