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Invited review

Lacustrine carbonates of Iberian Karst Lakes: Sources, processes and depositional environments

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ABSTRACT

Carbonates are the main components of Iberian Quaternary lake sediments. In this review we summarize the main processes controlling carbonate deposition in extant Iberian lakes located in Mesozoic and Tertiary carbonate-dominated regions and formed through karstic activity during the Late Quaternary. The lakes, relatively small (1 ha to 118 ha) and relatively shallow ($Z_{ma}x$ = 11 to 40 m) provide examples of the large variability of sedimentary facies, depositional environments, and carbonate sources. Hydrology is dominated by groundwater inflow except those directly connected to the fluvial drainage. Nine lakes have been selected for this review and the main facies in palustrine, littoral and profundal environments described and interpreted.

Clastic carbonates occur in all Iberian lakes due to the carbonate composition of the bedrocks, surface formations and soils of the watersheds. Low temperatures and dilute meteoric waters seem responsible for the low carbonate content of sediments in high elevation lakes in the glaciated terrains in the Pyrenees and the Cantabrian Mountains. Clastic carbonates are dominant in small karst lakes with functional inlets where sediment infill is dominated by fining upward sequences deposited during flood events. Re-working of littoral carbonates is common in shallow environments and during low lake level stages. In most lakes, endogenic carbonate production occurs in two settings: i) littoral platforms dominated by *Chara* and charophyte meadows and ii) epilimnetic zone as biologically-mediated calcite precipitates. Continuous preservation of varves since the Mid-Holocene only occurs in one of the deeper lakes(Montcortès Lake, up to 30 m) where calcite laminae textures (massive, fining upward and coarsening upward) reflect seasonal changes in limnological conditions. However, varves have been formed and preserved in most of the lakes during short periods associated with increased water depth and more frequent meromictic conditions.

Most Iberian lakes are in a mature stage and karstic processes are not very active. An outstanding example of a lake with intense karstic activity is Banyoles Lake where increased spring discharge after long rainy periods causes large remobilization and re-suspension of the sediments accumulated in the deepest areas, leading to the deposition of thick homogeneous layers (homogeinites).

The Iberian karst lake sequences underline the large variability of facies, carbonate sources, and depositional environments in small lake systems. They illustrate how lake types evolve through the existence of a lake basin at centennial or even smaller time scales. Hydrology is the paramount control on facies and depositional environment patterns distribution and lake evolution and, consequently, a lake classification is proposed based on hydrology and sediment input. A correct interpretation of carbonate sources and depositional history is a key for using lake sequences as archives of past global changes.

1. Introduction

Lakes occur almost in every geographic, geologic, and climatic context where geomorphic factors enable the creation of accommodation space (basin) and hydrologic balance is adequate to accumulate water. A variety of processes are able to create and maintain lakes on Earth: tectonics, aeolian, fluvial, karstic, volcanic, impact events and even anthropogenic activities (Gierlowski-Kordesch and Kelts, 2000; Cohen, 2003). In carbonate and evaporite bedrock, karstic processes such as dissolution and collapse are very effective in creating centripetal drainage patterns and depressions for lake development. Although karst

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lakes are particularly abundant in some regions such as North and Central America (Florida and Yucatan), southern China (Yunnan Province), and the Mediterranean Basin (Balkans, Italian and Iberian Peninsula), they occupy less than 1% of the total global lake area (Cohen, 2003). The dynamics of these lakes, particularly the hydrology and hydrochemistry are greatly controlled by exogenic and endogenic karstic processes. This activity leads to the generation of funnel-shaped dolines with steep margins, which have high depth/water surface ratios (Palmquist, 1979; Cvijic, 1981; Gutiérrez-Elorza, 2001). These steep-sided lakes are conducive to water stratification and contribute to a dynamic depositional environment with abrupt changes in geochemical and limnological factors, such as water chemistry, temperature, light penetration or oxic/anoxic conditions at the lake bottom (Renaut and Gierlowski-Kordesch, 2010). In addition, the direct connection to aquifers makes these systems very sensitive to regional hydrological balances, experiencing considerable lake level, water chemistry, and biological fluctuations in response to changes in effective moisture (Nicod, 2006; Morellón et al., 2009a; Sondi and Jura Ci, 2009). The development of lakes on evaporite and limestone substrates favors sulfate and carbonate-rich waters. Lakes within continental evaporitic provenance include Lac de Besse, France (Nicod, 1999); Lago di Pergusa, Italy (Sadori and Narcisi, 2001); Lake Demiryurt, Turkey (Alagöz, 1967) and Laguna Grande de Archidona, (Pulido-Bosch, 1989), Lake Banyoles (Julià, 1980), and Lake Estanya (Morellón et al., 2009a) in Spain. Generally carbonate-rich and chloride-rich lake waters develop on lakes within marine formations, e.g., Lake Vrana, Croatia (Schmidt et al., 2000) and Lake Zoñar, Spain (Valero-Garcés et al., 2003).

