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Title:

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_{max}= 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 deepest lake (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 key for using lake sequences as archives of past global changes.

Keywords: limnogeology, karst, lacustrine facies, Late Quaternary, endogenic and clastic carbonates, Iberian Peninsula

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, eolian, 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 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 (D'Amore, 1983); 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, 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; Magny et al., 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 ºC in the northern mountains (Pyrenees, Cantabrian) to 18 ºC 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 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 methods section). 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 and 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 Monné, 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 (40º32'N; 3º56'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 'whitings' during the summer (Vicente and Miracle, 1987; Dasi and Miracle, 1991; Miracle et al., 1992; Rodrigo et al., 1993; Julià et al., 1998; Romero-Viana et al., 2008; Romero-Viana et al., 2011). Short cores have been recently obtained from Lake **Lagunillo del Tejo** (López-Blanco et al., 2011; Romero-Viana et al., 2009), and the study of long cores from Lakes **Tejo** and **La Parra** is in progress by our team (Barreiro-Lostres et al., 2011; Barreiro-Lostres et al., 2013).

Lake El Tobar is the largest karstic lake in the region, with a maximum depth of 20 m and a surface area of 70 ha. It is composed of two sub-basins, a deeper, meromictic with an anoxic hypersaline (NaCl) hypolimnion and a shallower main basin (Vicente and Miracle, 1987; Miracle et al., 1992; Vicente et al., 1993; Romero Viana, 2007). Exokarstic processes, particularly tufa damming are responsible for the genesis of other lakes such as **Lake Taravilla**, a shallow (Z_{max}

= 12 m) lake, dammed behind a tufa barrage in a small tributary of the Tagus River. The lake is hydrologically open with a strong fluvial influence and also a large palustrine area.

ii) In the Cantabrian Mountains, the **Lake Enol** basin (43º11´N, 4º09'W, 1070 m asl) was deepened by a glacier, though previous karstic processes within these Carboniferous limestone (Valdeteja and Picos de Europa) and sandstone (Amieva series) formations were involved in the origin of the basin (Marquínez and Adrados, 2000). In the Pyrenees, we have selected two examples: Lakes Marboré (00º23´ E, 42º41´ N) and Basa de la Mora (42º32' N 0º19' E). Lake **Marboré** is a high altitude (2590 m asl), small (14.3 ha) and relatively deep (Z_{max}= 27 m) lake located in Mesozoic – Tertiary carbonate formations. The lake basin was also carved by glaciers and, although the last remnants of the Monte Perdido Glaciers occur in the peaks surrounding the basin, there is no hydrological connection between the lake and the glaciers nowadays. Lake Marboré has an extreme oligotrophic environment similar to other high altitude lakes in the Pyrenees with low alkalinity waters (Catalán et al., 2006). Lake **La Basa de la Mora** (1914 m a.s.l) is a shallow (Z_{max} < 4 m) lake developed behind a terminal moraine in the Cotiella Massif.

iii) In the mid-altitude areas of the western Ebro Basin and Pyrenean domain there are numerous examples of karst lakes, with four highlighted here:

Lake Arreo (42º46´ N, 2º59´ W; 655 m asl) is located on the southwestern edge of the Salinas de Añana diapir, an ellipsoidal, 5.5 x 3.2 km halokinetic structure developed in Upper Triassic evaporite formations in the NW Ebro River

Basin (Garrote Ruíz and Muñoz Jiménez, 2001). Lake Arreo is the best example in Spain of a karst lake formed in evaporites and constitutes the deepest body of water (Z_{max}= 24.8 m) with gypsum substrate in the Iberian Peninsula (Martín-Rubio et al., 2005). The lake (6.57 ha) has a funnel-shaped deep basin and a shallow platform occupies 2/3 of the lake´s total surface area (Rico et al., 1995). The lake is hydrologically open, with a small stream that enters the lake from the east and a small ephemeral outlet, a tributary of the Ebro River, which flows southward.

Balsas de Estanya (42°02' N, 0°32' E; 670 m asl) is a karstic lake complex located in a relatively small endorheic basin covering 18.8 ha (López-Vicente et al., 2009) that belongs to a larger Miocene structure, the Saganta-Estopiñan polje (Sancho-Marcén, 1988). The karstic system consists of three dolines with water depths of 7, 12 and 20 m, and one that is seasonally flooded. The largest lake is composed of two coalescent dolines, 20 and 12 m deep with no surface inlets or outlets. **Lake Montcortès** (42º 19´ N, 0º 59´ E, 1027 m asl) is one of the deepest karst lakes in the Iberian Peninsula (Z_{max}= 30m) (Alonso, 1998). The lake is almost circular in shape (maximum length = ~525 m, maximum width = ~450 m), has no permanent inlet, and an outlet stream located on the north shore controls maximum lake level (Camps et al., 1976). The lake is oligotrophic and meromictic, with permanently anoxic freshwater monimolimnion below 18 m in summer and 20 m in winter (Modamio et al., 1988).

Lake Banyoles (42º1'N; 2º4'E, 173 m asl) is the largest karst lake complex in Spain (118 ha surface area) with a maximum depth of 40 m, although some active sinkholes may reach up to 80 m. The basin developed in Tertiary evaporitic formations contains eleven karstic depressions (Bischoff et al., 1994; Canals et al., 1990) connected by their epilimnetic waters, but with isolated hypolimnions, which show differential anoxic periods, from 1 to 12 months/year (Prat and Rieradevall, 1995). The lake is hydrologically open, connected to a large Paleogene limestone and gypsum aquifer (Sanz, 1981; Brusi et al., 1990). About 80 % of the inflow is through groundwaters. Active springs in the sinkholes are responsible for sediment re-mobilization and development of sediment plumes (Serra et al., 2005).

iv) In the Guadalquivir Basin, **Lake Zoñar** (37º29' N, 4º41' W, 300 m a.s.l.) is the deepest (14.5 m) and largest lake (37 ha, surface area) (Valero-Garcés et al., 2006). The origin of this lake basin is related to karstic activity along some fault structures (Sánchez et al., 1992). The lake has no surface outlet and the inlets are temporary; groundwater is the main input to the lake.

