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Reconstruction of palaeoenvironmental conditions by investigation of Holocene playa sediments in the Ebro Basin, Spain: preliminary results

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Abstract

Endorheic basins are typical landscape elements found in several parts of the Ebro Basin, Spain. Mineralogical and geochemical analysis of sediment cores from the endorheic basins facilitates the reconstruction of local palaeoenvironmental and palaeoclimatic conditions during the Holocene. The different morphogenetic and lithological environments of the areas investigated allows one to calibrate such information. First results of the analysis of the geochemistry and mineralogy of sediments from two endorheic basins within the central Ebro Basin indicate that the climatic conditions governing sedimentation during the Holocene changed from humid and subhumid to the present subarid conditions, but was interrupted by a phase of increased humidity. The varying character of solid bedrock caused different weathering products, which are reflected in the varying geochemical and mineralogical composition of lake deposits.

Keywords: palaeoenvironmental; Holocene; endorheic basin; Spain

1. Introduction

During the Quaternary, the Iberian Peninsula was an area of interaction between the climatic effects of the North European glacial and interglacial periods and the North African so-called pluvials and interpluvials. So far there is no recognizable relationship between both climatic systems. The geographic position of northern and central Spain makes it possible to investigate this problem.

The Ebro Basin (Fig. 1) is surrounded by high mountains up to 3,000 m, which give rise to a continental climate and a large climatic gradient between the central Basin and the Sierras. Accordingly, the Ebro Basin's water budget is highly sensitive to climatic changes. Changes in the water budget in turn regulate the processes of erosion, transport and accumulation.

As the Ebro Basin functioned as a foredeep of the Pyrenees, the Iberian and the Catalonian Range, it was subject to high rates of detritic and evaporitic sedimentation during the Tertiary. These sediments are characterized by high solubility and consequently high sensitivity to water-budget changes (cf. Battarbee, 1991).

In the central part of the Ebro Basin sediments of endorheic basins were analysed to investigate the

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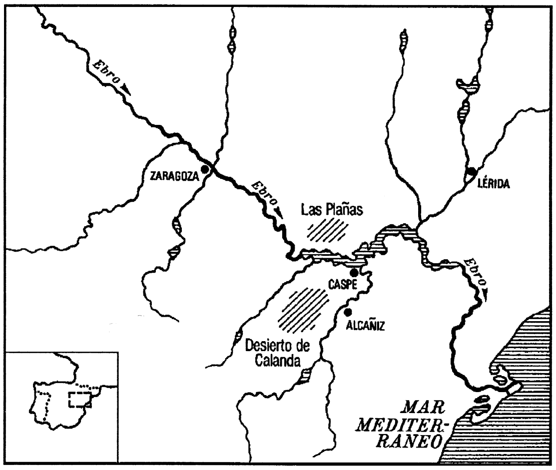

Fig. 1. Location of study sites in the Ebro Basin, Spain.

Holocene climatic system. A comparison was made between two areas: the Las Plañas de Bujaraloz (west of Zaragoza) and the Desierto de Calanda (southwest of Alcañiz) (Fig. 1).

2. Climate of the study area

The present climate of the central Ebro Basin is subarid Mediterranean with a mean annual precipitation of 300–350 mm. Precipitation peaks during autumn and spring when the region is under the influence of westerlies. Summer aridity lasts for four months. With a mean annual temperature of 14°C at the Zaragoza weather station, the mean annual potential evaporation is about 2000 mm.

The present annual water balance of the central Ebro Basin is negative with considerable variations (Fig. 2). The period 1953–1974 experienced a persistent highly negative annual budget of less than −2000 mm (data kindly provided by Instituto Nacional de Meteorología, Centro Meteorológico Zonal del Ebro/Sección de Climatología, Zaragoza).

3. Methods

Cores were taken along a section from the endorheic basin's marginal zone to the center. For better control, coring was done by alternating between two adjacent boreholes at each position, with about 0.5 m vertical displacement, using a modified KULLENBERG corer with a hydraulic core catcher to obtain undisturbed sediment samples. The two core drillings to be described were extracted in the center of the Laguna de Pito/Las Plañas de Bujaraloz (easting 737 200, northing 4588 750, UTM coordinate system; 2 m depth) and the Laguna Jabonera/Desierto de Calanda (easting 736 600, northing 4547 500, UTM coordinate system; 3.1 m depth). In both cases coring went down to the bedrock surface.

