Playa-Lakes and Yardangs in the Bujaraloz-Sástago Endorheic Area, Central Ebro Basin

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Abstract

The Bujaraloz-Sástago endorheic area occurs on an exhumed structural platform in the central sector of the Ebro Cenozoic Basin, essentially underlain by subhorizontally lying gypsiferous and mudstone units with some limestones. The dominantly flat topography of this structural surface is interrupted by around 150 closed depressions, some of which host playa-lakes of outstanding ecological and geomorphological value. The origin of the depressions is related to subsurface dissolution of the gypsiferous bedrock and aeolian deflation caused by the strong local wind, called *Cierzo*. The leeward side of the largest playas displays yardangs carved on bedrock and unconsolidated Holocene lake terrace deposits. These are the only yardangs documented in Europe so far. Modern and relict lunette dunes also occur on the downwind margin of some playa-lakes. Lacustrine terraces preserved on the margins of the largest basins record alternating periods of aggradation and excavation, attributable to more humid and drier periods, respectively. The available radiocarbon dates from the most extensive terrace, allow us to infer deepening of the largest playa (La Playa) by wind erosion of 6 m over the last 2 ka, yielding an average lowering rate of ca. 3 mm/year. This figure compares well with those calculated in several arid regions of the world, mainly using yardangs carved in Holocene lake deposits.

Keywords

Deflation basins • Lake terraces • Lunette dunes • Gypsum dissolution • Wind erosion rates

12.1 Introduction

The Bujaraloz-Sástago endorheic area includes around 150 closed depressions, some of which host the northernmost playa-lakes in Europe. These fragile semiarid environments, with unique habitats and numerous endemic species, have an outstanding ecological value (Conesa et al. 2011). In 2011, an area of 8,144 ha, including the most representative and best preserved closed depressions and playa-lakes, was declared a RAMSAR site. Moreover, most of the area has been designated by the Regional Government as ZEPA (SPA; Special Protection Area for wild birds) and LIC (SCI; Site of Community Importance). The playa-lakes of Bujaraloz-Sástago are also of remarkable geological interest, with geomorphic features unparalleled in Spain. The development of these basins results from subsurface dissolution of the gypsiferous bedrock and aeolian deflation, which operates when the floor of the playa-lakes is dry. The leeward side of the largest playas displays numerous yardangs oriented parallel to the dominant wind direction and carved in bedrock and lake terrace deposits (Gutiérrez-Elorza et al. 2002). To our knowledge, these are the only

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F. Gutiérrez and M. Gutiérrez (eds.), *Landscapes and Landforms of Spain*, World Geomorphological Landscapes,
DOI: 10.1007/978-94-017-8628-7_12,

