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LACUSTRINE RECORDS OF CLIMATE AND ENVIRONMENTAL CHANGE IN THE EBRO BASIN

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FIELD TRIP GUIDE

B-2

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Blas L. Valero Garcés[1], Ana Navas[2], Javier Machín[2], Penélope González-Sampériz[1], Ana Moreno Caballud[1], Antonio Delgado-Huertas[3], Toni Stevenson[4] and Basil Davis[4]
[1] Instituto Pirenaico de Ecologia, Consejo Superior de Investigaciones Científicas, Campus Aula Dei, Apdo 202, 50080 Zaragoza, Spain
[2] Estación Experimental de Aula Dei, Consejo Superior de Investigaciones Científicas, Campus Aula Dei, Apdo 202, 50080 Zaragoza, Spain
[3] Estación Experimental de El Zaidin, Consejo Superior de Investigaciones Científicas, Profesor Albareda 1, 18008, Granada, Spain
[4] University of Newcastle, Newcastle upon Tyne, NE1 7RU, UK.
E-mail: blas@ipe.csic.es Teléfono: 976 716112; Fax: 976 716019

1. Saline Lakes in the Central Ebro Basin

1.1. Geographic location.

The semi-arid climate and the occurrence of topographically- closed basins have favored 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).

The Ebro Basin is a large depression surrounded by the Pyrenees to the north, the Iberian Range to the southeast, and the Catalan Ranges to the east. It is mostly filled with Tertiary continental deposits (IGME, 1971, Ramírez, 1997) (Figs. 1 & 2). Most lake depressions in the central Ebro Basin occur in groups, particularly on the central plateau of Los Monegros (about 100, sixteen of them flooded every year) and in the Bajo Aragón area (Pueyo-Mur, 1979; García-Vera, 1996). The genesis of the depressions has been related to dissolution of the underlying Tertiary evaporites and carbonates, preferential water circulation through faults, differential erosion, and surface deflation (Pueyo-Mur, 1979; Benito *et al.*, 1998; Sánchez-Navarro *et al.*, 1998). Some depressions in the Ebro Valley originated during the Lower and Middle Pleistocene (Benito *et al.*, 1998). However, geomorphologic criteria and the presence of *Elephas meridionalis* indicate that many depressions also formed during the Upper Pleistocene (van Zuidam, 1980). Radiocarbon dating has demonstrated a lateglacial to full glacial age for the basal sediments of some depressions (Valero Garcés et al., 2000a,b, 2004, González-Sampériz, 2004).

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 the Ebro Basin (Pueyo-Mur, 1979; Davis, 1994; Burjachs *et al.*, 1996; Schütt, 1998a,b; Valero-Garcés *et al.*, 2000, 2004, Pérez et al., 2002, González-Sampériz, 2004).

1.2. Climate and vegetation

The central Ebro Basin is the most northern area of truly semi-arid climate in Europe (Fig. 1A). The climate is Mediterranean with a strong continental influence characterized by very hot summers, cold and dry winters, and low rainfall (300-350 mm yr^{-1}) due to the rain shadow effect of the Iberian Range (Capel Molina, 1981; García-Vera, 1996). Average values at Zaragoza airport are 320 mm of annual rainfall, 1194 mm of evapotranspiration, and 24.2 °C and 6.4°C average temperatures in July and January, the warmest and coldest months, respectively. Below freezing nighttime 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.

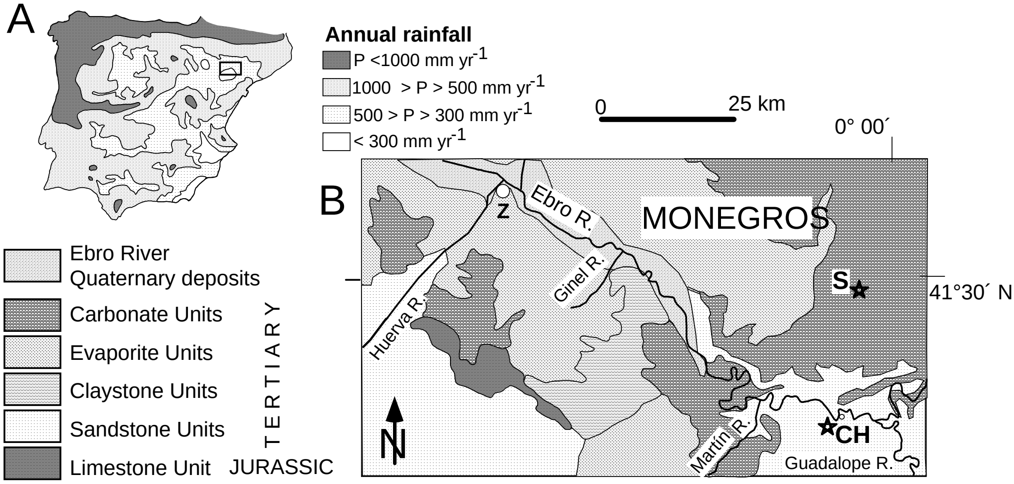

Figure 1. Geographic location of the study sites in the Los Monegros region, Central Ebro valley. A. Under modern climatic conditions, the region receives less than 300 mm per annum of precipitation. B. Geological location of the three sites: La Salineta and La Playa lake (S), and Salada Chiprana (Ch). Z= Zaragoza.

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. In the central Ebro Valley, spring and autumn precipitation account for more that 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).

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; Utrilla and Rodanés, 1997). This unique ecosystem is characterized by the presence of a number of endemic species and others typical from northern Africa and the cold steppes of central Eurasia. Small relict forests are dominated by *Pinus halepensis*, *Quercus coccifera*, and *Juniperus sp*. 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.

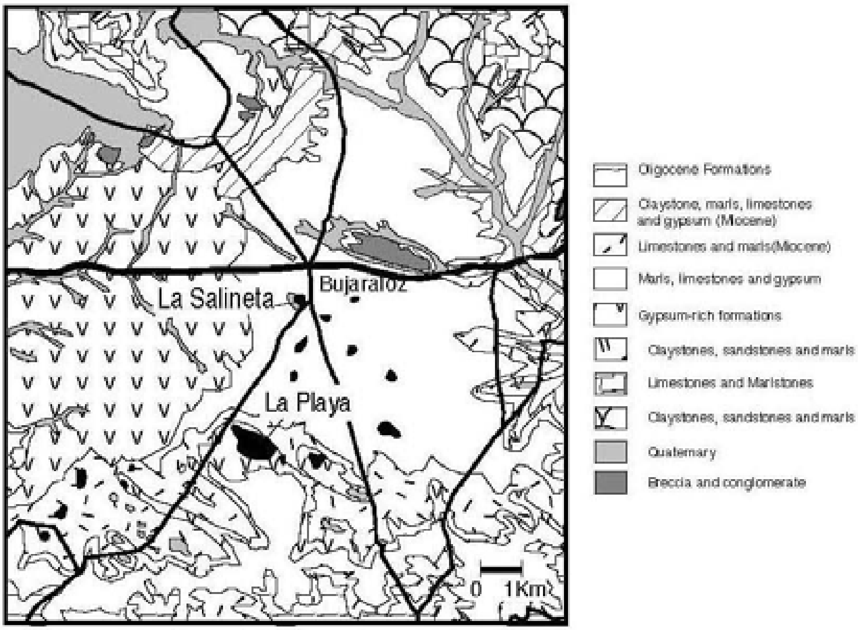

Figure 2. Geological map of La Playa and La Salineta area (adapted from IGME, 1971).