Initial analyses of the cores included a standard analysis of the sedimentary structure in order to obtain information on previous erosion, transport and

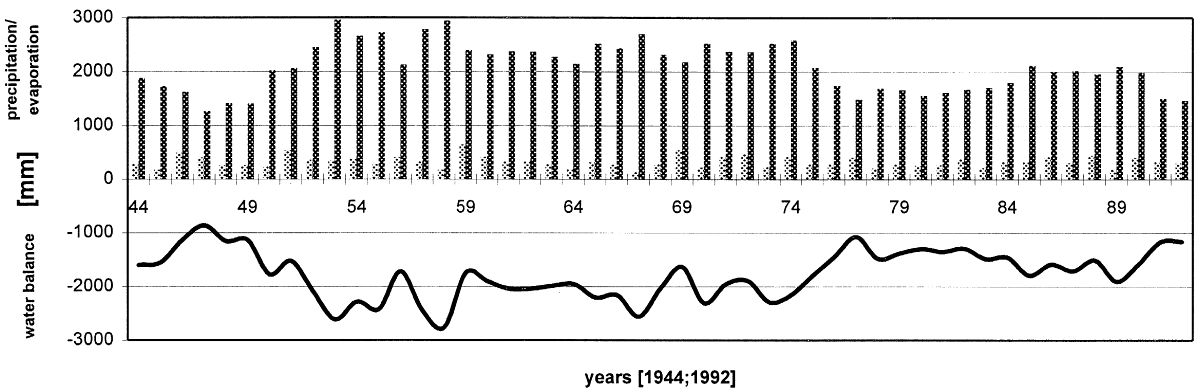

Fig. 2. Weather station Zaragoza (1944, 1992)—Annual precipitation [mm] (light grey shading) and annual evaporation [mm] (dark grey shading) and resulting water balance [mm] (-). (Source: Instituto Nacional de Meteorología, Centro Meteorológico Zonal del Ebro/Sección de Climatología, Zaragoza).

deposition. Additional mineralogical analysis (X-ray powder diffraction and thin-section analysis) and geochemical analysis (fluorescent X-ray) allowed for the reconstruction of the palaeolimnic environment of the endorheic basins.

4. Las Plañas de Bujaraloz

4.1. Site description

The area of Las Plañas de Bujaraloz (Fig. 1) is part of the southern foreland of the Monegros escarpment. The Rio Ebro drains the Las Plañas de Bujaraloz, an area with a drop in elevation of 200 m over a distance of 15 km (gradient ≈ 1.7%)

Bedrocks are Miocene gypsum and limestone, with a few intercalated beds of calcareous sandstone (Quirantes Puertas, 1965, Quirantes Puertas, 1969). Surficial and subsurface drainage of the Las Plañas de Bujaraloz area are exceedingly influenced by regional tectonics. Fracturing combined with the high solubility of the bedrock causes the karst landscape of this area. Some valleys have been developed from strings of solution depressions related to the fracturing of the limestone and gypsum formations (Sánchez Navarro et al., 1989).

Present erosion processes are barely evident. The high infiltration capacity of the decomposed bedrock largely prevents surface runoff. Redeposition of weathered material by wash processes occurs over short distances in the form of glacis and slope deposits (Sancho and Gutiérrez, 1993a). Subsurface solution is evident by the high concentration of solutes in the groundwater, with an average dry residue of 6658 mg/l (Sánchez et al., 1993).

The Laguna de Pito is an endorheic basin in the Las Plañas de Bujaraloz area. It is a collapsed depression about 20 m deep, with a lake floor less than 1 km in diameter. The lake floor is periodically covered by water and desiccates during summer (Sancho and Gutiérrez, 1993a).

4.2. Results

The most noticeable characteristics of the core are its very low concentration of organic matter (less than 1%) and two layers of coarse crushed rocks at a depth of 1.50 m and 1.80 m. These detrital deposits are derived from the calcites of the surrounding bedrock and are embedded in autochthonous precipitated lacustrine calcites (Table 1). These relatively pure precipitated calcites dominate the mineralogical composition of the core from its base up to a depth of 1.33 m below the surface.

Above a depth of 1.33 m simultaneously deposited calcites and gypsum are observed (Table 1). Thin sections show that this geochemical composition corresponds to idiomorphic gypsum embedded in a ground mass of medium-grained calcite.