3. Methods

For this review, we have selected nine lakes to summarize their sediment sequences from the twelve karst lakes listed in Table 1. Sedimentological data have been previously published except for Lakes La Parra, Banyoles, El Tejo and Marboré. All the sequences have been analyzed following similar methodologies and the detailed analyses and techniques applied to each lake are described in publications listed in Table 1. Lake watersheds were identified and mapped using topographic and geologic maps and aerial photographs. Surface sediments were sampled and long cores were retrieved using modified Kullenberg piston coring equipment and Uwitec© corers and platform. Physical properties (magnetic susceptibility and density) were measured with a Geotek Multi-Sensor Core Logger (MSCL) every 1 cm. The cores were subsequently split lengthwise in two halves and imaged with high-resolution cameras mounted in core scanners. Color parameters (l*, a*, b*) were extracted using Adobe Photoshop® and ImageJ software. Sedimentary facies were defined after visual description of core sections and microscopic observation of smear slides, following the methodology described in Schnurrenberger et al. (2003). This classification protocol is more adequate for unconsolidated soft sediments because it integrates meso-scale (visual descriptions) and micro-scale (microscopic) observations and it includes a semi-quantification of the main components (organic remains, mineral grains, biological content). For the purposes of this paper the facies described for each lake have been synthesized according to compositional and textural characteristics, mainly grain size and lamination. Compositional measurements include total organic (TOC) and inorganic (TIC) carbon and total nitrogen (TN). Bulk sediment mineralogy was characterized by X-ray diffraction and scanning electron microscope (SEM) observations completed textural and compositional characterizations. Large thin sections (100 x 15 x 35 mm) were prepared using the freeze-dry technique and subsequent impregnation with epoxy resin under vacuum conditions (Brauer and Casanova, 2001; Lotter and Lemcke, 1999).

The chronology of the selected sequences has been constrained with radiocarbon and $^{210}Pb/^{137}Cs$ techniques (see references in Table 1). They include the last 30000 years in Lake Enol, 22000 years in Lake Estanya, most of the Holocene in Lakes Banyoles, Marboré, and Basa de La Mora; the mid to late Holocene in Lake Montcortès (ca. 6000 years) and Lake Zoñar (ca. 4000 years) and the last millennia in Lakes Arreo, Tejo, La Parra and Taravilla.

4. Facies associations and depositional environments

Lacustrine environments are defined by depth and energy levels and include littoral, sublittoral and profundal (Renaut and Gierlowski-Kordesch, 2010). Littoral environments group the shallow-water zones around the lake margins affected by waves; sublittoral environments are transitional to deeper waters but still within the photic zone; finally, distal-profundal environments are below wave base with minimal to no sunlight penetration (Renaut and Gierlowski-Kordesch, 2010). Palustrine environments are transitional between lacustrine and terrestrial, and affected by significant periods of subaerial exposure and pedogenesis (Alonso-Zarza and Wright, 2010). Due to the small size of most Spanish karstic lakes, “distal” environments are quite close to the shoreline and we prefer to maintain the double name: distal-profundal. Also, we have included sublittoral and littoral in the same environment with examples of both, gently (bench, terrace or platform) and steeply sloping margins. Considering the characteristics of the Iberian karstic lakes (relatively small and shallow, significant clastic input) we have identified three main depositional environments: palustrine, littoral - sublittoral and profundal - distal). Gierlowski-Kordesch (2010) considered five main types of carbonate lacustrine facies; laminated, massive, microbial, marginal and open-water and Alonso-Zarza and Wright (2010) defined eleven palustrine carbonate facies. We have grouped the variety of facies in Iberian karstic lakes using key sedimentological (lamination and grain size) and compositional (carbonate versus siliciclastic and organic) properties (Table 2 and Figures 3 to 14). Detailed descriptions of sedimentary facies for each lake are provided elsewhere (see references in Table 1). Three facies associations and depositional environments can be identified in most Recent Iberian karstic lake basins (Fig. 15): i) palustrine, ii) littoral-sublittoral and iii) profundal- distal.

4.1 Palustrine Facies Associations

Facies.

There are two main types of palustrine sedimentary facies (P, Table 2):

1. Clastic Facies. Clastic facies are well developed in palustrine areas with alluvial inlets such as Lakes Banyoles, Taravilla, and Arreo. They include gravels and sands (Palustrine Coarse, PC) and fine sands and silts (Palustrine Fine, PF). In Lake Arreo massive to banded conglomerate layers with a sandy matrix and silty sand layers with abundant plant remains occur at the base of the littoral sequences. Fine, massive carbonate facies have edaphic textures, bioturbation and evidence of subaerial exposure (root traces, cracks) (Fig. 4). In Lake Taravilla the fining-upwards sequences are composed of gravel beds up to 25 cm thick composed of Cretaceous rock fragments and tufa clasts with a carbonate and quartz sandy matrix and coarse silts with abundant plant remains (Figs. 3A and 5).

