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Late Holocene evolution of playa lakes in the central Ebro depression based on geophysical surveys and morpho-stratigraphic analysis of lacustrine terraces

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ABSTRACT

The origin and morpho-stratigraphic evolution of the largest playa-lake system (La Playa–El Pueyo) in the Bujaraloz–Sástago endorheic area, located in the semiarid central sector of the Ebro Depression, are analysed. The enclosed depressions are developed on gypsiferous Tertiary bedrock and show a prevalent WNW–ESE orientation parallel to the direction of the prevalent strong local wind (Cierzo). Yardangs have been carved in bedrock and unconsolidated terrace deposits in the leeward sector of the largest lake basins. A sequence of three lacustrine terrace levels has been identified by detailed geomorphological mapping. The treads of the upper, middle and lower terrace levels are situated at +9 m, +6 m and +0.5 m above the playa-lake floors, respectively. Seismic refraction and electrical resistivity profiles acquired in La Playa reveal a thin basin fill (~2 m) with a planar base. These data allow ruling out the genetic hypothesis for the depressions involving the collapse of large bedrock cavities and support a mixed genesis of combined widespread dissolution and subsidence by groundwater discharge and eolian deflation during dry periods. The 5 m thick deposit of the middle terrace was investigated in hand-dug and backhoe trenches. Six AMS radiocarbon ages from this terrace indicate an aggradation phase between 3.9 ka and ca. 2 ka. These numerical ages yield a maximum average aggradation rate of 2.6 mm/yr and a minimum excavation rate by wind deflation of 3 mm/yr subsequent to the accumulation of the middle terrace. The latter figure compares well with those calculated in several arid regions of the world using yardangs carved in palaeolake deposits. The aggradation phase between 4 and 2 ka is coherent with other Iberian and Mediterranean records showing relatively more humid conditions after 4 ka, including the Iron Ages and the Iberian–Roman Period.

1. Introduction

The central sector of the Ebro Depression in NE Spain (Fig. 1) constitutes a particularly interesting and challenging area for palaeoclimatic investigations due to several reasons: (1) It is the northernmost semiarid region in Europe, bounded by mountain ranges that were glaciated during the Quaternary. (2) Climate variability during the last glacial cycle may differ substantially from other European areas (Harrison et al., 1996; Prentice et al., 1998; Valero-Garcés et al., 2000a; Davis et al., 2003; González-Sampériz et al., 2008) due to the combined influence of both North Atlantic and sub-tropical climates (Summer et al., 2001). (3) Lacustrine records are largely restricted to saline lakes of poorly understood geomorphic origin and evolution, including the northernmost playa-lakes with active evaporite deposition in Europe. Studies focused on saline lake sediments provide evidence for a complex palaeohydrological evolution over the last glacial cycle in the semiarid Ebro Depression, with several abrupt and rapid arid/humid transitions (Valero-Garcés et al., 1998, 2000a; González-Sampériz et al., 2008). However, the chronological control of most lake sequences is rather limited due to the scarcity of organic remains in the sediments and the presence of erosional hiatuses.

Holocene palaeoenvironmental interpretations of the Ebro Depression are based mostly on cores drilled in saline lakes located in internally drained depressions: Mediana (Valero-Garcés et al., 2000a,b), Bujaraloz–Sástago (Pérez-Obiol and Roure, 1990; Stevenson et al., 1991; Davis, 1994; Schütt, 1998; Davis et al., 2003; Moreno et al., 2004; González-Sampériz et al., 2008; Mees et al., 2011), Chiprana (Davis, 1994; Valero-Garcés et al., 2000b), Alcañiz (Stevenson et al., 1991; Davis, 1994) and Hijar areas (Davis, 1994). In spite of the large efforts carried out to investigate their stratigraphic record from a palaeoenvironmental perspective, the origin and morpho-stratigraphic evolution of the enclosed basins remain unclear. The lack

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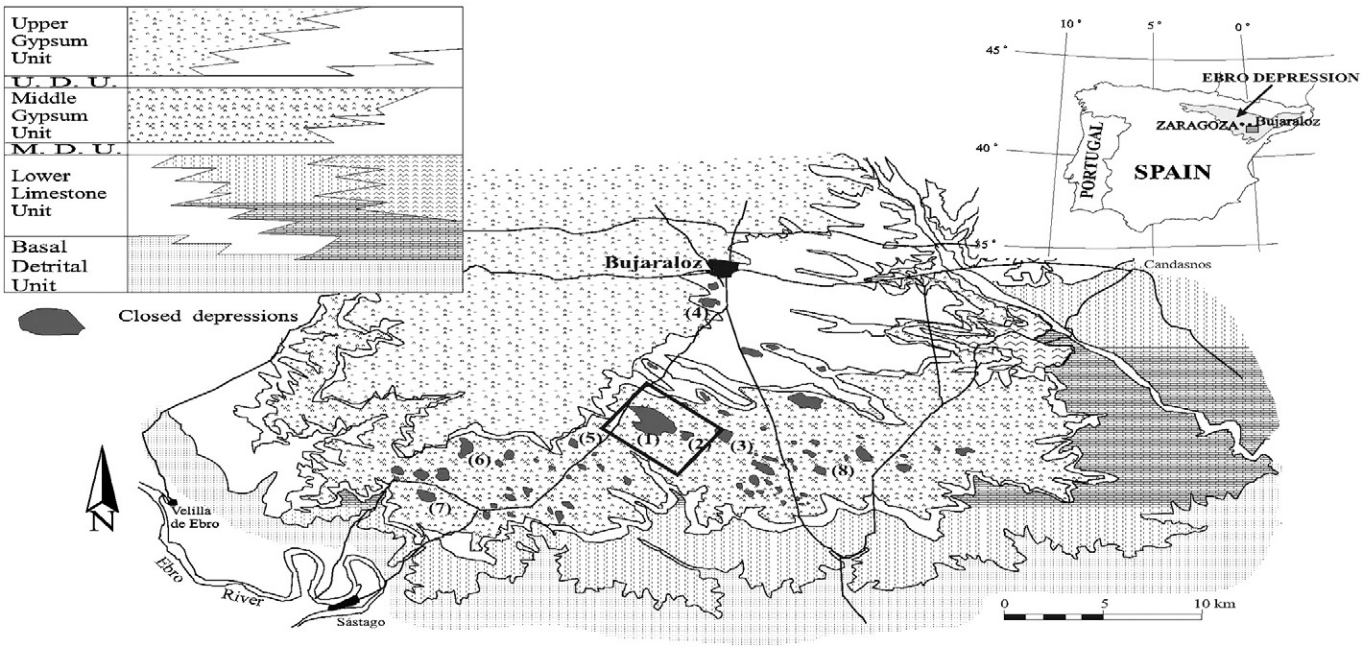