Corresponding to the mineralogical character of the core calcium oxide is the predominant geochemical element in the section from 1.33 to 1.95 m (Fig. 3). Above a depth of 1.33 m increasing sulphur concentration marks the onset of gypsum precipitation. The higher magnesium oxide concentration in the upper part of the core corresponds to the increased dolomite content in this section (Table 1). Concentrations of iron, titanium, manganese and aluminum oxide and silicon dioxide are similar (Fig. 3). In the section 0.96–1.95 m large oscillations in the concentration of these substances are noticed, whereas in the section from 0.20 to 0.96 m metal oxides and silicon dioxide concentrations are relatively low; oscillations are again seen in the concentration of these substances in the beds immediately below the surface. Upwards of 1.33 m the graphs for the sodium and potassium oxide concentration run parallel to, for example, that of titanium oxide. The concentration of sodium and potassium oxide below a depth of 1.33 m is low and close to limit of detection.

Sedimentary phosphorus concentrations (Fig. 3) show a similar distribution in only a few parts of the graphs discussed above. No significant relationship between the concentration of phosphorus and metal oxides ($t < t_{95\%}$) was found. At a depth of 0.1 m a strong increase of phosphorus concentration occurs, whereas gypsum precipitation decreases to a minimum. A second maximum of phosphorus concentration is recognizable at a depth of 1.4 m. In most parts of the core phosphorus concentration is close to limit of detection.

4.3. Discussion

The relatively purely precipitated autochthonous idiomorphic calcites in the section from 1.33 to 1.95

Table 1
Laguna de Pito, Drilling III: Mineralogical composition of limnic sediments

Depth (cm)	Calcite	Dolomite	Gypsum	Kalinite	Anhydrite	Bassanite	Kainite	Halite	Calcium chlorite	Quartz	Muscovite	Clay minerals	Goethite
−2	+ +	+ +	+ + +	+	+	+ +	+	+ +		+		+	+
−8	+ + +	+ +	+ + +		+ +	+		+ +		+ +		+ +	
−19	+ + +	+ +	+ + +		+	+ +		+ +		+		+	+
−31	+ +	+ +	+ + +		+	+ +		+ +				+	
−46	+ +	+ +	+ + +		+ +	+ +	+	+ +					
−66		+ +	+ + +		+ +	+ +	+	+ +				+	
−84	+ +	+ +	+ + +		+	+ +	+	+ +		+		+	
−96	+ +	+ +	+ + +		+	+ +	+	+ +		+ +		+	
−103	+ +	+ +	+ + +		+ +	+ +	+	+ +				+	
−106	+ +	+ +	+ + +		+	+ +	+	+ +		+		+	
−112	+ +	+ +	+ + +		+	+ +	+	+ +		+		+	
−121	+ + +	+ +	+ + +		+	+ +	+	+ +		+ +		+	
−133	+ + +	+	+		+	+		+				+	
−141	+ + +	+ +			+	+		+ +		+		+	
−147	+ + +	+			+			+					
−150								stoneline					
−166	+ + +	+			+	+		+		+ +		+	
−170	+ + +	+			+		+	+ +		+ +		+	
−174	+ + +	+			+	+		+		+ +		+	
								stoneline					
−189	+ + +	+	+		+			+		+		+	
−195	+ + +	+	+			+		+		+		+	
−200	+ +	+ +	+ + +	+	+	+	+	+ +		+		+	

Max. counts p.s.; + + + major components; + + minor components; + traces.