Interpretation. Coarse facies arranged in fining-upward sequences represents deposition in palustrine areas and proximal littoral zones with a strong alluvial/deltaic influence. Finer facies represent deposition in wetlands with lower alluvial influence and subsequent subaerial exposure, colonization by terrestrial vegetation and development of incipient soils. These coarse clastic layers show similarities with carbonate-filled channels facies in modern wetlands and ancient palustrine settings (Alonso-Zarza and Wright, 2010).

2. Organic – rich (PO). Cm to dm thick, massive organic-rich silts with abundant plant remains occur at the top of fining-upward sequences in Lake Taravilla and are common in shallow palustrine settings at Lake Arreo (Fig. 4).

Interpretation. These facies represent organic accumulation in low energy palustrine settings (wetland type) with abundant vegetation. They are similar to organic-rich marlstone and clays facies defined by Alonso-Zarza and Wright (2010)

4.2. Littoral Facies Associations

Facies

1.Coarse clastic (LC). Coarse (gravel, sand and coarse silt size) facies occur in most sequences, although they are minor components. These facies are well represented only in Lake Banyoles, where shallow (ca. 10 m), flat platforms are extensively developed in the northern sub-basin. In Lake Banyoles, the littoral sediments are banded to massive carbonate-rich (up to 95 % calcite) (Pérez-Obiol and Julià, 1994) organized in sand-silt-mud fining-upward sequences (Valero-Garcés et al., 1998; Höbig et al., 2012). These facies contain bioclasts (*Chara* fragments, gastropods, ostracods and reworked carbonate coatings with plant remains (Morellón et al., in review). In Lake Arreo, massive silty sand layers occur at the southern margin, with high carbonate content (up to 80%) and significant amounts of siliciclastic material, (up to 10 %) and organic matter (up to 6% of TOC; Fig. 4). In the northern margin, some massive layers occurred at the feet of the steep scarps. The lacustrine sequence in Lake Taravilla contains meter-thick fining upward sequences with three components (Fig. 5): i) decimeter-thick, massive dark grey carbonate-rich silty-sand to coarse sand; ii) centimeter- to decimeter-thick, massive to faintly laminated light grey carbonate silt and iii) centimeter to decimeter-thick, massive to faintly laminated, dark grey carbonate silt and mud. Rarely centimeter-thick silt layers with abundant plant macroremains are also deposited. Coarse facies (gravels and sands) are relatively common in La Parra sequence (Fig. 6) and include dm-thick massive gravel beds, cm-thick fine gravels and coarse sands and cm-thick, massive fine sands arranged in finning-upward sequences. Coarse facies are minor in topographically – closed basins with no surface inlet. In Lake Enol, they only occur as cm-thick thick carbonate sandy layers with abundant shell fragments.

Interpretation: Coarse carbonate facies arranged in fining-upward sequences and with sedimentary structures indicative of sub-aqueous transport (lamination) represents deposition in littoral zones with a strong alluvial/deltaic influence. They are better developed close to the surface inlets feeding the lakes in Taravilla and Banyoles. Massive layers at the feet of steep scarps (e.g., northern margin of Lake Arreo) are interpreted as debris deposits related to cliff erosion.

2. Massive to banded carbonate – rich silts and muds (LF).

Carbonate-rich silts and muds are the most common facies in Iberian karst lakes. This group of facies shows a large variability depending on stratification features (massive, banded and laminated), amount of carbonates and siliceous minerals and the abundance of littoral biota and flora remains. If present, sedimentary structures indicate current or wave action. In Lake Taravilla, deposition in littoral areas close to the tufa barrage is characterized by massive to faintly laminated, dark grey, organic-rich (up to 10% in organic matter) carbonate silts with gastropods and mollusks and charophyte remains (Fig. 5). Finer facies are deposited in deeper areas. Most littoral sediments in Lake Banyoles are made up of these facies (Valero-Garcés et al., 1998; Höbig et al., 2012). In Lake Enol, Holocene sediments are composed of banded to finely laminated coarse silts with variable carbonate content (mostly coarse-silt calcitic detrital particles), silicate minerals, macrophytes and terrestrial organic matter (Fig. 13). In Lake Arreo the sequence from the littoral core is composed of alternating fine and coarse silts with some intercalating clastic carbonate silts with fining upwards texture (Fig. 4). In Lake Montcortès, cm-thick, greyish-brownish layers of carbonate silty mud with abundant organic matter, *Chara* and gastropod fragments are indicative of deposition in carbonate-producing littoral environments (Corella et al., 2011b). Similarly to Lake Arreo, some facies are dominated by grey, silty, carbonate layers, pointing to higher carbonate clastic input from the drainage basin and re-working of carbonates in the littoral platform, while other are richer in organic matter suggesting higher organic productivity in the littoral zone. In Lake Estanya, banded to laminated dm–thick silt layers are mainly composed of calcite as well as minor amounts of quartz and clay minerals (Fig. 11). Carbonates are biogenic grains (*Chara* fragments, micrite oncoids, carbonate coatings) and small crystals derived from the re-working of particles produced in the littoral environments, although some euhedral morphologies point to direct precipitation in the waters. In Lake Basa de la Mora, carbonate-rich silts (2 – 7% TIC) with variable, but relatively high organic matter content (TOC 1-3%) and relatively low magnetic susceptibility, are arranged in massive to banded deposits with thin intercalations of organic-rich silt (Fig. 7).