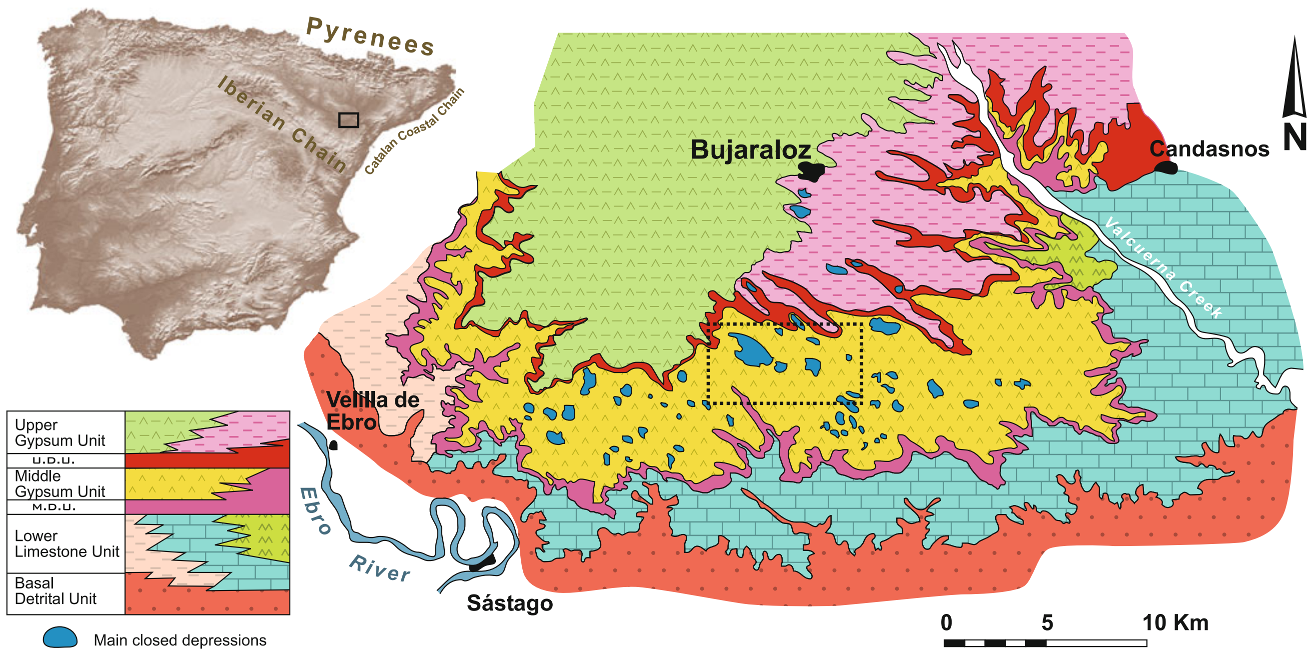

Fig. 12.1 Location and geological map of the Bujaraloz-Sástago endorheic area, developed on a structural surface perched around 200 m above the Ebro River. Note that, most of the closed depressions and playas occur on the unit with a higher proportion of gypsum; Middle Gypsum Unit (based on Salvany et al. 1996). *Dashed line rectangle* indicate area covered by Fig. 12.2

yardangs reported in Europe (Goudie 2007), together with some examples from Hungary (Sebe et al. 2011). The lacustrine terraces mapped in the margins of the largest basins record alternating periods of aggradation and excavation, attributable to more humid and drier periods, respectively (Gutiérrez et al. 2013). Excavation rates estimated on the basis of radiocarbon ages obtained from a Holocene terrace reveal the geomorphic effectiveness of aeolian deflation caused by the strong local wind (*Cierzo*) in this peculiar environment. The playa-lakes in this sector of the Ebro Basin have been some of the most intensely studied lakes in Spain for paleoenvironmental interpretations, based on cores drilled in the bottom of the depressions (González-Sampériz et al. 2008; Gutiérrez et al. 2013 and references therein). However, these investigations have encountered significant limitations in the analysed stratigraphic records, like the low thickness of the deposits, the presence of significant hiatuses related to wind erosion, or the difficulty of finding datable material. Recent studies illustrate that these drawbacks may be partially overcome by incorporating a geomorphological perspective in the investigations and considering the lacustrine terraces preserved in the basin margins. These terraces may be used to (1) establish the morpho-stratigraphic evolution of the basins and identify major paleoenvironmental changes; (2) enlarge the completeness of the stratigraphic record and dating possibilities; and (3) estimate rates of aeolian deflation. The ongoing irrigation plan (Monegros II), affecting ca. 200 km^2 of the endorheic area, will cause significant alterations on the hydrology of these highly sensitive wetlands, with negative consequences on the biocoenosis and some geomorphic processes.

12.2 Geological Setting, Climate and Hydrology

The analysed playa-lake and yardang systems are located in the central sector of the Ebro Cenozoic Basin, NE Spain (Fig. 12.1). This sedimentary basin, deeply dissected by the fluvial network, constitutes a large topographical depression drained by the trunk NW–SE-oriented Ebro River and bounded by the Pyrenees and the Iberian Chain to the north and south, respectively. The Bujaraloz-Sástago internally drained area, characterised by numerous closed depressions with a marked WNW–ESE elongation, has developed on an exhumed structural platform lying at 310–370 m a.s.l., hanging 200 m above the deeply entrenched Ebro River to the south (Fig. 12.1).