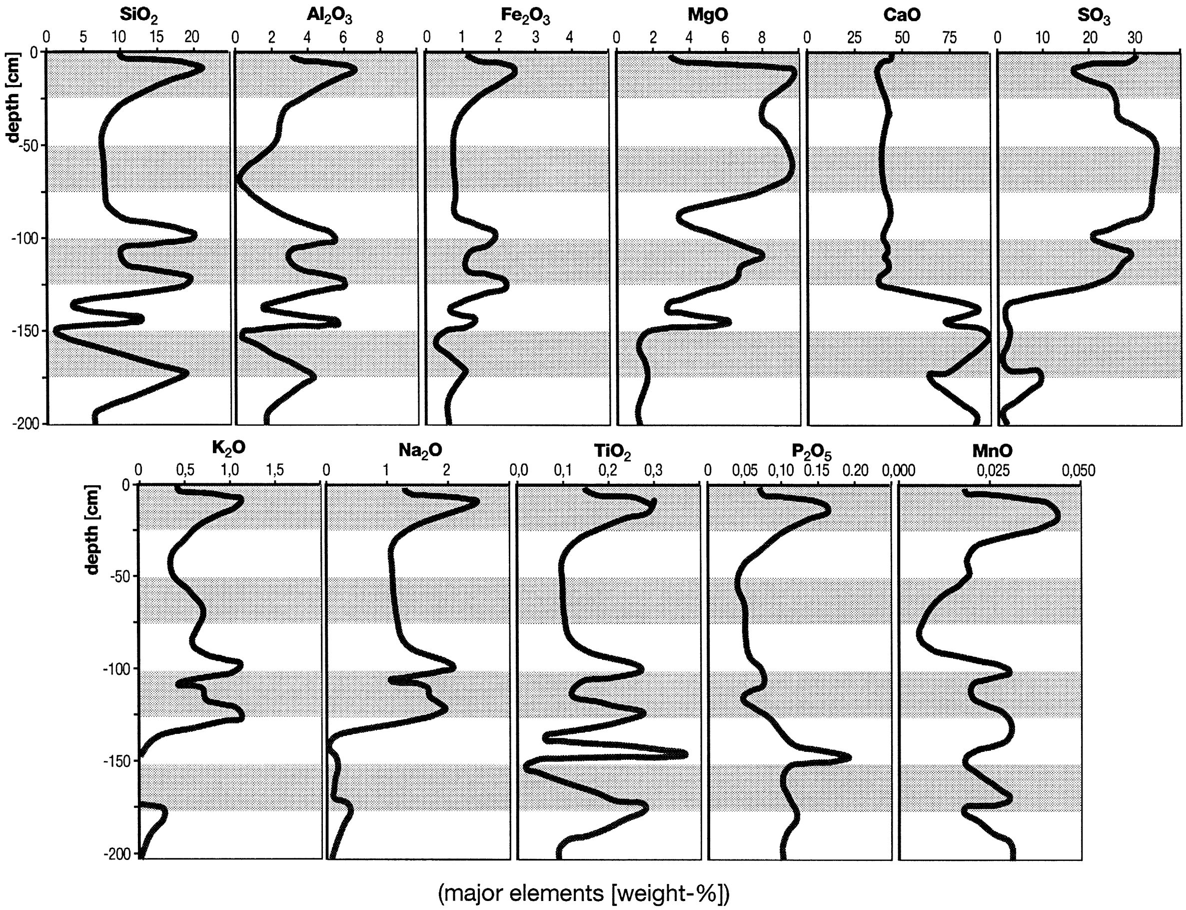

Fig. 3. Laguna de Pito, Drilling III: major elements (wt.%).

m (Table 1) indicate a period dominated by a freshwater lake (cf. McKenzie, 1985). These sediments correspond to chalk as defined by Merkt et al. (1971, p. 619; calcium carbonate content $\geq 90\%$). The absence of gypsiferous sediments—which were certainly dissolved within the drainage basin— is attributed to exterior drainage during this phase. The particles from the two rock layers are interstratified with the chalks at 1.50 and 1.80 m depth. They are interpreted as remnants of a detrital deposition event triggered by excessive rainfall. They were deposited in a calcite-saturated lacustrine environment which prevented further decomposition of the rock fragments (cf. Trudgill et al., 1980a,b).

The former existence of a freshwater lake indicates a humid or subhumid climate, whereas precipitated gypsum above 1.33 m (Table 1) indicates increased aridity (cf. Williams et al., 1993, p. 123). During a subarid climatic phase there was a shallow ephemeral lake with prevailing evaporite precipitation (cf. Einsele, 1992, p. 79). During low lake-level phases, the poorly cemented upper sediments became redeposited and homogenized. The change from the precipitation of pure calcite to the precipitation of a calcite–gypsum mixture either indicates a change from a more or less subhumid to a subarid climate, or a change in the drainage system to endorheic basin conditions (cf. Eugster and Kelts, 1983, p. 332/333).

This hypothesis is confirmed by the comparative analysis of metal oxide concentrations (Fig. 3). The release of metals from the bedrock occurs predominantly by weathering and soil-forming processes (cf. Chesworth, 1992, p. 26). The presence of water necessary for chemical weathering and soil formation also sustains a vegetation cover and humification of organic matter. The resulting increase in soil acidity causes exchange reactions that buffer the acidity (cf. Gruhn et al., 1985; Holthusen, 1982; Trudgill et al., 1980a,b). Large concentration oscillations characterize the graphs (Fig. 3) of various oxides for the basal part of the core (1.33–1.95 m). This indicates that during a freshwater lake phase changes in humidity occurred accompanied by plant growth, humification and soil-forming processes (cf. Mackereth, 1966, p. 178; Pennington et al., 1972, p. 243).

During the ephemeral lake phase, gypsum and metal oxide relationships are inversed (sediments above 1.33 m). During that period predominantly subarid climatic conditions impeded the processes of chemical weathering and soil formation in the drainage basin of Laguna de Pito, resulting in low concentrations of metal oxides in the lake sediments. Increased concentrations of sodium and potassium in these sequences, corresponding to increased precipitation of potassium and sodium minerals, emphasize the relatively arid climate (Turner et al., 1987).