Interpretation. Banded silty mud and carbonate silty sand with abundant plant remains, gastropods, mollusks and charophytes reflect deposition in a carbonate-producing littoral environment with restricted clastic input from the watershed. The lack of sedimentary textures is interpreted as a result of bioturbation in well-oxygenated, shallow waters. Banded sediments represent re-working and re-deposition of the charophyte meadows and other carbonate-encrusted littoral sediments. These facies are similar to marl/micrite facies ubiquitous in littoral settings of carbonate lakes (Magny et al., 2006; Magny et al., 2007; Renaut and Gierlowski-Kordesch, 2010). Finer silts with faint lamination and less fossil content suggest relatively deeper, littoral to sublittoral depositional environments. In more profundal areas, darker, massive to faintly laminated silt and mud represents deposition during periods of low energy, less fluvial influence, restricted water mixing, and episodic occurrence of anoxic bottom conditions. Massive or graded silty layers deposited in the littoral realm during periods of higher run-off in the watershed.

3. Massive to banded carbonate – rich silts and muds with mottling and evaporite minerals (gypsum) (LFs).

These facies are similar to the previous LF facies but may include gypsum nodules, other carbonates minerals (aragonite, dolomite, Mg-calcite) and bioturbation features (root traces, coarse plant remains, mottling). Good examples occur in the Lake Arreo and Zoñar sequences (Figs. 4 and 9).

Interpretation. These facies deposited in shallow, sometimes ephemeral environments and were affected by prolonged periods of subaerial exposure, soil development and evaporative mineral formation. They are similar to some of the palustrine facies identified by Alonso-Zarza and Wright (2010) as mottled, nodular and brecciated, and with root cavities.

4.3. Distal-Profundal Facies Associations

Facies

1. Banded to laminated carbonate silts (DB)

These facies are the most common in open – water, relatively deep environments but include a large range in grain size (from fine to coarse silts), sedimentary textures (banded to laminated), color (grey, black, brown) and composition (from carbonate–rich to silicate–rich). Although biogenic components (gastropods, mollusks, *Chara*) are present, they are less abundant than in littoral facies. Cm- to dm- thick sequences are usually defined by grain size variability. Examples of these facies occur in most lakes, such as in Lake Basa de la Mora, where thin carbonate-rich massive silts were deposited during the late Holocene (Fig. 7). Sedimentation in the distal areas of Lake Estanya during the last 1000 years (Morellón et al., 2009a; Morellón et al., 2011) (Fig. 11) and Lake Banyoles (Fig. 14) are also dominated by banded carbonate silts.

Interpretation. This facies association represents deposition in the distal open water areas of permanently or seasonally oxygenated lakes. They include the massive (structureless) and laminated carbonate muds and silts from open water – offshore facies (Renaut and Gierlowski-Kordesch, 2010).

2. Finely laminated (DL)

Finely laminated sediments (layers thinner than 1 cm) are the most characteristic lacustrine facies. They vary in thickness and lateral extent (continuous to discontinuous) and form when sediment supply changes with time (seasonally, annually) and preservation conditions are met (Glenn and Kelts, 1991). In the Iberian lakes we have identified three main facies associations: i) annually laminated (varves), ii) finely laminated (laminites), and iii) rhythmites,

2.1. Varves (DLV). Intervals with finely, laminated facies occur in most lake sequences, although only in some (Lakes Zoñar, Montcortés, Arreo, La Cruz) they are annual in nature. We have identified two main types:

- With calcite laminae (DLV(c)). These facies occur in most karst lakes, but are best developed in Lakes Montcortès and Zoñar (Figs. 3, 8, 9 and 10). They are composed of mm-thick triplets of three laminae: i) white layers, mostly made of rhombohedral calcite crystals of variable (4–20 μm-long) sizes, ii) greenish-brownish, organic-rich laminae with abundant diatoms, amorphous organic matter and variable detrital content and iii) clastic grey laminae made up of allochthonous carbonate, clay minerals, and quartz grains, commonly with a fining-upward texture. Grey laminae are not always present. In some intervals, varves are poorly preserved; laminae are thicker and clastic laminae more common and thicker too. Varved facies occur through the whole sequence in Lake Montcortès (last 5000 years) (Corella, 2011b) (Fig. 8). In Lakes Zoñar, Arreo, El Tejo, La Cruz, El Tobar and La Parra laminated facies are restricted to specific intervals and in Lake Banyoles only in the northernmost sub-basin. In Lake Zoñar they are well developed in the lower part of the sequence (2600-1600 cal yr BP) (Fig. 9) and some intervals contain varves poorly preserved and without the organic-rich layers (Martín-Puertas et al., 2008). In Lake Arreo, varves composed of mm-thick triplets of endogenic calcite, organic, and detrital laminae frequently occur in the whole sequence of the distal core (Corella et al., 2011a; Corella et al., 2013a) (Fig. 12).

Several microfacies can be distinguished in the calcite layers (Fig. 10). In Lakes Montcortès and Zoñar there are three main types: i) fining upward (C-F), with a lower sub-layer of coarser calcite crystals (averaging 12 μm in thickness) and an upper sub-layer of finer crystals (average length of 5 μm), ii) coarsening-upward (F-C), and, iii) homogeneous coarse crystals. Most of the sub-layers show an abrupt boundary, indicating two distinct calcite precipitation pulses (Martín-Puertas et al., 2008; Corella et al., 2012). In Lake Zoñar, *Botryococcus* blooms are associated with the calcite sub-layer (Fig. 10b). Two main microfacies also occur (Martín-Puertas et al., 2009): (1) microfacies 1c is composed of thicker calcite layers (1-2 mm), higher crystal density and smaller calcite grain size (5-7μm) than (2) microfacies 1a (0.1-0.8 mm and 10-15 μm).