2. The Bujaraloz—Sástago Saline Lake Complex

2.1. The modern lakes

Over a hundred closed depressions – almost 20 of them temporarily flooded – (Pueyo-Mur, 1979) occur in Los Monegros area, a structural platform at around 320-350 m a.s.l. between the Santa Quiteria Sierra to the north, and the Ebro River to the south (Fig. 2). Three Late Oligocene and Early Miocene evaporite-bearing formations have been identified in the Los Monegros platform (Salvany et al., 1996). The closed basins show flat bottoms and scarped to gentle margins, and they are strongly elongated following the WNW-ESE direction. 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. The platform is a hydrologically - closed basin with two main aquifers (García-Vera, 1996). Brines are of (Cl^-) - $(SO_4^{=})$ - (Na^+) - (Mg^{2+}) type and undergo strong seasonal oscillations in concentration because of groundwater input, evaporation and progressive salt precipitation (Castañeda, 2002). La Playa is the largest playa lake in the area (1.72 km^2) and it has scarped margins and some gullies. Available limnometric data (Castañeda, 2002) show a maximum depth of 51 cm during the winter months, and complete desiccation during the summers. The data show a clear relationship between presence of water and rainfall for all the saline lakes in the area, although with individual responses for each system. La Playa shows the longest, time-lag between the rainfall onset and maximum water depth, and the shortest time to desiccation, likely due to its larger surface area. In winter, mirabilite precipitation occurs in some lakes. Algal mats develop during the flooded phases, and sulfates and chlorides precipitate during the summer forming a salt crust that covers the bottom of the lake. The upper salt crust is re-dissolved during the following year (Pueyo Mur, 1979). A detailed geomorphological study showed three stepped levels of lacustrine terraces and a suite of *yardangs* associated to the lacustrine terraces (Gutiérrez-Elorza et al., 2002). The oldest terrace (T3) is located at 7.5 m, the intermediate T2 at 3.5-3 m has the greatest extent, and the youngest one (T1) is located at 0.3-0.5 m.

La Salineta 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 gL^{-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 and average TDS of 5 gL^{-1}. Stable isotope data (García-Vera, 1996) suggest that groundwater, rainwater, and runoff (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 interfluves and highlands. Hydrological modelling suggests that the upper aquifer discharges one third of the total recharge (5822 m^3 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, the presence of the thickest salt layers, and the considerable higher salt production compared to La Playa (about 4600 ton/yr versus 1400 ton/yr in La Playa in 1862 in Davis, 1994)

2.2. Core sections and Chronology

We have studied both saline lakes described above: La Salineta and La Playa. Outcrops and lake cores have been described in La Salineta. A section with paleolake sediments located in the southeastern cliff of La Salineta, and a core collected below the cliff with a Hiller corer (320m a.s.l., 41°28’55’’ N , 0°09’30’’ W.) was recovered in 1991 (Davis, 1994). The total length of this section was 465 cm long (0-360 cm from the open section, 360-465 cm from the core). The analyses performed included pollen, charcoal, macrofossils and geochemistry, and the results are described in detail elsewhere (Davis, 1994). Another 8 m long 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. A 1.6 m long core was retrieved from La Playa and the Miocene gypsum substrate was reached. The sediment cores were split, described, and sampled for organic matter, mineralogy, geochemistry, stable isotope, and pollen analyses following methods described elsewhere (Valero-Garcés *et al.*, 2000a, b). Sedimentological and geochemical analyses provided the basis for facies identification and unit definition in the core (Smoot and Loweinstein, 1991).

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, 1998a,b; Valero-Garcés *et al.*, 2000b, González-Sampériz, 2004). Only one AMS date is available for La Playa core (8.773 ± 73 ^{14}C yr BP). Organic macrofossils were very scarce in both La Salineta Section (Davis, 1994) and La Salineta Core. *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 at about 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, 1992), although in the Northern Meseta, the Iberian Range and the eastern Pyrenees, *Fagus* pollen grains have been recorded at about 7-8 kyr B.P. (Franco-Múgica et al., 2001; González-Sampériz, 2004).

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 macrofossils 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 ^{14}C dates ranging from 18,790 ± 500 ^{14}C yr B.P to 23,900 ± 140 ^{14}C yr B.P. Four more dates from the upper units show reversals and the validity of these dates must 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 (13050 ± 85 ^{14}C yr B.P and 13950 ± 160 ^{14}C yr B.P) 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.

2.3. The sedimentological and geochemical record.

2.3.1 La Salineta Record.

Five sedimentary units have been defined in the La Salineta core based on sedimentological, lithological and geochemical criteria (Fig. 3). Depositional environments for saline lake sediments can be identified integrating a variety of criteria (see Valero-Garcés *et al.*, 2004): 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). 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, the presence of calcite as the only carbonate mineral in Unit 5B, and the lowest oxygen compositions (between -5 and -3 ‰) 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. Oxygen isotope values increase at the base of unit 4 and remain high (+3 to +5 ‰) to the top of this unit.