Lakes are active agents in the carbon cycle (Dean and Gorham, 1998; Schrag et al., 2013) and, in particular, karst lakes are key elements in the recycling of old carbonate and evaporite formations. Besides endogenic carbonate deposition, allochthonous siliciclastic and carbonate material is delivered to the lakes from the watersheds and re-distributed in the lake through waves in the littoral areas, and turbidite – type (Moreno et al., 2008; Valero-Garcés et al., 2008) and mass-wasting processes (Morellón et al., 2009a) in the distal realm.

Lacustrine depositional models have been extensively described in the literature (Kelts and Hsü, 1978; Dean, 1981; Dean and Fouch, 1983; Eugster and Kelts, 1983; Wright, 1990; Gierlowski-Kordesch and Kelts, 1994; Talbot and Allen, 1996; Gierlowski-Kordesch and Kelts, 2000) and some reviews have been recently published (Gierlowski-Kordesch, 2010; Renaut and Gierlowski-Kordesch, 2010; Last and Last, 2012). Massive, fine-grained carbonates with abundant fauna and flora remains and laminated carbonates are common facies in the geological lacustrine record as well (Gierlowski-Kordesch and Kelts, 1994; Gierlowski-Kordesch and Kelts, 2000). Most lake sediments contain some carbonate and the variety of lacustrine facies reflects the different settings: carbonate-rich lakes (Platt and Wright, 1991), ephemeral and shallow saline lakes (Last, 1990; Smoot and Lowenstein, 1991; Renault and Last, 1994), volcanic-related lakes (Negendank and Zolitschka, 1993; Pueyo et al., 2011), glacial and periglacial lakes (Kelts, 1978; Hsü and Kelts, 1985; Davaud and Girardclos, 2001). Karst lakes have provided numerous paleohydrologic and paleoclimate reconstructions e.g., Lago d'Accesa, Italy (Magny et al., 2006, 2007); Lake Banyoles, Spain (Pérez-Obiol and Julià, 1994; Valero-Garcés et al., 1998; Höbig et al., 2012); Lago di Pergusa, Italy (Sadori and Narcisi, 2001; Zanchetta et al., 2007); Lake Zoñar, Spain (Martín-Puertas et al., 2008; Martín-Puertas et al., 2009). Several sequences have been described in detail in the last decade: Petén Itza (Anselmetti et al., 2006; Hodell et al., 2008), Ohrid (Lézine et al., 2010; Lindhorst et al., 2010; Vogel et al., 2010), Estanya (Morellón et al., 2009b), however, comprehensive facies and depositional models for karstic lakes are scarce (see Morellón et al., 2009a).

In this paper we review the available sedimentary sequences from extant permanent karst lakes in Spain. In the Iberian Peninsula these lakes are relatively small (1–118 ha surface area) and not very deep (max depth range between 11 and 40 m) but they occur in a variety of geographic, geologic and climatic contexts. These relatively small, perennial Iberian karst lakes may serve as facies analogs for larger systems and help to identify sources and processes controlling lacustrine carbonate deposition in modern lakes and pre-Quaternary lacustrine formations. Detailed facies analyses and depositional models would also help to untangle the endogenic and clastic contribution to carbonate budget. These depositional models provide a dynamic framework for integrating all paleolimnological data necessary to decipher the high-resolution paleoenvironmental information archived in these lake sequences (Last and Smol, 2001; Renaut and Gierlowski-Kordesch, 2010).