The missing of a significant relationship between the concentrations of phosphorus and iron oxide was established ($t < t_{95\%}$) (Fig. 3), which indicates the absence of absorption of dissolved phosphorus by iron oxides as described by Mackereth (1966) and Engstrom and Wright (1984) for phosphorus deposition by abiotic processes. Positive deflections of the phosphorus curve point, rather, to increased biotic precipitation (cf. Bortleson and Lee, 1974).

At the top of the core (0.1 m depth), increased metal oxide concentrations coincide with a maximum of phosphate concentration (Fig. 3). This may indicate a period with increasing humidity resulting in a sudden increase of biomass production from limnic flora and fauna (cf. Birch et al., 1980). This process was aided by an increasing amount of available nutrients due to an increasing rate of chemical weathering. At the same time, gypsum precipitation decreased. With a change towards lake desiccation, suspended and dissolved substances were deposited recognizable by a maximum phosphorus and metal oxide content at 0.1 m depth. With renewed transition to a subarid climate, precipitation of sulphur and gypsum resumed.

The slight increase of phosphorus concentration at 1.4 m (Fig. 3) corresponds to the end of the freshwater lake phase. Increasing aridity resulted in a reduced influx of freshwater, an increased concentration of solutes and nutrients in the lake and a temporarily increased biomass production.

5. Desierto de Calanda

5.1. Site description

The region of the Desierto de Calanda southwest of Alcañiz (Fig. 1) is characterized by a plain built of slightly cemented Miocene clay strata with palaeochannels of calcareous sandstone (Riba et al., 1967). The receiving stream of the Desierto de Calanda is the Rio Guadalope, a tributary of Rio Ebro, with a drop in elevation of 40 m over a distance of 5 km (gradient ≈ 1.0%), half that of the Las Plañas de Bujaraloz area. Endorheic basins developed in combination with subsurface erosion of underlying gypsum layers and selective erosion of clay strata (Ibáñez, 1973; Gutiérrez Elorza and Peña Monné, 1994). The present solution of evaporitic rocks is reflected in high groundwater salinity (5765 mg/l dry residue, $n = 13$; Schütt, field data, 1994). Present processes of surface erosion occur, but are periodically removed by ploughing the fields. Concave profile of the slopes draining into the endorheic basins suggests that some suspended load wash occurs (cf. Ahnert, 1987). The Laguna Jabonera is an endorheic basin comparable in size to the Laguna de Pito/Las Plañas de Bujaraloz with a depth of ca. 20 m and a lake-floor diameter of 1 km.

5.2. Results

Powder-X-ray analysis shows that the sediments of the Laguna Jabonera (Table 2) have a much higher content of clogged clays and detritic quartzes than the sediments of the Laguna de Pito (Table 1). The main mineralogical constituents are also calcite and gypsum, but they were precipitated differently than those of the Laguna de Pito/Las Plañas de Bujaraloz core. The whole core is characterized by

Table 2
Laguna Jabonera, Drilling I: Mineralogical composition of limnic sediments

Depth (cm)	Calcite	Dolomite	Gypsum	Kalinite	Anhydrite	Bassanite	Kainite	Halite	Calcium chlorite	Quartz	Muskovite	Clay minerals	Goethite
−3	+ + +	+ +	+ +		+			+ +	+ +	+ + +	+	+ +	+
−10	+ + +	+ +	+		+			+	+ +	+ + +	+	+ +	+
−18	+ + +	+ +	+ +		+			+	+ +	+ + +	+	+ +	
−29	+ + +	+ +	+ +		+			+	+ +	+ + +	+	+ +	+
−45	+ + +	+ +	+ +		+			+	+ +	+ + +	+	+ +	
−58	+ + +	+ +	+ + +		+	+		+	+	+ +	+	+ +	
−77	+ + +	+ +	+ +		+	+		+	+ +	+ + +	+	+ +	+
−91	+ + +	+ +	+ +		+	+		+	+ +	+ + +	+	+ +	+
−108	+ + +	+ +	+ + +		+	+		+	+	+ + +	+	+ +	
−125	+ + +	+ +	+ +		+	+		+	+ +	+ + +	+	+ +	
−141	+ +	+ +	+ + +		+	+		+	+	+ + +	+	+	+
−165	+	+ + +	+ +		+	+		+		+ + +	+	+ +	
−169	+	+ +	+ + +	+	+	+		+ +	+	+ +	+	+	
−180	+ +	+ + +	+ + +	+	+	+		+ +	+	+ +	+	+ +	
−201	+ +	+ +	+ + +		+	+		+ +	+	+ +	+	+ +	
−213	+	+ +	+ + +		+	+		+	+	+	+	+	
−222	+	+ +	+ + +	+	+	+		+	+	+ +	+	+	
−232	+ +	+ +	+ + +		+	+		+ +	+	+ +	+	+	
−246	+	+ + +	+ + +	+	+	+		+	+	+ + +	+	+	+
−261	+ +	+ +	+ + +			+		+ +		+ +	+	+	
−262	+	+ +	+ + +		+	+		+	+	+ +	+	+	
−265	+ +	+ +	+ + +		+	+		+ +		+ +	+	+	
−271	+	+ +	+ + +		+	+		+ +		+ + +	+	+	
−282	+	+ +	+ + +			+		+ +		+ + +	+	+	+
−292	+ +	+ +	+ + +		+ +	+ +		+ +		+ +		+	
−299	+ +	+ +	+ + +	+	+	+		+ +		+ + +	+	+ +	
−303	+	+ +	+ + +	+	+	+		+		+ + +	+	+	