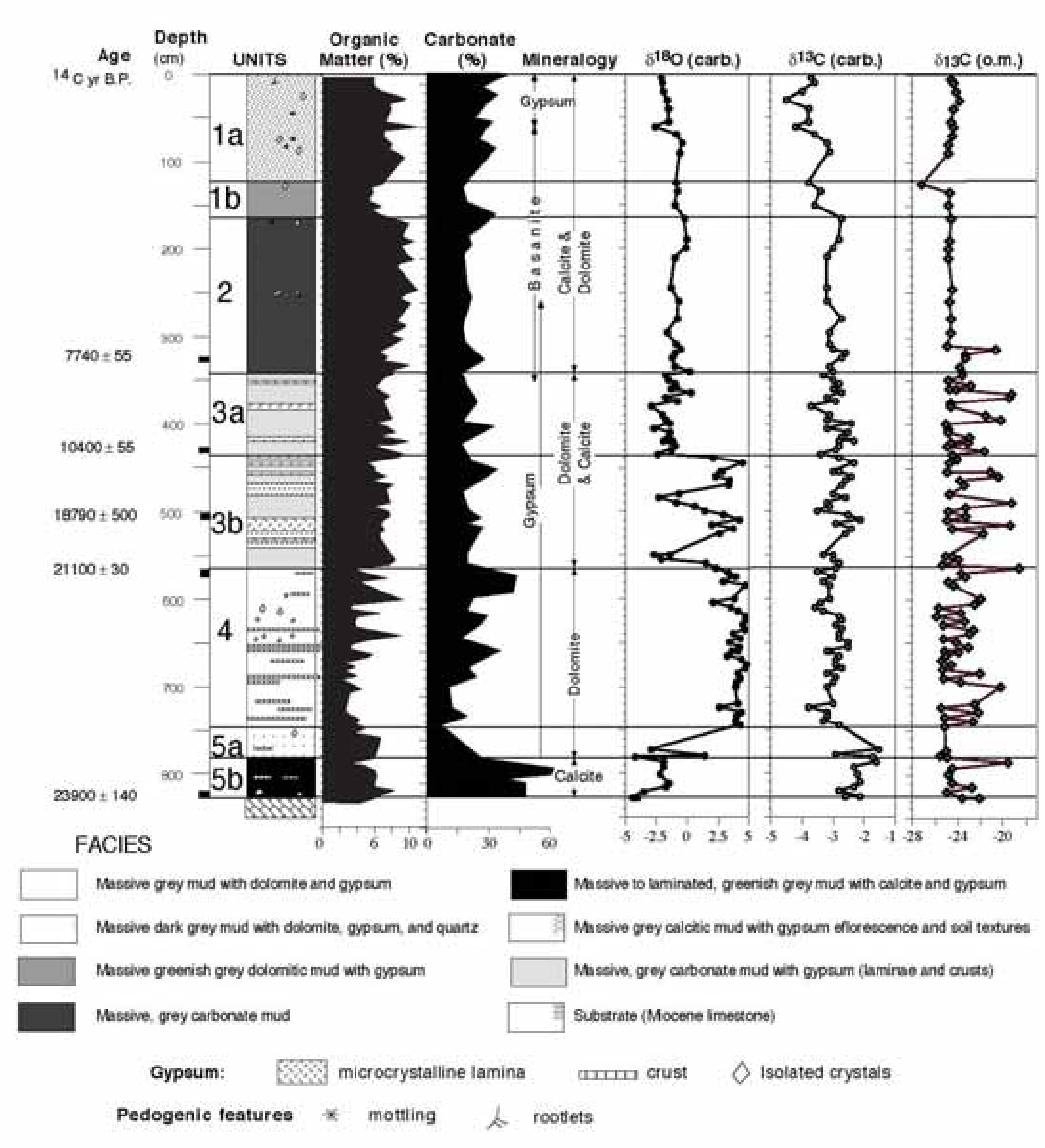

Figure 3. La Salineta sedimentological, mineralogical, geochemical and isotopic record.. The stable isotope ($\delta^{18}O_{carb.}$ and $\delta^{13}C_{carb.}$) values are from bulk carbonate samples. The $\delta^{13}C_{(o.m.)}$ values are from bulk organic matter samples.

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 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 (Subunit 3B), peak in the middle part, and decrease again towards the top (Subunit 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). Unit 3 is characterized by a marked negative $\delta^{18}O$ excursion at the base, and relatively higher and more variable values in subunit 3B, with two main positive excursions (500- 530 cm and at around 450 cm). Increased calcite and organic matter content in unit 2 suggest that flooded and relatively low chemical concentrated waters dominated during deposition of unit 2. The upper unit 1 shows soil textures as evidence of modern farming practices. The $\delta^{18}O$ values in the upper units 3A, 2 and 1 are relatively lower (between 0 and –3 ‰) and more constant.

The $\delta^{13}C_{carbonate}$ record shows three distinctive intervals. Unit 5 has the heaviest $\delta^{13}C$ (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). The relatively lighter compositions ($\delta^{13}C_{org} <$ -24 ‰) suggest a dominance of terrestrial over lacustrine carbon sources. 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 -20 to -24 ‰ PDB).

2.3.2. La Playa Record.

The sedimentary section is composed of a basal, dolomite – rich unit (u. 5), two units with gypsum intercalations (units 4 and 2), and two calcite–rich units (u. 1 and 3) (Moreno et al., 2004) (Fig. 4) Unit 5 shows the highest carbonate, quartz and clay mineral contents, the lowest in gypsum, and peaks in terrigenous elements as Fe and Al. Gypsum and calcium content show similar trends through the sequence. Magnesium is associated with sulfate and dolomite. Unit 4 shows an increase in gypsum and calcium and a decrease in quartz and clay minerals. Organic matter content starts to increase in unit 4 and continues in unit 3. Unit 3 is characterized by higher calcite and organic matter content. Gypsum peaks in unit 2, where it occurs as mm-long crystals. The top unit is marked by an increase in calcite.

The La Playa record contains three sedimentary sequences that represent the evolution of a saline system from carbonate-dominated towards more sulfate and saline conditions. It is likely that hiati occur between the sequences (base of units 3 and 1) with long periods of subaerial exposure and aeolian deflaction. These sequences reflect hydrological changes in the saline lakes. The basal sequence (units 5 and 4) could represent one of the climatic fluctuations during the Lateglacial. The intermediate sequence suggests relatively more humid conditions during the Early Holocene and the transition to increased aridity after 8.5 ka. The upper sequence is interpreted as a dominance of flooded stages in the Salada during more recent periods in the late Holocene.

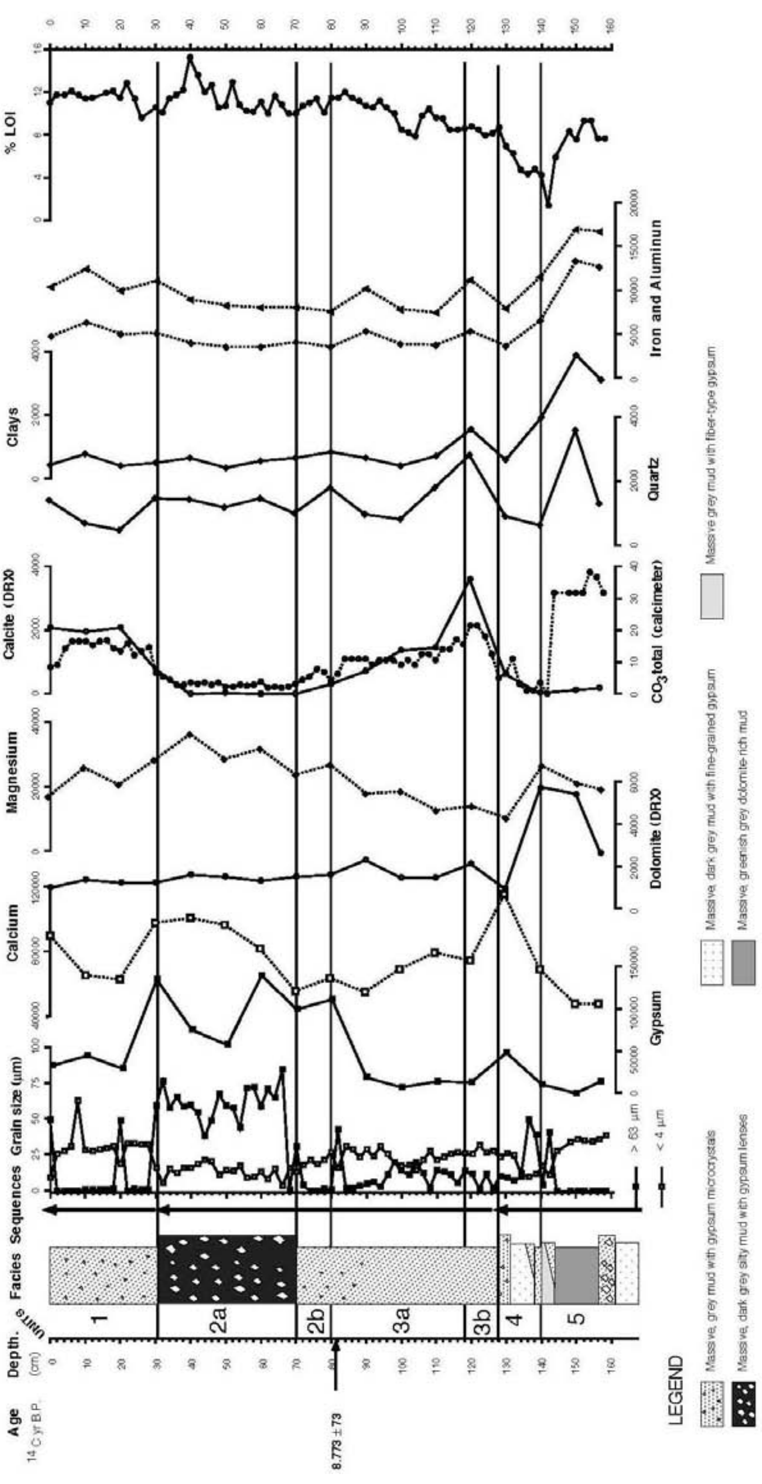

Figure 4. La Playa sedimentological and mineralogical record.