The sedimentary fill in this sector of the Ebro Basin is made up of Oligo-Miocene sediments deposited in evaporite and carbonate shallow lakes and in distal alluvial fan environments (Fig. 12.1). The strata, which show a very low (<2°) NW to NE dip, form part of the southern limb of a very open WNW–ESE syncline whose pericline is located SE of Bujaraloz (Quirantes 1978). The structural platform is underlain by the Lower Miocene Bujaraloz-Sariñena Unit, mostly composed of gypsum, mudstone and limestone

(Ramírez 1997; Solá and Costa 1997). Salvany et al. (1994, 1996) differentiate two main gypsum-rich units, each underlain by a detrital unit primarily composed of red mudstones (Fig. 12.1). From base to top, these are Middle Detrital Unit (15–20 m), Middle Gypsum Unit (40 m), Upper Detrital Unit (5–6 m) and Upper Gypsum Unit (100 m). Most of the closed depressions have developed on the Middle Gypsum Unit, exposed in the southern sector of the platform (Fig. 12.1). This unit has a much lower proportion of clay than the thicker Upper Gypsum Unit. Moreover, the size and spatial frequency of the depressions decrease towards the east, consistently with the wedging out of the Middle Gypsum Unit and the lateral change to less soluble facies (Salvany et al. 1994, 1996).

The climate of the central sector of the Ebro Basin is characterised by very hot summers and cold dry winters. The records from Bujaraloz meteorological station indicate that the average annual precipitation and temperature are 360 mm and 14.4 °C, respectively. Precipitation shows a bi-modal seasonal pattern, with the highest rainfall in spring and autumn (Rodó et al. 1997). Annual potential evapotranspiration values reach 788 and 909 mm, according to the Thornthwaite and Blaney–Criddle methods, respectively (García-Vera 1996). The area is characterised by strong winds with prevailing WNW direction, parallel to the dominant trend of the depressions and yardangs, locally designated as *Cierzo*. This cold and dry wind blows mainly in winter and spring, channelled along the Ebro Depression and controlled by the coexistence of anticyclonic conditions in the Cantabrian Sea and low pressure in the Mediterranean Sea (Puicercús et al. 1997). At Zaragoza meteorological station, located 60 km to the NW, the maximum wind speed recorded over the period 1942–2010 reached 135 km/h in February 1954 with a WNW direction. Data recorded in the Bujaraloz anemometric station, restricted to March 1991–January 1993, indicate that the WNW winds reach the highest velocities (<100 km/h) and represent about 75 % of the aeolian energy (Puicercús et al. 1997).

The Upper and Middle Gypsum Units constitute two aquifers separated by the Upper Detrital Unit, which behaves as a leaky aquitard (Fig. 12.1). Permeability in the gypsiferous units is mainly related to solutionally enlarged joints and reaches the highest values in the bottom of the depressions due to enhanced karstification by groundwater flow discharge (García-Vera 1996; Samper-Calvete and García-Vera 1998). The groundwater flow in this internally drained area is controlled by the topography of the platform, an extensive plateau riddled by enclosed depressions. Underground water flows towards and discharges at the bottom of the main basins, forming local and centripetal groundwater flow cells (Sánchez-Navarro et al. 1998). The groundwater salinity increases progressively along the flow path, changing from Ca–SO_4 composition in the recharge areas, into an Na–Mg–Cl–SO_4 hydrochemical facies in the discharge zones (García-Vera 1996; Salvany et al. 1996). Brines in the playa-lakes lead to the precipitation of salts both at the surface and within the lake sediments (Pueyo 1978/1979; Pueyo and Inglés 1987). Moreover, the extremely flat topography of the playa-lakes is controlled by the water table, which limits erosional lowering in the basins floor by aeolian deflation (Rosen 1994; Yechieli and Wood 2002).