Max. counts p.s.; + + + major components; + + minor components; + traces.

the simultaneous occurrence of gypsum and calcite with gypsum predominant in the parts below 1.3 m, and calcite in the upper part. Thin sections show that the mineralogical composition is idiomorphic calcite and gypsum embedded in an alternating medium- to fine-grained ground-mass of calcite and gypsum in the whole core.

The chemical composition of the sediments varies more (Fig. 4): In the basal part of the core (3.1–2.4 m depth), alterations in the concentration of silicon dioxide, sulphur and metal oxides occur. While graphs of silicon dioxide and metal oxides are positive correlated ($t > t_{95\%}$) the graph of sulphur concentration is inversely correlated to the graphs of metal oxides ($|-t| > t_{95\%}$). In the underlying sediment (2.4–1.7 m depth) simultaneous precipitation of gypsum and calcite occur, as well as steady and relatively low concentrations of silicon and metal oxides. At a depth of 1.7 m there is a change in chemical sediment composition. From the lower to the higher layer, lime and sulphur concentrations decrease stepwise while the concentrations of most metal oxides and of silicon dioxide increase. At a depth of 0.5–0.7 m the sulphur graph shows a marked deflection, while concentrations of silicon dioxide and metal oxides are reduced.

5.3. Discussion

In humid phases the vegetation cover obstructs surface runoff and erosion, and infiltration rates increase. As conditions are reversed during arid phases, surface erosion increases and infiltration rates and subsurface flow are reduced. In the Desierto de