2. 4. The Pollen record

A detailed review of the available pollen records in the central Ebro Valley spanning the Upper Pleistocene and Holocene can be found in Davis (1994), González et al., (2003), and González-Sampériz (2004). Davis (1994) also provides a detailed description of the 4.65 m long La Salineta Section. 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. 5). Arboreal pollen is dominated by *Pinus*, while Chenopodiaceae oscillations may reflect changes in lake surface. In La Playa sequence, *Pinus* is the dominant taxa, but the variable ratios of *Quercus ilex-coccifera* type and *Juniperus* underline changes in the regional vegetation. Aquatic taxa and Chenopodiaceae correlate with the inferred hydrological interpretations based on sedimentological proxies.

2.5 . Environmental and climatic implications.

The combined analyses of sedimentary facies, geochemistry and pollen from the two saline lake sediment records (La Salineta and La Playa), provide new data to characterize the vegetation and lake level status during the Last Glacial (LGM), Lateglacial and Holocene in the central Ebro Valley (NE Spain). La Salineta Lake originated during glacial times (prior to 23900 ± 140 ^{14}C yr B.P.) due to karstification of the underlying Miocene limestone. Periods of increased evaporite dissolution and karstic activity are likely to reflect higher effective moisture. A period of increased river flow prior to 28 ka would be responsible for the genesis of large sinkholes in the Gállego river floodplain like the San Juan de Mozarrifar (Valero-Garcés et al., 2004). Although absolute dates for deglaciation in the Gállego Upper valley are absent, basal dates from glacial lakes (García-Ruiz et al., 2003; González-Sampériz, 2004) 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 28 ka would have caused an increased in river flow responsible for increased evaporite dissolution and sinkhole genesis in the lower reaches of the river crossing the Tertiary evaporite formations. 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. After this period with relatively dilute waters (Unit 5), chemical concentration of the lake waters greatly increased (Unit 4). Unit 4 represents a dry period, and according to the chronology, also corresponds to full glacial conditions (prior to 21 Kyr).

These records show the presence of phases of increased effective moisture and lake sediment aggradation while regional vegetation was dominated by steppe species. The results indicate that - at least for some intervals during full glacial and lateglacial times – when cold steppe vegetation dominated the region, some lakes experienced more positive water balance than today, and run-off was also higher. Two major hydrological fluctuations occur during the Lateglacial, and more humid conditions are recorded during the early and late Holocene. The results are coherent with the hypothesis that – at least for some periods- the ice-age climate of the western Mediterranean was characterized by cold winters, with relatively higher effective moisture (precipitation minus evaporation ratio) and summer droughts. 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.

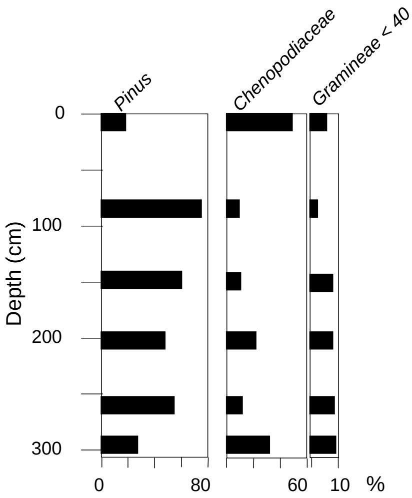

Figure 5. Main pollen taxa (in %) from the upper 3 m of La Salineta core sequence. Samples below 3 m were sterile.

Some other Iberian records also suggest periods of increased effective moisture during glacial times. Deep-water sedimentary facies and a large negative $\delta^{18}O$ excursion in the Banyoles record indicates that immediately after the LGM - dated as 22,890 ± 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, 2000 b, c) 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 Ka. Palynological evidence for cold climate in the Central Ebro valley during glacial times (around 18 ka) comes from the Valmadrid slope deposits (Valero-Garcés et al., 2004; González–Sampériz, 2004).

The three lacustrine terraces described in La Playa (Gutiérrez-Elorza et al. 2002) are not dated, and consequently, the correlation with the paleoenvironmental evolution reconstructed from the cores is hypothetical. The three terraces could be the geomorphological reflection of the three sedimentary sequences described in the core. The terrace systems show the alternation of periods of increased lacustrine deposition (wetter) and periods of entrenchment (erosion and aeolian deflaction). The sediments accumulated in the oldest terrace T3 could correspond to deposition of units 5 and 4. A drier period would be responsible for the entrenchment of the terrace and the origin of a hiatus in the sediment sequence. The most extensive terrace T2 would be related to a period of increased sediment accumulation with dominant flooding conditions (unit 3 and 2) in a large lake including La Playa, El Pueyo and El Pito saline lakes during the early Holocene. Another entrenchment episode with intense aeolian erosion would be responsible for the segmentation of the former lake, and the genesis of the *yardangs* would also be related to this dry period during the mid Holocene. The upper sequence (unit 1) would correspond to increased deposition during the late Holocene and the genesis of the modern terrace.

Both, geomorphological features and the sediment record in La Salineta also show evidence for a period of sediment accumulation in a larger lake to and a subsequent period of entrenchment that would have generated the current smaller lake basin. The sediment sequence described in the core shows accumulation during full glacial, late glacial and the early Holocene (23 to 7 k years). The formation of the inset lake occurred after deposition of the sediments accumulated in the terrace, i.e. after 7.7 Ka. Both, La Salineta and La Playa record suggest a relatively more humid early Holocene, very dry conditions during the mid Holocene, and a small recovery during the late Holocene.

3. The Chiprana Lake

3.1. The Modern Lake

3.1.1. Limnology and Hydrology.

The *Salada Chiprana* (N 41° 14’ 30” , W 0° 10’ 50”, 150 m a.s.l.) lies on the Upper Oligocene - Miocene Caspe Formation (Fig. 1), composed of elongated sandstones (infilling of meandering palaeocanals) embedded in fine-grained siltstones deposited in a fluvial floodplain environment (IGME, 1971). The different erodibility of these rock formations has resulted in a ‘negative’ relief with small topographically-low areas surrounded by palaeocanals. The *Salada Chiprana* (surface area = 13.25 ha) belongs to a group of wetlands and lakes hydrologically connected that includes: *Las Roces*, *Clota de El Farol* to the SW, *Campo de Saladas*, and *Plana de San Marcos* (Fig. 6). The watershed of the complex is about 516 ha, and about 156 ha belong to the *Salada Chiprana*. The *Salada Chiprana* waters are of (SO_4^{2-}) - (Mg^{2+})- (Na^+) type, with low carbonate and calcium contents, high Mg/Ca ratios, and an average salinity of 40 mg l^{-1} (EPTYSA-DGA, 1997). Average water depth is 3.2 m, and the volume about 1 hm^3 (7, 8, 13). Brine salinity and composition does not vary greatly during the year, and chemical and thermal water stratification has been documented (Vidondo and Guerrero, 1992, LIMNOS-DGA, 1996).