- without calcite laminae (DLV(o)) In Lake Montcortès this facies is composed of couplets of two laminae: i) mm-thick, brown to greenish, organic-rich laminae with higher content of amorphous aquatic organic matter, diatoms and clay minerals, and ii) mm-thick terrigenous grey silt layers composed of clay minerals, carbonate, and quartz grains (Fig. 3I). This laminated facies has the highest TOC values in the sediment sequence (up to 18%) and thicker diatom- and organic matter-rich laminae, suggestive of high biological productivity and organic matter preservation in the lake. In Lake Zoñar, there is also a finely laminated microfacies (microfacies 1b) characterized by the absence of a calcite layer (Fig. 9). In El Tobar some of the finely-laminated organic facies are made of detrital and organic – rich laminae, but the annual nature has not yet been demonstrated.

Interpretation. The development of long periods of anoxia, possibly related to the development of temporary meromictic conditions, the strong seasonality of the climate in Mediterranean areas, and the occurrence of algal blooms in spring and summer allowed the formation and preservation of biogenic varves in these small, relatively deep karst lakes. Varves with three sublayers correspond to the classic biogenic varves described in lakes located in carbonate bedrock (Brauer, 2004). Varves have also been described in other settings: volcanic lakes (e.g., Eifel maar lakes (Brauer, 2004); Nar Golü, Turkey, (Jones et al., 2006)); glaciated terrains of British Columbia, (Renault and Last, 1994), and coastal lagoons (Ariztegui et al., 2010). Calcite crystals originate from endogenic precipitation in the lake epilimnion caused by ion saturation enhanced by algal blooms and increasing water temperatures (Brauer, 2004; Kelts and Hsü, 1978; Romero-Viana et al., 2008). Epilimnetic formation of calcite during spring/summer is typical in lakes emplaced in carbonate-rich bedrock areas (Brauer et al., 2008). Similar late spring to summer calcite precipitation has been described in hard water lakes in Germany (e.g., (Koschel, 1997)), Switzerland (e.g., (Kelts and Hsü, 1978)), and the Iberian Peninsula (Lake La Cruz, (Julià et al., 1998; Romero-Viana et al., 2008)). Calcite grain size and texture give evidence on past temperatures, seasonality, and anthropogenic activities in the lake´s catchment (Teranes et al., 1999a; Teranes et al., 1999b). Occurrence of larger calcite grain size has been interpreted in some lacustrine environments as precipitation during spring season responding to higher phosphate content (Teranes et al., 1999a; Teranes et al., 1999b). Thicker calcite laminae and smaller crystal size may also suggest either that saturation conditions or organic productivity periods lasted longer (warmer summers) or that the concentration of calcium and bicarbonate ions in the waters was higher (increased supply due to higher winter precipitation and aquifer recharge) as shown in Lake

La Cruz (Romero-Viana et al., 2008). Reduced calcite thickness and development of fine to coarse (F-C) calcite sub-layering in Lake Montcortès is interpreted as colder temperatures and prolonged winter conditions (Corella et al., 2012).

The organic-rich lamina represents deposition after the period of calcite precipitation. The variable content in clay minerals within the organic lamina would reflect seasonal changes in sediment delivery to the lake, likely controlled by run-off and rainfall. The detrital laminae were deposited when sediment delivery from the watershed to the lake was intensified during stronger, rainier periods. The thickness and number of those layers contain information on storm seasonality and frequency (Corella et al., 2012).

2.2.Laminites (DLL)*.* Finely laminated facies with no clear indication of annual lamination are included in this category. They are gypsum–rich -DLL(g)- and/ or organic – rich DLL(o) - facies.

Gypsum is a common mineral in Iberian karst lakes because of the presence of evaporites in the bedrock, which often constitutes the karstified substrate. The higher salinity of the groundwaters and the strong evaporation in some of these hydrologically – closed lakes is conducive to the formation of gypsum. Gypsum-rich facies DLL(g) in open water environments are dominated by endogenic gypsum crystals and they occur in Lakes Estanya, Zoñar, and Arreo. In Lake Arreo, these laminated facies are composed of mm-thick triplets (average thickness 2-3 mm) of organic matter, terrigenous, and gypsum layers with endogenic prismatic gypsum crystals (Fig. 3E). Calcite laminae are also present in some triplets (Figs. 3F and 12).

Lake Estanya contains the only sequence located in the Iberian Peninsula with a thick interval of finely-laminated gypsum layers; these facies contain prismatic and nodular gypsum and intercalate with carbonate mud layers with a mixed mineralogy (aragonite, calcite, high –Mg calcite, dolomite) (Fig. 11). In Lake Zoñar, gypsum – rich facies occur as cm-thick layers intercalated in the varved facies (Fig. 9). They are composed of gypsum crystals around 10-30 μm long, also appears as irregular cm-thick nodular gypsum layers, and cm-thick layers of carbonate silt with mm-long gypsum nodules and isolated longer gypsum crystals.

There are two types of finely laminated organic-rich facies DLL(o): sapropels and microbial mats. In Lake Estanya, both facies are present and always associated with gypsum. Brown, massive sapropel layers associated with gypsum laminae composed of idiomorphic, well-developed crystals ranging from 25 to 50 μm in length are common in the Holocene sediments. Cm-thick microbial mats also occur (Fig. 11). In Lake Zoñar, microbial – algal mats only occur in a thin interval in the upper part of the sequence and they are not associated with evaporite minerals (Fig. 9). These microbial- algal mats are the only microbial carbonate facies (after (Gierlowski-Kordesch, 2010) in Iberian karst lakes.