12.3 Geomorphology of the Playa-Lakes and Closed Depressions

12.3.1 General Features and Origin

A total of 149 closed depressions, locally designated as *hoyas*, *clotas* or *saladas*, have been inventoried in the Bujaraloz-Sástago endorheic area (Balsa et al. 1991; Conesa et al. 2011). These topographical basins cover 19.2 km^2, approximately 5 % of the structural platform with internal drainage. The majority of the depressions are markedly elongated and oriented in the WNW–ESE direction, coinciding with the prevailing wind trend (Figs. 12.2 and 12.3). La Playa is the largest lake with 3.5 km in length and covering 1.72 km^2, approximately 9 % of the cumulative area of the bottom of the depressions (Fig. 12.2). This local name might be the source of the term exported by the Spaniards to the SW of the United States, where ephemeral saline lakes are designated as playas (Gutiérrez 2013). The structural platform is also carved by poorly hierarchized flat-bottom infilled valleys with dominant WNW–ESE orientation, most of which flow into closed depressions (Fig. 12.2). A significant proportion of the depressions shows scarped edges, generally controlled by a laterally extensive limestone bed situated in the upper part of the Middle Gypsum Unit (Quirantes 1965). Approximately 20 depressions host ephemeral saline wetlands that get flooded every year (Balsa et al. 1991). These playa-lakes have flat and moist bottoms, indicative of a topography controlled by the water table and capillary fringe (Rosen 1994). Water depth reaches the highest values in winter and rarely exceeds 50 cm (Castañeda 2002; Castañeda et al. 2005). These elongated lakes tend to have asymmetric geometry in plan view, with higher width in the downwind half than in the windward one, which may have a pointed margin (Fig. 12.4). Goudie and Wells (1995) indicate that deflation basins excavated in lake deposits within paleolacustrine basins typically display two types of geometries: (1) ovoid, almost subcircular, with the long axis perpendicular to the formative airflow; and (2) cusp-shaped, with the apex pointing upwind and oriented parallel to the formative wind. A significant proportion of