2. Geologic and geographic settings

The Iberian Peninsula is composed of three main geological units (Gibbons and Moreno, 2002): i) the Iberian Massif, made up of Palaeozoic and Proterozoic rocks, ii) the Alpine Ranges (Pyrenees, Betics and Iberian Mountains), composed of Mesozoic and Cenozoic sedimentary formations affected by the Alpine orogeny, and iii) large tectonic Cenozoic basins, such as the Ebro, Duero, Tagus and Guadalquivir basins. Karst lakes occur in the Alpine Ranges and the Cenozoic basins where carbonate bedrock is dominant (Fig. 1).

The climate of the Iberian Peninsula is varied, displaying strong temperature and humidity gradients due to the altitudinal variability, the presence of mountain ranges, and the interplay of Mediterranean and Atlantic processes (Sumner et al., 2001). The inland areas and the mountain ranges experience a moderate continental climate while oceanic climate dominates in the north and west and a warm Mediterranean climate along the Mediterranean coast. Average annual temperatures range from 0 °C in the northern mountains (Pyrenees, Cantabrian) to 18 °C in the southern and eastern areas; highest precipitations are recorded on the northern mountains (>1500 mm/yr), while the inland and southern regions are drier (<500 mm/yr) (Capel Molina, 1981).

Permanent karst lakes occur in a variety of geological settings in Spain (Figs. 1 and 2): 1): glaciated terrains (Lakes Enol, Basa de la Mora and Marboré), spring and tufa – dammed areas (Lakes Taravilla, Basturs, Ruidera and Banyoles), fluvial drainages (Guadiana River and Daimiel National Park), carbonate formations in the Iberian Range (Lakes of Cañada del Hoyo and El Tobar), the Pre-Pyrenees (Lakes Estanya and Montcortès), and the Guadalquivir Basin (Lakes Zoñar, Archidona, Medina and Fuentepiedra), and in halokinetic salt structures (Lake Arreo). Some ephemeral saline lakes in Tertiary continental basins (e.g., Monegros in the Ebro Basin) formed by combined karstic and aeolian processes. A few karstic systems – Lake Banyoles (Sanz, 1981; Brusi et al., 1990), Lake Estanya (Pérez-Bielsa et al., 2012), Lake Zoñar (Valero-Garcés et al., 2006) – have quantitative water balances that demonstrate that groundwaters are the main input to these lakes. Qualitative hydrogeological models suggest that this is common to all karstic lakes in Spain except those directly connected to fluvial drainages (Lakes Taravilla, and Ruidera).

For this review we have selected lakes with detailed facies descriptions that have been studied by our research group during the last decade following a similar approach and methodology (see Section 3). The selected case studies illustrate different hydrological and limnological situations in four carbonate-rich regions: i) The Iberian Range, ii) high altitude lakes in the Pyrenees and the Cantabrian Mountains, iii) mid-altitude lakes in the western Ebro Basin and the Pre-Pyrenees and iv) the Guadalquivir Basin (Table 1, Figs. 1, 2).

i) The karst lakes in the Iberian Range formed during an Upper Pliocene–Pleistocene karstification phase affecting mostly Jurassic limestones (Gutierrez-Elorza and Peña Monne, 1979). The karstification led to the formation of sinkholes, examples include the seven dolines in Cañada del Hoyo (39°N, 1°52′W, 1000 m a.s.l.), the Lake Taravilla (40°39′ N, 1°58′ W, 1100 m asl) and Lake El Tobar (40°32′N; 3°56′W, 1200 m asl). Sediment cores are available for four of the Cañada del Hoyo lakes: La Cruz, Lagunillo del Tejo, El Tejo and La Parra (see Fig. 1 for location). Laguna de la Cruz (surface area = 1.4 ha; 132 m of diameter; Z_{max} = 25 m) exhibits meromixis and the occurrence of