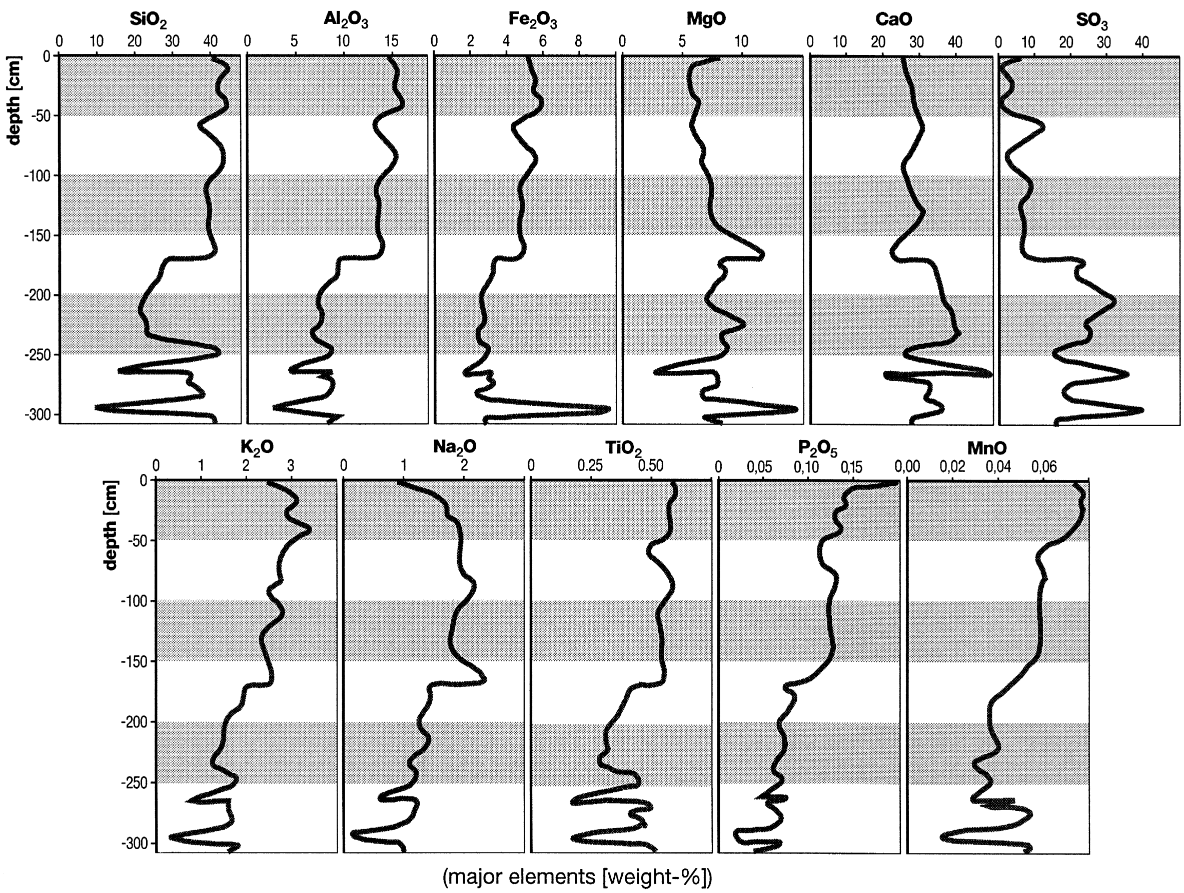

Fig. 4. Laguna Jabonera, Drilling I: major elements (wt.%).

Calanda surficial import and therefore decomposition of detritus from evaporitic sediments may be excluded, as there are almost no outcrops of evaporitic sediments within the drainage area. Precipitation of evaporites in the Laguna Jabonera therefore has to be explained by subsurface inflow of aqueous solution, which will mostly take place in response to more humid conditions.

The alternating subarid and subhumid climatic conditions resulted in alternating geomorphological phases. Changing climatic conditions led to predominantly evaporitic precipitation during the subhumid phases and to predominantly silicon dioxide and metal oxide deposition (Fig. 4) during the subarid phases in the basal part of the core (3.1–2.4 m depth).

Sediments between 2.4 and 1.7 m are predominantly evaporitic, with silicates only as minor compounds (Table 2). As mentioned above, such a composition of lake sediment is typical for subhumid phases. In the upper layer (1.7–0.7 m) concentrations of silicon dioxide and metal oxides increase stepwise, and gypsum precipitation is secondary (Fig. 4). This change of decomposition is attributed to a gradual change in the process system. Sedimentation of the lower bed was mainly caused by subsurface inflow and reduced surface runoff, and therefore only little input of clay and detritical quartz occurred. During deposition of the upper layer a decreased vegetation cover favoured surficial erosion and deposition of detritic sediments, whereas subsurface input by aqueous solution was reduced. The climate gradually changed from subhumid to subarid.

Similarly, the transition from subhumid to subarid climate caused the type of sedimentation of the uppermost part of the core. Sediments at a depth of 0.7 m indicate a brief subhumid phase, as noted in the deflection in the sulphur graph (Fig. 4). A brief phase of increasing humidity resulted in an increasing input of solutions by subsurface flow, while