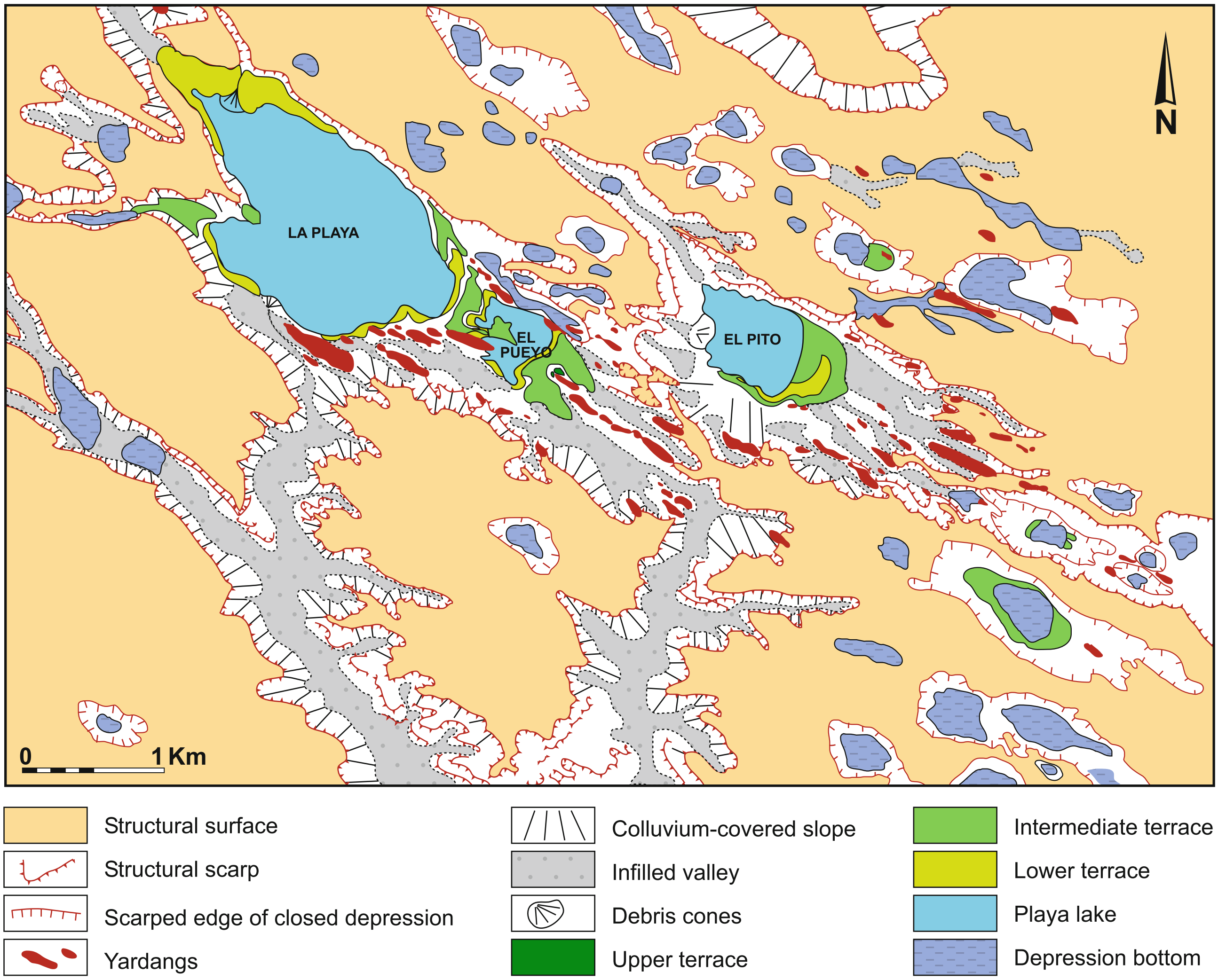

Fig. 12.2 Geomorphological map of the La Playa, El Pueyo and El Pito playa-lakes and surrounding areas, illustrating the distribution of lake terraces, yardangs and other minor closed depressions (redrawn from Gutiérrez-Elorza et al. 2002). The remnants of the Upper terrace are depicted by *small polygons* SE of El Pueyo

the playas in the studied area shows similar characteristics to the latter morphological type.

Evaporation of the brines in the playas leads to precipitation of salts (Pueyo 1978/1979; López et al. 1999). Algal mats 3–4 mm thick develop in the playa-lake floor during flooding periods. Saline efflorescences (bloedite, halite and thenardite) precipitate on the lake floor when the water level recedes. Beneath the surface, there is a black sapropelic mud with a high content in sulphides resulting from reduction of sulphates by bacterial activity. Desiccation cracks develop during dry periods and evolve into saline polygons, eventually framed by tepee-like features as well as bent and overthrusted edges. Saline crusts and algal mats locally show blisters formed by the expelling of gases derived from organic matter decomposition and volume increase related to salt crystallisation (Pueyo 1978/1979).

The margins of the lakes typically display an aureole of halophilous vegetation and wind-transported particles accumulate within and in the leeward side of these plants forming elongated nebkha dunes (Fig. 12.5). These dunes are commonly made up of sand-sized lenticular gypsum crystals. Trains of nebkhas may merge, resulting in linear dunes several tens of metres long. Moreover, some playas display rounded lunette dunes along their leeward side (Hills 1940; Goudie and Wells 1995), currently under investigation (Fig. 12.4). Some lunettes are modern deposits located on the bottom of the depressions, whereas others correspond to relict dunes perched on the downwind margin of the lake basins. Several processes favour wind deflation in the bottom of the playa-lakes during desiccation periods: (1) Drying cycles involve a significant reduction in cohesion of the particles, increasing their susceptibility to wind

Fig. 12.3 Aerial view of El Pito (*foreground*) and La Playa-El Pueyo (*background*) playa-lakes. The WNW–ESE trending elongated hills on the downwind side of the playas correspond to wind-fluted yardangs. *Arrow* indicates prevailing wind direction. Image taken on July 2005

Fig. 12.4 Oblique aerial photograph of Guallar playa, oriented parallel to the prevailing wind. The lake basin has a wider downwind half and a pointed upwind edge. Note the rounded and arcuate modern lunette dune developed along the leeward margin of the playa-lake (*white arrows*). Image taken on July 2005

entrainment; (2) Precipitation of salts at the surface may involve the accumulation of light and loose crystals and the preparation of particles for deflation by salt weathering; (3) Trampling by animals (Thomas 1988; Goudie and Wells 1995); and (4) Accumulation of significant volumes of faecal pellets by worms.