The most conspicuous feature of *Salada Chiprana* is the presence of very distinct lacustrine sub-environments defined by depth, physical and chemical water properties, and biological assemblages (Vidondo and Guerrero, 1992, LIMNOS-DGA, 1996, Valero-Garcés et al., 2000c): i) littoral areas, ii) sub-littoral charophyte meadows, iii) benthic cyanobacterial mat communities, and iv) an anoxic hypolimnion. The littoral sub-environments are dominated by *Ruppia maritima L*. var. *maritima* between 0-0.8 m water depth. The charophyte meadows composed of *Lamprothamium papulosum*, develop in deeper sub-littoral waters. The benthic communities, mostly composed of the cyanobacterium *Microcoleus chthonoplastes* able to develop in nutrient-poor, transparent and oxygenated waters, form 2-3 mm--thick mats, up to 1-1.5 m water depth. The deep anoxic waters are the habitat of green phototrophic sulfate-reducing bacterium (*Chlorobium vibrioforme*).

Salada Chiprana is fed by rainfall, groundwater, runoff, and irrigation returns. The ultimate source of the solutes in groundwaters and playa lakes in the central Ebro basin is the dissolution of the carbonate and evaporite rocks in Tertiary formations (García-Vera, 1992, Mingarro et al., 1981; Sánchez-Navarro et al., 1998). The quantitative contributions of the main water inputs for the Salada, particularly groundwater-and irrigation returns, are still unknown (LIMNOS-DGA, 1997; EPTYSA-DGA, 1997; ESHYG-DGA, 1994). Most hydrological surveys do not favor a large groundwater input of high salinity waters and suggest that irrigation returns are large enough to maintain the actual hydrological levels (Baquer, 1999).

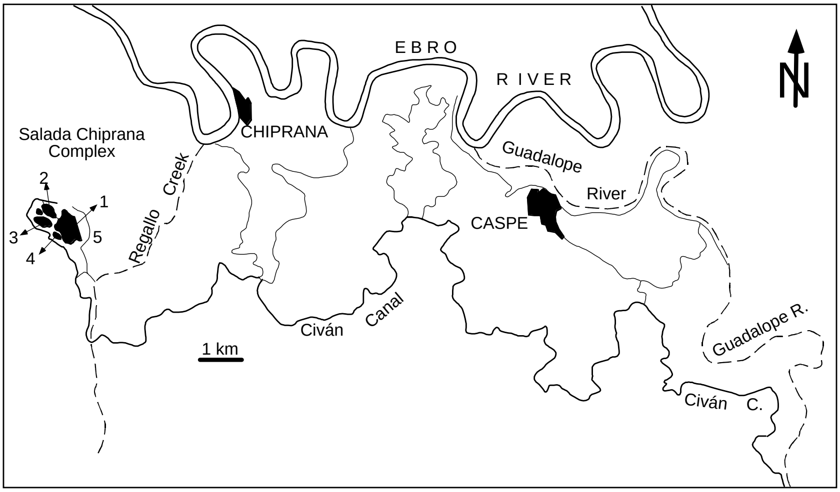

Figure 6. The irrigation system in the Chiprana - Caspe area. Waters are diverted from the Guadalope River through the Civán Canal. Several subsidiary canals allow irrigation of most of the land between the Civán Canal and the Ebro river. The Civán Canal ends nearby the *Salada Chiprana* Complex, where irrigation return flows are diverted. The *Salada Chiprana* Complex consists of several lakes and depressions: 1. *Salada Chiprana,* 2. *Laguna de las Roces*, 3. *Prado del Farol,* 4. *Campo de las Saladas*, and 5. *Plana de San Marcos.*

3.1.2. Irrigation and Water Use

About 4100 ha from the Chiprana and Caspe areas are irrigated with the Civán Canal. This canal, a diversion of the Guadalope river, runs parallel to the Ebro river for about 52 km and ends in the surroundings of the *Salada Chiprana* (Fig. 6). The irrigation return flows are diverted to the Regallo Creek, to the *Salada de Las Roce*s, and thence to the *Salada Chiprana*; the average annual flow is estimated as 2.5 l sec^{-1} and the total freshwater input during 1993 as 103,826 m^3 (LIMNOS-DGA, 1997; EPTYSA-DGA, 1997; ESHYG-DGA, 1994). Currently, 43.8 ha are irrigated within the *Salada Chiprana* watershed. The main crops are barley, alfalfa, sunflowers and olive trees, and irrigated by flooding.

Records of irrigation activities exist from 1838, when a committee composed by the 40 land owners with the largest properties was formed. The irrigated surface reached 3912 ha during the 1950s and was reduced by the construction of the Mequinenza dam in the Ebro river in 1967; about 400 ha of rich farm land was covered by the scheme. The construction of the Civán reservoir in the Guadalope River in 1992 has enabled the irrigation of an additional 200 ha. Olive was the main crop until 1970 when a severe winter killed many trees and led many farmers to replace olives with corn and alfalfa. The higher water needs of these new crops, and the low efficiency of the irrigation techniques has subsequently resulted in an increase of water consumption.

The Aragón Regional Government has been monitoring the Salada Chiprana during the last 2 decades, including measurements of the water quality and the lake level during the period 1993 – 1996. During low salinity periods triggered by increasing irrigation returns, *Artemia salina* disappeared and the lake was colonized by a brackish fauna. The waters were anoxic below 3 m, and benthic microbial communities were not very well developed. During the summer of 1995, the lake reached a low lake level stage that isolated one of the bays, and a hypersaline brine developed (73 - 100 g L^{-1}). Waters were more transparent, anoxic bottoms reduced, and cyanobacterial mats expanded to deeper areas. These qualitative observations demonstrate that the main lake level fluctuations and lake water compositions are related to the changes in the irrigation return flows.

3.2. Core Stratigraphy and Chronology

Two cores were retrieved from the deepest area of the lake in 1991 (core I, Davis, 1994) and 1997 (core II, Valero-Garcés et al., 2000c). The sediment sequence in core II is composed of: i) massive grey muds with abundant isolated gypsum crystals at the base, ii) massive red clays, and iii) finely laminated, organic-rich black sediments at the top (Fig. 7). Six sedimentary units were defined based on the sedimentary facies and all the measured compositional and geochemical parameters. Although the boundaries between units are not located at the same depths, the main units are present in both cores and are easily correlated. Davis distinguished in core I: (Fig. 8) 1) a basal unit (206-192 cm – SC-6) composed of grey lacustrine playa clays that correlates with sedimentological Unit 6 (175 - 148 cm, core II); 2) a unit composed of red clays (192 - 130 cm – SC-5) that correlates with Unit 5 (148 - 95 cm, core II); 3) a unit composed of grey/blue lacustrine clays (130 - 45 – SC-4) that corresponds to sedimentological Unit 4 (95 - 55 cm, core II), and 4) a laminated organic mat and lacustrine clays unit (unit 4: 45-0 cm – SC1-3) that corresponds to Units 3 to 1 (55-0 cm, core II).

The chronology for *Salada Chiprana* Core I is based on three AMS radiocarbon dates from a mixture of Chenopodiaceae plant remains and Carophyllaceae seeds at 50-51 (315 ± 60 ^{14}C yr BP) and 73-75 cm (420±50 ^{14}C yr BP), and charcoal from 191-194 cm (5725±60 ^{14}C yr BP) (Davis, 1994). The chronological framework for *Salada Chiprana* is improved with another AMS ^{14}C date from charcoal at 145 cm (core II) and a ^{210}Pb chronology for the upper sediments (core III) (Valero-Garcés et al., 2000c). The ^{210}Pb chronology helps constrain the main limnological changes occurring in *Salada Chiprana* during the last centuries. For the estimation of the sedimentation rates, the constant flux:constant sedimentation model has been used (Olsson, 1986). These results give a mean sedimentation rate of 0.10 g cm^{-2} yr^{-1} (e.g., the upper 17 cm represent about 80 years). Assuming a similar average accumulation rate for the upper Units 1 and 2, the spread of cyanobacterial mats in the lake (Unit 2) would have occurred at the beginning of the XIX century, and the transition to the finely laminated, organic-rich sediments of Unit 1 at the beginning of the XX century.