Fig. 1. Geographic location and geological sketch of the Bujaraloz–Sástago endorheic area (modified from Salvany et al., 1996). U.D.U.: Upper Detrital Unit. M.D.U.: Middle Detrital Unit. Note that most of the closed depressions occur on the Middle Gypsum Unit, with a higher proportion of gypsum. The rectangle indicates the area covered by the geomorphological map of Fig. 2. Ephemeral lakes in which palaeolimnological–palynological studies have been conducted: 1. La Playa, 2. El Pueyo, 3. El Pito, 4. La Salineta, 5. Guallar, 6. Camarón, 7. Rebollón, 8. La Clota.

of data on the subsurface geometry of the basins precludes evaluating the validity of the different hypotheses proposed to explain the formation of the closed depressions in evaporitic bedrock. Additionally, reconstructing the evolution of these lacustrine basins requires taking into account the scarcely investigated terraces preserved at the lake margins.

As González-Sampériz et al. (2008) point out, stratigraphic records from the bottom of playa-lakes in the Ebro Depression pose significant limitations to palaeoenvironmental studies for several reasons: (1) limited thickness and temporal length of the sequences; (2) significant hiatuses attributable to enhanced wind erosion, difficult to identify in cores; (3) very low pollen content and material datable by the radiocarbon method; (4) significant diagenetic overprinting favoured by the continuous upward discharge of saline groundwater flows and the inherent instability of evaporitic minerals (Warren, 2006); (5) reworking and contamination processes; and (6) limited preservation potential of biological indicators. Recently, detailed geomorphological mapping has revealed the presence of stepped sequences of aggradational lacustrine terraces at the margin of some playa-lakes in the Bujaraloz–Sástago area (Gutiérrez-Elorza et al., 2002). This finding opens new prospects to palaeoenvironmental investigations in playa-lakes, since terrace deposits, in combination with cores from the lake bottoms, may help to improve the completeness and resolution of lacustrine records. Moreover, lacustrine terraces may be used to reconstruct the morpho-stratigraphic evolution of the playa-lakes and identify major aggradation and excavation periods as potential responses to significant palaeoenvironmental changes. Advantages of the terrace deposits, situated at the lake margins and above the water table, with respect to the sediments situated beneath the lake bottoms, include: (1) higher preservation potential of the stratigraphic record than in the lake bottom, where eolian deflation may remove a substantial amount of sediment; (2) less severe overprinting by diagenetic processes; and (3) they may be studied in natural exposures or excavated trenches, allowing the architecture of the deposits to be analysed and increasing the likelihood of finding datable material. Moreover, the identification of the boundary between lake deposits and weathered bedrock can be carried out with a greater level of confidence in exposures; argillaceous karstic residues are frequently misinterpreted as lacustrine deposits. Once the sequence of lake terraces has been established, the main challenge is to determine the stratigraphic and chronological relationships between the terraces and the deposits situated in the lake bottom. Some of the stratigraphic units identified in cores from the bottom of lakes may not have chronostratigraphic equivalents in terraces and vice versa. The main constraint for integrating such data is the availability of reliable numerical dates.

This paper is focused on the Bujaraloz–Sastago endorheic area, and particularly on the largest La Playa–El Pueyo lake system. The main goals of this multidisciplinary work include: (1) evaluating the different hypotheses proposed to explain the origin of the closed depressions developed in evaporitic bedrock in the light of new data on the subsurface geometry of the basin inferred by complementary shallow geophysical techniques (electrical resistivity tomography and seismic refraction); (2) reconstructing the morpho-stratigraphic evolution of the playa-lake on the basis of the spatial distribution of lacustrine terraces and the obtained numerical dates; (3) calculating rates of vertical accretion and eolian deflation using the numerical ages obtained for the most extensive terrace; and (4) making an attempt to integrate the terrace (trenches) and lake bottom (cores) stratigraphic records and relate the palaeohydrological changes recorded by the terraces with other palaeoenvironmental proxies in the Ebro Depression, the Iberian Peninsula and the global context.

2. The study area

2.1. Geological setting

The study area is located in the central sector of the Ebro Tertiary Basin, NE Spain (Fig. 1). This sedimentary basin, deeply dissected by the fluvial network, constitutes a topographic depression drained longitudinally by the NW–SE-oriented Ebro River and bounded by the Pyrenees and the Iberian Chain to the north and south, respectively. The investigated La Playa–El Pueyo playa-lake complex form part of a field of closed depressions with a marked WNW–ESE elongation designated as the Bujaraloz–Sástago endorheic area (Figs. 1 and 2). This internally