Several hypotheses have been proposed to explain the origin of the closed depressions in the Bujaraloz-Sástago endorheic area: (1) Differential dissolutional lowering of the ground surface controlled by fractures (Mingarro et al. 1981). According to this interpretation, the depressions would correspond to solution sinkholes generated by downward vadose flow in the epikarst zone. However, the playas nowadays behave as groundwater discharge zones; (2) Collapse of large cavities generated by structurally controlled subsurface dissolution in the gypsum bedrock; i.e. bedrock collapse sinkholes (e.g. Quirantes 1965). However, no significant cavities have been found in the boreholes drilled in the area and, according to geophysical surveys conducted in La Playa (Gutiérrez et al. 2013), the lake fill displays a limited thickness and tabular geometry; and (3) Widespread subsurface dissolution and subsidence

Fig. 12.5 Nebkha dunes mostly made up of gypsum crystals trapped by *Salicornia sp*. North-eastern margin of La Playa

in combination with aeolian deflation (Sánchez-Navarro et al. 1998; Gutiérrez et al. 2013). Initially, the depressions may form and evolve as solution sinkholes by percolating water in the vadose zone. Infiltration is favoured by the flat topography of the area. Once the bottom of the dolines reaches the water table zone, local groundwater flow cells that discharge in the depressions are established. That is, a recharge basin is transformed into a hydrologically closed discharge playa (Rosen 1994; Yechieli and Wood 2002). The underground flows that converge in the basins cause widespread dissolution of the bedrock, leading to gradual subsidence. The gypsum removed from the bedrock as solutes precipitates in the lake contributing to vertical accretion. During desiccation periods, the strong WNW winds may cause the erosional lowering of the basins' floor by deflation. These should be also the periods more favourable for the development of yardangs in the leeward sector of the playas.

12.3.2 Yardangs

Yardangs are elongated hills produced by wind erosion in combination with other processes such as weathering and gullying (Laity 1994, 2008; Goudie 1999). The term yardang corresponds to a local word introduced by Hedin (1903) from his study of the Taklimakan Desert, eastern China. The vast majority of the yardangs documented worldwide are located in hyperarid areas (McCauley et al. 1977; Goudie 2007). However, the yardangs associated with the Bujaraloz playas occur in a semiarid environment and are the only yardangs reported in Europe (Goudie 2007).

A total of 50 yardangs with a dominant WNW–ESE (N122E) orientation were mapped in the leeward side of the largest playas, mainly La Playa (1.72 km^2), El Pueyo (0.14 km^2) and El Pito (0.35 km^2) lakes (Gutiérrez-Elorza et al. 2002). This spatial association indicates that the formation of these landforms is related to the increase in the concentration of wind-blown particles in the playas during dry periods, increasing significantly the abrasive capability of the air currents (Figs. 12.2 and 12.3). Forty-four yardangs are developed on Miocene gypsiferous bedrock and six have been recognised in unconsolidated Holocene terrace deposits (Fig. 12.6). There is no consistent relationship between the orientation of the yardangs and the strike of the joints measured in several locations within the study area. The maximum length, width and height of the mapped yardangs are 264, 40 and 17 m, respectively, and the average aspect ratio (length/width) is 4.1. These landforms correspond to meso- and mega-yardangs according to Cooke et al. (1993) and to yardangs and mega-yardangs following the terminology of Livingstone and Warren (1996). The windward slope is always steeper than the leeward side. Following the morphological classification proposed by Halimov and Fezer (1989) from their studies in central Asia, the following yardang types may be differentiated: ridge-yardangs, which constitute elongated appendixes of structural surfaces and are the most frequent ones, mesa-yardangs, cone-yardangs, saw-tooth crest-yardangs and keel yardangs.