Interpretation: The pyramidal shapes, the homogeneous size of crystals, and the random distribution of the crystals in the DDL(g) laminae suggest gypsum precipitation within the water column (Smoot and Lowenstein, 1991), a consequence of chemically concentrated lake waters and saturated conditions for sulfates. Interestingly, the presence of planktonic saline diatoms suggests relatively high lake levels during deposition of these facies in Lake Estanya (Morellón et al., 2009a). The nodular textures indicate gypsum formation from the sediment interstitial brine waters (Hardie et al., 1978) that may occur in both, shallow ephemeral settings and relatively “deep” and concentrated hypolimnetic waters in meromictic saline lakes (Last, 1994).

Organic-rich sediments and saline minerals (gypsum) point to deposition in lake environments with a high microbial/algal bioproductivity and strong evaporation processes for DDL (o). Preservation of laminated facies in shallow lakes occurs commonly in saline environments which reduced bioturbation (Last, 1990; Schreiber and Tabakh, 2000).

2.3. Rhythmites (DLR). Laminated, siliciclastic carbonate-poor facies only occur in high altitude lakes with a mix siliciclastic and carbonate provenance (Lakes Basa de la Mora, Enol and Marboré) and where glacier and periglacial processes occur. In Lake Enol laminated facies (up to 4 % TIC) occur in the pre-Holocene sequence (Moreno et al., 2011) (Figs. 3J and 13). Lamination is composed of three laminae: (a) grey, clay – rich, (b) light brown with 10-15% of silty calcitic grains, and (c) brown, coarser with calcite and siliciclastic particles. In Lake Marboré, the Holocene sediments are made up of banded to laminated, carbonate-poor, coarse and fine silts. Carbonate content is low (TIC < 1 %) and composition is dominated by quartz and clay minerals, with low organic matter content. Finer-grained laminae are lighter in color and coarser laminae are darker with more biotites. In Lake La Basa de la Mora, carbonate – poor (< 2 % TIC) sediments, with also low TOC and MS occur in laminated or banded intervals of fine silts (Fig. 7). Although all these lakes are present in carbonate bedrock, TIC percentages are surprisingly low (2-3 %).

Interpretation. Sedimentological and textural features of the Lake Enol facies are similar to proglacial lake sediments (Leonard and Reasoner, 1999; Ohlendorf et al., 2003). They are interpreted as rhythmites deposited in lakes fed by glacier meltwater with a strong seasonality: the calcite-rich, coarse silt laminae deposit during the melting season and the fine-grained clay-rich laminae during the winter, when the lake was ice-covered. Coarser laminae were deposited during years with stronger melting pulses. In proglacial environments, better development of laminated sediments would occur during periods of stronger seasonality with higher melting and run-off discharges during spring and summer and longer ice-covered winters (Ohlendorf and Sturm, 2001; Ohlendorf et al., 2003).. More massive facies are finer-grained and clay-rich with no carbonate. They would deposit during periods with less marked seasonality (colder summers), less available water for run-off when only fine glacial sediment were mobilized ("glacial flour"). Higher carbonate content in Lake Enol proglacial sediments is clearly associated with coarser sediment fraction since finer fraction includes more clay minerals (Moreno et al., 2011).

In Lakes Marboré and Basa de la Mora, lamination reflects changes in annual clastic input to the lake and changes in the seasonality: coarser clastic materials are delivered to the lake during the summer and finer sediments are deposited during the ice-covered winter.

3. Massive and Graded Facies

Cm- to dm-thick massive (DM) and graded (DG) facies are common in distal areas of karst lakes. Graded facies are common in relatively deep lakes, such as Taravilla, Montcortés, Arreo, Estanya and El Tobar. Both facies are characterized by high magnetic susceptibility values, graded textures, and mixed carbonate and silicate composition. In most lakes the facies occur as i) mm-thick laminae and ii) cm- to dm-thick layers. The cm- to dm-thick layers show fining-upward textures, erosive basal surfaces with abundant plant remains, and a sandy basal sub-layer. Some layers incorporate sub-angular calcite particles in the base, likely related to the re-working of older carbonates in the catchment.

Graded facies are particularly well developed in Lake Taravilla deposits, where they occur as up to dm-thick massive, graded, fining-upward layers, ranging from coarse sands with plant remains at the base to silts at the top (Valero Garcés et al., 2008) (Figs. 3A and 5). In Lake Arreo, massive, cm-thick silty sand layers with abundant plagioclase and pyroxene crystals, erosive basal surfaces, and high magnetic susceptibility values occur in the profundal areas (Fig. 4). In Lake Zoñar these facies are less common and occur as cm-thick layers composed of massive to graded coarse sand and silt sediments with abundant amorphous aquatic and terrestrial organic matter remains (Fig. 9).

Homogeneites facies (DH) only appear in the Lake Banyoles sequence (Fig. 14). They occur as up to 75 cm thick homogeneous layers composed of fine calcitic mud, intercalated within distal, blackish, massive fine-grained silts in the cores located in the 20 m deep flat platforms surrounding the deepest and most active sinkholes.

Interpretation. The sedimentological features of graded and massive facies are characteristic of turbidite-type or storm-related deposits (Mangili et al., 2007; Moreno et al., 2008). The graded nature indicates deposition by turbidity currents that separate the coarse bed load from the fine grains in suspension. The coarse basal layer and the erosional surfaces likely result from underflow current processes (Sturm and Matter, 1978). Fine particles with a fining upwards texture would have been deposited by settling afterwards. The presence of reworked carbonate material may indicate erosion of the littoral platform during the periods of more intense flooding in the watershed. The fine, massive texture of some facies indicates rapid deposition in distal areas of the lake of suspended clay-rich materials that were transported by creeks that drain the catchment during flooding episodes. These facies are similar to those described in alpine lakes (Wilhelm et al., 2012). In Lake Taravilla, turbidites DG result from delta collapse episodes associated to flood events in the lake (Moreno et al., 2008). In Lake Arreo massive facies DM are similar to recent deposition of massive, sandy facies related to documented scarp failures in the ophyte outcrops located along the northern shore of the lake.