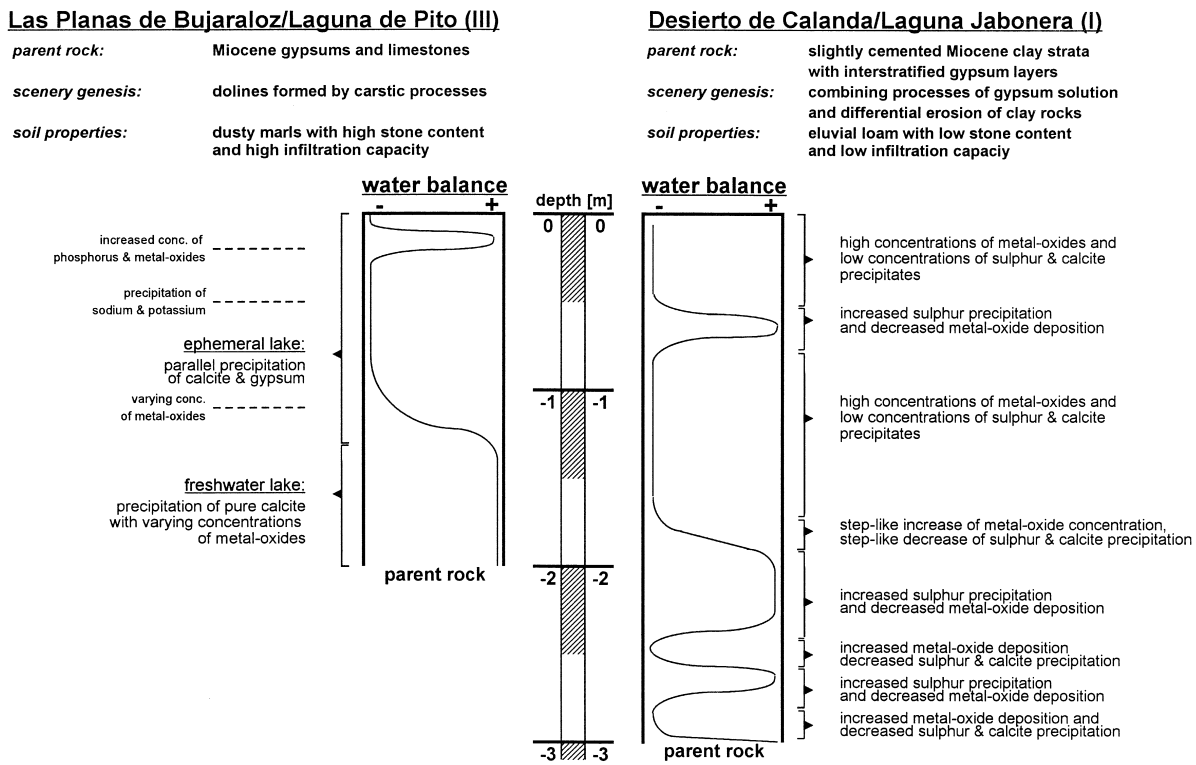

Fig. 5. Reconstruction of water balance in the areas of Las Plañas de Bujaraloz and the Desierto de Calanda by evaluation of mineralogical and geochemical investigations of the drill cores from Laguna de Pito and Laguna Jabonera.

input of detritical sediment from surface erosion was reduced. During the following subarid phase the desiccation of the lake resulted in high precipitation rates of gypsum and calcites and a decrease of metal oxide concentrations.

6. Conclusions

A preliminary analysis of the geochemistry and mineralogy of the sediments of two endorheic basins of the central Ebro Basin indicates that the climatic conditions governing sedimentation during the Holocene changed from humid and subhumid in the past to the present subarid conditions, interrupted by a phase of increased humidity (Fig. 5). Different types of bedrock caused different weathering products and lake deposits with different geochemical and mineralogical compositions. The depositional system of Laguna de Pito/Las Plañas de Bujaraloz is influenced by karstic processes. Superficial erosion and transport of detritical gypsum and limestone by suspended load wash and wind dominated during arid periods. In an ephemeral lake this detritic material was first disintegrated and then reprecipitated, and therefore cannot be distinguished from the influx of aqueous solutions. Conversely, during humid periods processes of solution and transport of dissolved load by subsurface runoff and groundwater flow were more important. Evaporites from solutions with increased amounts of metal oxides were deposited in addition to detritical sediments.

The geomorphological system of the Desierto de Calanda is characterized by combining processes of subsurface solution of lower gypsum layers and differential erosion of the solid Miocene clay strata. By weathering processes, an eluvial loam developed from the solid bedrock. Thus during periods of arid climate, missing vegetation cover favoured surface runoff and superficial erosion. Sediments deposited by these processes have relatively high rates of detritical quartzes, clay minerals and metal oxides and low rates of saline precipitates (Fig. 5). This relationship is inverted during periods of more humid climate. During these periods surface runoff and superficial erosion are confined by vegetation cover. Increased infiltration rates caused increased rates of solution and transport of dissolved load by subsurface flow. Lake sediments resulting from this process are evaporites with reduced amounts of detritical quartz, clay minerals and metal oxides.

Palynological analysis of cores from the neighbouring basins of Laguna de Pito/Las Plañas de Bujaraloz and Laguna Jabonera/Desierto de Calanda confirm the hypothesis of climate change (Stevenson et al., 1991a,b). By investigating dissected triangular slope facets in the Ebro Basin Sancho and Gutiérrez (1993b) arrived at similar conclusions about Holocene climate change. Comparative studies of limnic sediments and slope deposits narrow the time bracket for the as yet undatable lacustrine sediments. Moreover, mineralogical and geochemical analyses of lacustrine sediments will yield more detailed information on palaeoenvironmental conditions than is available to date.

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