12.3.3 Lake Terraces and Morpho-Stratigraphic Evolution

Three lacustrine terraces have been identified in La Playa and El Pueyo by means of detailed geomorphological mapping; upper, intermediate and lower terraces situated at 9, 6 and 0.5 m above the lake bottom, respectively (Gutiérrez-Elorza et al. 2002; Gutiérrez et al. 2013) (Fig. 12.2). The intermediate terrace is the most extensive, and its upper surface merges with the top of the deposits

Fig. 12.6 Yardangs in the downwind side of La Playa (*right*) and within El Pueyo (*left*). The densely vegetated yardangs in El Pueyo have been carved in Holocene lake terrace deposits, whereas the sparsely vegetated elongated hills correspond to yardangs developed on gypsiferous bedrock. The perched flat surface between La Playa and El Pueyo corresponds to the intermediate lake terrace, deposited when both lakes used to form a single and larger lacustrine system

filling flat-bottomed valleys that drain into the playa-lakes. The spatial distribution of this terrace indicates that during its accumulation, La Playa and El Pueyo used to form a single lake around 2.7 km^2, suggestive of more humid conditions. Subsequently, differential aeolian erosion compartmentalised the lake basin into the present-day playas, nowadays separated by a remnant of the intermediate terrace (Figs. 12.2 and 12.6).

The intermediate terrace has been investigated in the NE margin of La Playa by means of two trenches. Here, the 5-m-thick terrace deposits are underlain by a karstic residue 45 cm thick, and mainly consist of tabular and horizontally bedded gypsiferous silts and sands, with a high proportion of lenticular gypsum crystals. Seven radiocarbon dates indicate that the accumulation of the lacustrine deposits took place from ca. 3.9 ka to soon after 2 ka, yielding a maximum average aggradation rate of 2.6 mm/year. Considering the approximate area of La Playa-El Pueyo paleolake during deposition of the intermediate terrace (2.73 km^2) and assuming that 5 m of sediments were accumulated on average during the aggradation phase, a total sedimentary input of 13.65 million m^3 can be estimated. This volume, supplied in a minimum time span of 1.9 ka, yields a maximum sedimentary input rate of 7184 m^3/year and a specific value of 26.31 m^3/ha/year. Subsequently, the lake bottom underwent entrenchment by aeolian deflation, briefly interrupted during the formation of the lower terrace. Differential wind erosion resulted in the segmentation of La Playa and El Pueyo lakes. Considering that the top of the deposits of the intermediate terrace are situated 5.95 m above the lake bottom and that the erosional phase started sometime after 2 ka, a minimum mean erosion rate by wind deflation of 3 mm/year can be estimated. This rate also applies to the yardangs carved in the deposits of the intermediate terrace. Considering the current area of La Playa and El Pueyo (1.72 km^2), aeolian deflation has evacuated a volume of around 11.07 million m^3 in a time period shorter than 2 ka. This means a maximum long-term erosion rate of 5533 m^3/year and a specific rate of 30 m^3/ha/year. The estimated deflation rate for La Playa-El Pueyo lake system compares well with those calculated in several arid regions of the world, mainly using yardangs carved in Holocene lake deposits (Williams 1970; McCauley et al. 1977; Boyé et al. 1978; Cooke et al. 1993; Goudie et al. 1999; Anderson et al. 2002; Washington et al. 2006; Liu et al. 2011).

The morpho-stratigraphic sequence records an overall deepening trend interrupted by net aggradation periods. Aggradation phases are attributed to relatively more humid periods, whilst excavation phases are ascribed to relatively more arid phases, during which the playas remain dry during longer periods, favouring the lowering of the surface by deflation (Gutiérrez et al. 2013 and references therein). These are probably also the evolutionary phases more favourable for the development of yardangs and lunette in the downwind side of the playas. The deepening of the lake bottom is limited by the position of the water table and the capillary fringe, controlling the development of extremely flat surfaces (Stokes 1968; Rosen 1994; Yechieli and Wood 2002). Once the surface meets the water table, the basins cannot get any deeper, but expand laterally through retreat of their margins, especially in easily erodible lake terraces. Further geochronological data may help improving the morpho-stratigraphic model and may contribute to better understanding the temporal relationships between the different landforms (terraces, yardangs, lunettes), as well as the role played by recent environmental changes.

Acknowledgments This work has been supported by the Spanish national project CGL2010-16775 (Ministerio de Ciencia e Innovación and FEDER) and the Regional project 2012/GA-LC-021 (DGA-La Caixa).

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