Homogeneites DH facies are only present in cores recovered from the platforms surrounding the deepest sinkholes in Banyoles with active groundwater flow processes. Morellón et al (in review) propose that sediment fluidification events during periods of higher groundwater discharge are likely responsible of the episodic deposition of these homogeneous layers in the internal platforms. This depositional mechanism has been documented during the last decades (Colomer et al., 2002; Serra et al., 2002; Serra et al., 2005): after intense and prolonged rains in the catchment, groundwater flow in the depressions increases, sediments are mobilized and transported by turbidite currents sweeping over the southern platforms of Lake Banyoles The occurrence of homogeneites in the Banyoles sequence demonstrate that groundwater activity may be a significant factor controlling sediment deposition in karstic lakes.

4.Gravitational deposits facies (G)

In several sequences (Lakes El Tobar, Montcortès, Enol) discrete intervals show convoluted and disrupted textures with folds, microfractures, and microslides (Facies GF). Coarser, chaotic facies with cm long sandstone and limestone clasts within a sandy matrix also occur at the base of some gravitational units in Lake Montcortès (Facies GC).

In particular, Lake Montcortès provides a remarkable example of several major slide units, delimited by surfaces with little deformation and slide structures (Corella et al., 2011b) (Fig. 8). In Lake Estanya a large mass flow (5 m thick, 150 m in maximum length) was identified in the deepest sub-basin by a geophysical survey (Morellón et al., 2009a) coinciding with a major change in sedimentation, from organic-rich into clastic-rich sediments (Fig. 11). Smaller deposits occurred in the north-western basin, likely associated with early stages of development of the lake basin. Gravitational deposits have also been identified in Lake Enol by multiple core correlation (Fig. 13) (Moreno et al., 2010; Moreno et al., 2011).

Interpretation. Convoluted and chaotic facies are interpreted as a result of gravitational processes affecting fine laminated or coarse lacustrine deposits. Local instability in submerged sediment-covered slopes (Strasser et al., 2007) originates from various processes such as erosion, rapid sedimentation, gas release or migration and earthquake shaking (among others) (Hampton et al., 1996; Locat and Lee, 2002; Girardclos et al., 2007; Corella et al., 2013b). Mass wasting processes are generated when gravitational downslope forces overcomes the static threshold of the shear stress in the sediments (Hampton et al., 1996). These processes are frequent in lakes with steep margins (Chapron et al., 2004; Girardclos et al., 2007).

4.4. Lacustrine environments

Carbonate sedimentary facies in Iberian karst lakes group in three main environments (Fig. 15): palustrine, littoral-sublittoral and distal-profundal

Palustrine environments are associated with hard-water lakes and wetland settings (Alonso-Zarza and Wright, 2010). The Florida Everglades, USA (Platt and Wright, 1991) and the Tablas de Daimiel wetlands, Spain (Alonso-Zarza et al., 2006) are examples of extensive palustrine environments. In Iberian karstic lakes, they occur in the transitional zone between the submerged littoral and the emerged areas surrounding the lake. Their surface area is controlled by lake basin topography and hydrology and they are characterized by fluctuating water levels with alternating periods of flooding and subaerial exposure. They are better developed in lakes with an extensive shallow area as Lakes Taravilla and Arreo. More than half of the surface area of the Lake Taravilla lake basin is occupied by a palustrine environment (Fig. 2B and 7) while a significantly large wetland occurs in the southern part of Lake Arreo (Fig. 2I and 5). In these relatively large shallow areas, vegetation develops and organic matter production and accumulation processes led to deposition of organic-rich facies and peat layers as in Lake Taravilla (Valero Garcés et al., 2008), Arreo (Corella et al., 2013a) and Banyoles (Höbig et al., 2012). Lakes with inlets have littoral carbonate and siliciclastic facies intercalated with the carbonate and organic-rich facies. Coarse palustrine carbonates are composed of extraclasts from the watershed, endoclasts (bioclasts, coated grains, intraclasts, Chara fragments, shell material) and endogenic carbonate precipitated by microbial and algal activity (Alonso-Zarza and Wright, 2010). The vegetation belt stabilizes the substrate and acts as a barrier for allocthonous material transported into the lakes by run-off as shown in many case-studies (Platt and Wright, 1991; Alonso-Zarza et al., 2006; Alonso-Zarza and Wright, 2010).

The littoral environment constitutes a relatively shallow flat to sloping area, partially colonized by vegetation, that provides support for epiphytic fauna, and largely contributes to the production of carbonate particles (Renaut and Gierlowski-Kordesch, 2010). In the Iberian lakes, the extension of the present-day littoral areas differs enormously in size, although sedimentological and compositional features of the littoral facies in all lakes are relatively similar. In Lake Estanya there is an internal littoral platform, 5 to 10 m wide, extending from the vegetation belt to the lake shoreline. Sediment is mainly composed of light grey, massive, bioturbated (root casts, worm traces, mottling sediment textures) carbonate – rich (up to 10 % TIC) coarse silts with abundant plant fragments. The external littoral platform (0 to 4.5 m water depth) permanently submerged between the shoreline and the slope is colonized by macrophytes and charophytes. In Lake Arreo, the littoral realm occupies > 60 % of the lake total area mostly in the southern area of the lake and it is very narrow in the northern side due to the presence of a steep margin. In contrast, the steep margins in Lake Montcortès limit the littoral, carbonate-producing sub-environment to 10% of the lake total area. In Lake Taravilla, a very narrow littoral zone developed with thick aquatic vegetation overhanging at the edge of the steep lake margins and submerged plants coated with carbonate (Valero Garcés et al., 2008).