3.3. The sedimentological, geochemical and pollen record

Figure 7 shows the main sedimentological and geochemical proxies for the Salada Chiprana record. Unit 6 is composed of massive grey-green muds with abundant isolated gypsum crystals (< 1 mm), and calcite as the only carbonate mineral. Displacive textures and matrix mud inclusions in the crystals suggest that the gypsum crystals were formed as a result of intrasediment growth in a saline mudflat environment. This is confirmed by the palynology which is suggestive of a playa type environment (Fig. 8). *Salada Chiprana* during deposition of unit 6 (mid Holocene, 6000 - 4000 ^{14}C yr B.P.) was an ephemeral, shallow saline lake similar to the current lakes in the Central Ebro Basin.

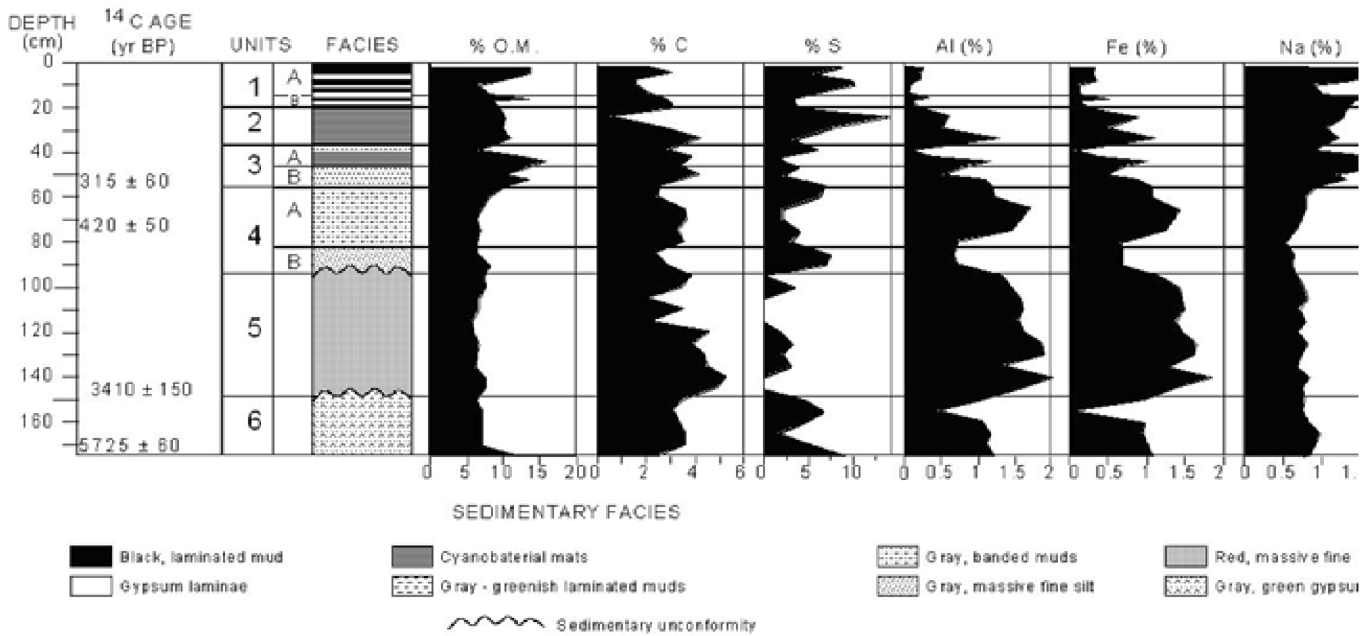

Figure 7. Sedimentary facies, sediment composition (percentages of organic matter, total carbon, and sulfur), chemical composition (Al, Fe, Na and Sr) of the Chiprana core I.

The sharp change to the reddish massive fine muds of Unit 5 (148 cm) indicates that an abrupt change in the depositional environment took place prior to 3500 ^{14}C yr BP. This abrupt boundary is located at 130 cm depth in core I. Sediments of Unit 5 are characterized by higher clay mineral and lower gypsum contents. Higher concentrations in aluminium and iron also reflect the higher clay content. The oxidized, detrital nature of the sediments, together with lack of aquatic pollen and seed types and Chenopodiaceae pollen suggests frequent desiccation stages with accumulation of wind-blown material in the small surface depressions of a dry playa lake.The sharp changes in lithology indicate that Unit 5 is bounded by erosive unconformities. The upper boundary at 95 cm depth represents a sedimentary hiatus of unknown age developed during periods when the lake dries-out. Erosion during this and/or other arid periods has resulted in a long sedimentary hiatus, and the Late Holocene sequence is not complete. The decline of the Pinus forest had occurred in the area during this period, prior to historical times (Fig. 8)

The deposition of massive, coarser brown and grey silts with more abundant gypsum crystals and lower clay content (Unit 4B) indicates an increase in the water balance, and the re-establishment of a shallow ephemeral saline lake. Periods of more frequent desiccation are indicated by increases in the clay content, and related elements (Al, Fe). The increases in organic matter and Na contents at the top of Unit 4A suggest deposition in a shallow saline lake with the water table close to the surface even during desiccation stages. This is confirmed by the pollen results which sees increases in *Ruppia* and *Potamogeton* pollen together with high levels of Chenopodiaceae pollen. An AMS ^{14}C date from this unit provides an age of 420 ± 50 yr BP, which indicates that the water table rise in *Salada Chiprana* at the base of Unit 4 occurred around 600 years ago, in the XIV century. The boundary between SC-5 and SC-4 evidences a marked deforestation as pine woodland gives way to *Juniperus* and other steppe plants like *Artemisia*.

Another abrupt sediment change inaugurates Unit 3. The upper units 3, 2 and 1 are composed of organic- gypsum, and aragonite-rich finely laminated sediments. Both, clay mineral and aluminum contents decrease reflecting a lower detrital input. The presence of aragonite indicates waters with higher Mg/Ca ratios. Strontium preferentially substitutes Ca^{2+} in aragonite and, consequently, it is also more abundant in the upper Units. The preservation of lamination, the increase in organic matter and Na contents, and the change in the carbonate mineralogy, together with high levels of *Ruppia maritima* var *maritima* seeds, *Ruppia* pollen and *Lamprothamnium papulosum* oospores point to deposition in a permanent, deep saline lake (Fig. 8). Unit 3B is composed of an alternation of organic-rich grey muds and gypsum laminae; Unit 3A groups organic-rich muds and bacterial mats not very well developed that grade upwards into the same alternation of facies characteristic of Unit 3B. Organic-rich muds and gypsum laminae indicate hypersaline, anoxic conditions and the development of water stratification in *Salada Chiprana*. During lower lake levels, meromixis was disrupted and oxygenated bottom waters allowed development of bacterial mats in the deepest part of the basin. The increase in water levels correlate with the onset of an increasing trend in *Olea* and decrease in *Pinus* pollen.

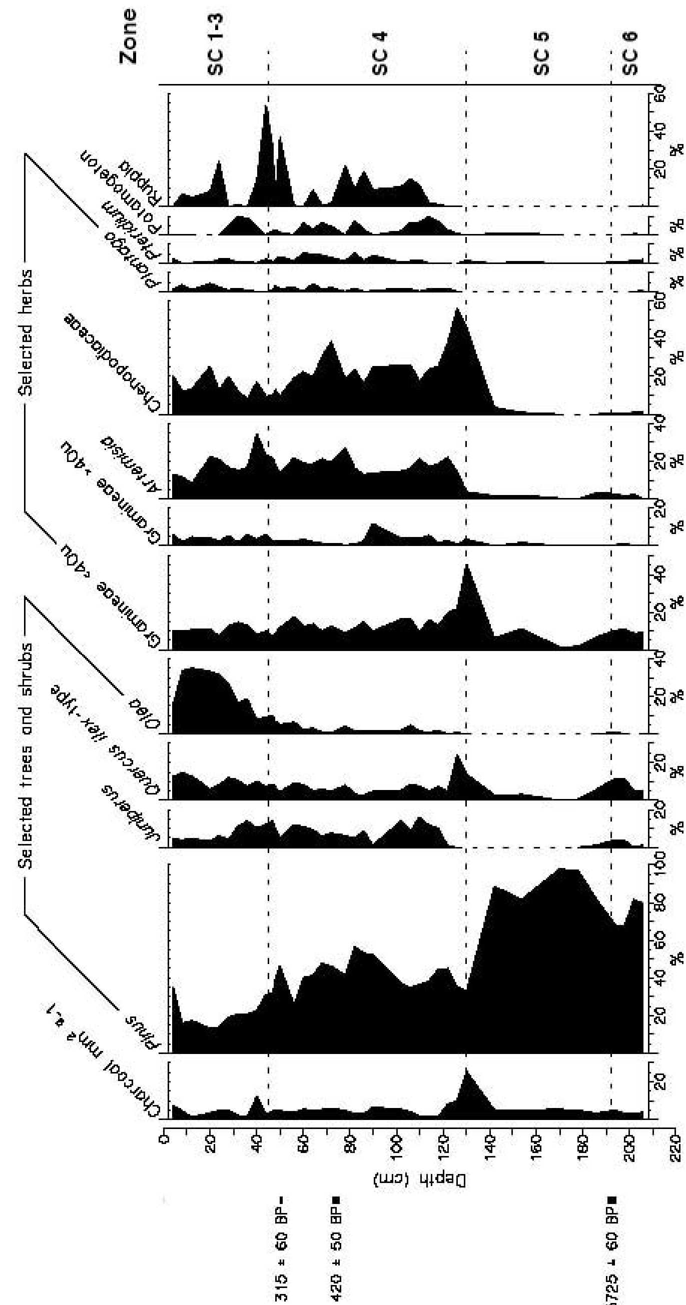

Figure 8. Summay pollen and charcoal diagram of the Chiprana sequence (core II). The depicted zones are provided to depict the lithostratigraphical correlation with core I (right column). Only selected plant taxa are shown.

3.4. Environmental and climatic implications.

The depositional evolution of the lake and the correlation with the main agricultural events is summarized in Figure 9. *Salada Chiprana* during deposition of unit 6 (6000 - 4000 ^{14}C yr B.P.). was an ephemeral, shallow saline lake similar to the current lakes in the Central Ebro Basin. The sharp change to the reddish massive fine muds of Unit 5 indicates that an abrupt change in the depositional environment took place prior to 3500 ^{14}C yr BP. These features suggest that *Salada Chiprana* was a dry mudflat with the local watertable below the surface during most of the Late Holocene. This arid episode coincides with the decline of Bronze Age settlements in the central Ebro Basin (Sopena Vicien, 1998; González-Sampériz and Sopena, 2002). Erosion during this and/or other arid periods has resulted in a long sedimentary hiatus, and the Late Holocene sequence is not complete.

The increase in the water balance, and the re-establishment of a shallow ephemeral saline lake (base of Unit 4) occurred around 600 years ago, in the XIV century. The watertable increase in *Salada Chiprana* at the onset of Unit 4 correlates with large agricultural changes in the area, a marked deforestation, and also the climatic fluctuations at the end of the Medieval Warm Period (Pfister et al., 1998). The use of the Guadalope river water for irrigation purposes in the Caspe and Chiprana area is likely to have started during the Arab epoch (VIII - XII centuries). No archaeological or historical studies have been conducted, although some stonework close to the beginning of the Civán Canal, date from the XII-XIII centuries (Civán Committee Manager, pers. comm.). The first historic document dated from 1413 when King Ferdinand of Antequera gave the privilege of the use of the Civán channel to the city of Caspe, as a reward for his election as the new king of Aragón in Caspe. During the XV century a tunnel was planned to eliminate 6 km of the channel, and to reduce the costs of annual cleaning but was abandoned after structural problems led to collapse of the tunnel roof.

On the other hand, the XIV - XV centuries were also a period of climate change in western Europe, after the end of the Mediaeval Warm Period (AD 900 - 1300; Pfister et al., 1998). Dendroclimatological reconstructions for the Central Ebro valley (Creus et al., 1996, 1997) show a high climate variability (rainfall and temperature) since the XIII century, after the relatively low variability of the Medieval Warm Period. During the 1400s - 1600s both droughts and floods were more frequent. Climate variability was particularly higher during the 1480 - 1520 AD period when annual precipitation increased and temperature decreased. Rainfall was higher during the XVI century than during the XV century. Although some irrigation returns could have been diverted to the Salada, those were likely to be small, and we consider that these climatic changes are enough to explain the hydrological changes in the Salada. Increased precipitation and lower evaporation brought by reduced temperatures during the XV-XVI centuries could account for the small watertable rise experienced in Laguna Salada during the period of deposition of Unit 4 (Fig. 7). The sharp increase in water levels represented by the onset of sedimentation of Unit 3 occurred in the XVII century, a period of reduced rainfall in the central Ebro valley (Creus et al., 1996, 1997). Although extreme precipitation events occurred during the XVII-XVIII, the increase in total annual precipitation was moderate in Iberia (Barriendos, 1997). The limnological changes in the *Salada Chiprana* are more coherent with the history of the agricultural use of the area. Modern agriculture was established in the XV-XVI centuries with increasing farm land, massive expansion of olive plantations and widespread introduction of irrigation. The *Salada Chiprana* pollen record clearly shows this expansion in olive cultivation about 300 yrs ago (Fig. 8).

The period of stable and relatively low lake levels characterized by the dominance of the cyanobacterial mats (Unit 2) ended with a period of fluctuating and generally increasing lake levels at the end of the XIX century conducive to more frequent anoxic bottom conditions (Unit 1B). Increasing agriculture use of the land at the end of the XIX century could be responsible for the increase in lake levels, and the frequent anoxic bottom conditions that characterize the transition to Unit 1. Several studies (Vidondo and Guerrero, 1992; LIMNOS-DGA, 1996; EPTYSA-DGA, 1997; ESHYG-DGA, 1994) have documented large changes in the limnological parameters during the last decades. *Laguna de Las Roces* was likely a saline lake 30 or 40 years ago, according to vegetation surveys (Braun-Blanquet and Bolos, 1957). Increasing irrigation in the area produced a drop in water salinity in the *Laguna Las Roces* and flooding of the surrounding fields. Higher lake levels in Chiprana during the 1950s correlate with the introduction of farm machinery. After a short period (mid 1960s - mid 1970s) of higher salinities, the water depth increased again (Fig. 9). The change from olive trees to corn and alfalfa crops in the 1970s resulted in an increase of irrigation water consumption from the Civán Canal, and larger return inflows into the *Salada Chiprana*.

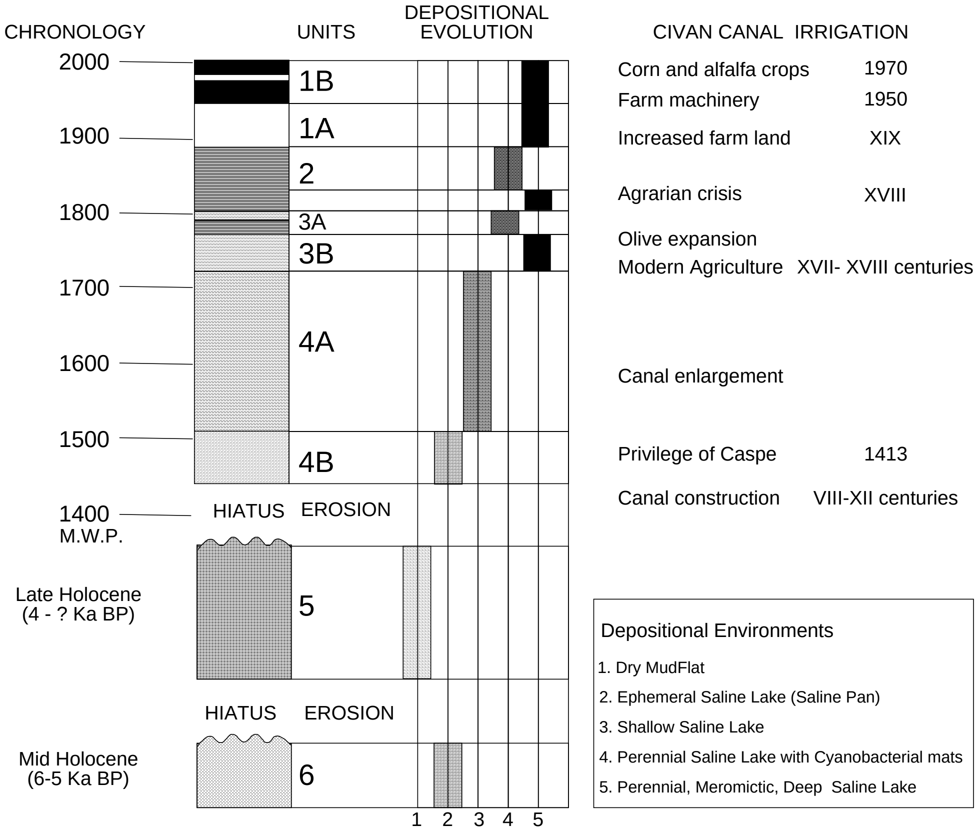

Figure 9. Summary of environmental changes in the Salada Chiprana compared to the main historic events of the Civán Irrigation Canal.

A recent rise in lake levels has been also documented in other sites in the Ebro basin (Davis, 1994; Valero-Garcés et al., 2000a,b; Burjachs et al., 1996; Schütt, 1998a,b), but the studies lack the chronological control to solve the precise timing and the possible causes. However, more detailed dendroclimatological reconstructions for precipitation and temperature do not show any trends comparable to the Chiprana record (Creus et al., 1996). The XX century is characterized by reduced rainfall, but sedimentological evidence indicate that lake levels during deposition of Unit 1 were generally higher than during Unit 2. Finally, meteorological records for the last decades do not correlate with the increasing lake levels in Chiprana Salada: a humid period with annual rainfall higher than 350 mm (1969-1976) and an arid period since then punctuated with some humid years (1983, 1986, 1987, 1988). Therefore, the hydrological changes in the *Salada Chiprana* during the last few centuries do not correlate with the reconstructed or measured rainfall because they are obliterated by the direct impact of irrigations returns.

4. Acknowledgements.
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Stop 1: Bujaraloz.
At the outskirts of the town of Bujaraloz we will describe the main geographical, geological and hydro-geological characteristics of the exhumed Bujaraloz-Sástago platform. We will also have a general view of the irrigated fields of Los Monegros and the new plans for the expansion of the irrigated area, including some of the saline lakes in the platform.

Stop 2: La Salineta.
La Salineta lake is located 1.5 km south of the town of Bujaraloz at an altitude of 325 m a.s.l. 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 grey lacustrine clays. In some sections, remains of a small cliff (1 m high) mark the boundary of the maximum extent of the lake. We will walk around the margins of the lake and stop at the outcrops to examine the lacustrine sediments. The lake usually holds some water even during the summer, so we will able to recognize the different depositional environments (dry mudflat, saline mudflat, salt pan). Halophytes dominate the shoreline and algal mats cover the lake bottom and are more visible when the halite crust re-dissolves with the rains. We will compare the present lake subenvironments with those interpreted in the sediment cores retrieved from the basin that illustrate the environmental and paleohydrological evolution of the basin since the Last Glacial Maximum.

Stop 2: La Playa
La Playa is the largest playa lake in the Ebro Basin (193 ha), located about 5 km south of Bujaraloz. The lake is seasonal, holding water for up to 8 months and drying completely during the summer. In winter, mirabilite precipitation occurs. Algal mats develop during the flooded phases, and sulfates and chlorides precipitate during the summer forming a salt crust that covers the

bottom of the lake. The upper salt crust is re-dissolved during the following year. We will have a general view of the lake from the ruins of the old salt mining facilities and walk into the lake plains to recognize the different depositional environments (dry and saline mud flats). The salt mining ruins will provide an opportunity to understand the salt extraction process and its past significance for the area. We will describe the Holocene lake evolution based on the sediment cores, and discuss the possible impacts of the new irrigation plans recently approved in the hydrology of the basins and their implications for the conservation and management of the saline lakes.

Stop 3: La Salada de Chiprana

During this stop we will walk around the margins of Salada Chipran to recognize the main features of the basin morphology and the geological constrains for the basin morphology and distribution of the main depositional subenvironments. We will stop at the main irrigation canals and the drain channel from Las Roces to Salada Chiprana to understand the modern surface hydrology of the Salada. After the observation of the modern depositional environments and hydrology, we will discuss the results of the lacustrine core sections and the interpretation of the paleohydrological and environmental changes in the basin since the Mid Holocene.

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ROAD LOG:

Departure from the Conference Hall at 8:30

0-72 km A-2 (E-90) Highway to Bujaraloz city (about 1 hour). **Stop 1** after the Freeway Exit (road A-230). Description of the main geological and geographic features of the Los Monegros structural platform. Coffee stop at Café Español in Bujaraloz.

72-75 km Road A-230 to the southern end of Bujaraloz. Stop at the junction with road A-2105 and short walk to La Salineta (**Stop 2**). Description of the main depositional environments of La Salineta and the reconstructed paleoenvironments based on the studied cores. Impacts of the new irrigation plans on La Salineta.

75-83 km Road A-2105 to La Playa. Description of the main geological and geographic features of the Saline lakes in La Playa area (**stop 3**). Description of the main depositional environments of La Playa and the reconstructed paleoenvironments based on the studied cores. Impacts of the new irrigation plans on La Playa

83-115 km The coach will take us back to Bujaraloz and then to the city of Caspe (road A-230) where we will have lunch at “El Mar de Aragón” restaurant.

115-130 km Highway A-221 towards Escatrón. Stop at Salada Chiprana (**Stop 4**)

130- 260 km. Trip to Caspe (Road A-221), then to Bujaraloz (A-230), and back to Zaragoza

Expected arrival time to the Conference Hall: 19:00.