This littoral environment is the main carbonate factory in the Iberian karstic lakes, comprising biogenic carbonates (ostracods, gastropods and *Chara* sp. particles) and non-biogenic carbonates (coatings around submerged macrophytes and the lake substrate). Detrital carbonates are also present as a result of re-working of the endogenic carbonate and also as clastic sediment delivered from the watershed. Storms and wave activity lead to the re-working of these particles, as indicated by the rare presence of ripples (Morellón et al., 2008; Corella et al., 2013a)..

Sedimentation in littoral areas is mainly governed by physical processes (waves and currents) (Imboden, 2007) and by changes in lake levels (Renaut and Gierlowski-Kordesch, 2010). The oscillations in the hydrological dynamics would play an important role in these sensitive environments as it is directly related to water depth, chemical composition, and light penetration. Thus, increasing water salinity and/or reduced light penetration would control the existence of different biota sensitive to changes in the limnological conditions (Wright, 1990). However, the sediment input into the lake, controlled by hydrology, climate (increased precipitation), and human activities (changes in land use) would also affect the water turbidity – which is also a limiting factor in the development of algal blooms (Reynolds and Walsby, 1975) - and nutrients inputs into the lake. The combination of these factors (fluctuating lake levels, water chemistry, clastic input) are inter-related and would respond to internal thresholds that triggers the changes in the lateral and vertical sedimentary facies distribution in littoral environments (Wright, 1990; Valero-Garcés and Kelts, 1995).

There are numerous examples of recent and Holocene carbonates deposited in littoral settings. The classical bench margins models of Murphy and Wilkinson, (1980) and Treese and Wilkinson (1982) contain charophyte – rich facies with numerous intraclasts and rippled carbonates. Tucker and Wright (1990) and Platt and Wright (1991) present facies models for carbonate shorelines depending on the slope (benches in moderately steep margins and ramps in gentler slopes) and the energy conditions. Littoral settings in Iberian karst lakes are always low-energy, but they present similarities with both: steep margins (bench) as in Lake Montcortés and gradual margins (ramp) in Lakes Taravilla and Arreo. Low-energy bench margins contain massive and banded carbonate facies in the littoral zones and bedload – transported carbonates with slumps, turbidites, and re-sedimented carbonates from the littoral zone. The mid-Holocene Lake Montcortès sedimentary record (Corella et al., 2011b) is an example of this type of margin. The Lake Taravilla and Arreo littoral sequences are examples of low energy ramp lake margins with palustrine facies, subaerial exposure textures, and some fluvial intercalations.

The distal-profundal environments include the deeper zone of the transitional talus and the central, deepest, and relatively flat areas. The transitional talus is a narrow area characterized by steep morphology, limited presence of vegetation due to the lack of light, and the occurrence of small mass movements as a result of sediment destabilization. Transport processes are dominant over sedimentation in this spatially-restricted environment. Carbonates originating in the littoral platform are transported to the talus and the distal areas. Slope instability in the talus is more common in deeper lakes with steeper morphologies where small and large slides and mass wasting deposits have been identified with seismic and multiple core stratigraphic analyses (Lakes Estanya, Montcortès and Enol). In addition, turbidite currents frequently remobilize and erode talus sediments and bring the eroded material to distal areas.

Distal areas are characterized by the deposition of darker, massive to laminated, fine-grained carbonate silts. Laminated fine sediments occur in the distal areas of all studied lakes. Carbonate content is variable (0.1-10 % TIC) reflecting the distance to the producing littoral areas and to the dissolution processes that remove small carbonate particles. According with the predominantly oxic or anoxic conditions at the bottom of the lake, and the salinity, three main sub-environments are identified: i) Dominantly oxic hypolimnion with only seasonal anoxic conditions characterized by the deposition of banded carbonate silts; ii) Anoxic, freshwater hypolimnion, with deposition of varves (Lake Montcortés); iii) Anoxic, saline hypolimnion with deposition of laminated facies with gypsum (Lakes Arreo, Tobar, Estanya)

Seasonal or permanent anoxic hypolimnetic conditions greatly reduce bioturbation processes and enhance organic matter preservation (up to 8 % TOC) and sulfide formation. Recent deposition of finely laminated sediments occurs in Lakes Montcortès, Arreo, and La Cruz. Precipitation of small calcite crystals in the epilimnion associated with algal bloom seems to be a smaller contributor to total carbonate production in most lakes.

The size of these sub-environments differs largely in comparison with the littoral sub-environments (80 % of the total surface in Lake Montcortès and 15% of the total area in Lake Arreo). The morphology of these basins consisting of funnel-shaped dolines with steep margins and a high depth/area ratio and the limnological and hydrological features lead to the development of anoxic conditions during most of the whole annual cycle, with limited bottom bioturbation, allowing the preservation of finely laminated sediments (O'Sullivan, 1983; Brauer, 2004; Zolitschka, 2007). These facies occur in several Iberian lakes (e.g., Lake La Cruz; (Julià et al., 1998; Romero-Viana et al., 2008), Lake Zoñar, (Valero-Garcés et al., 2006; Martín-Puertas et al., 2008b), Lake Banyoles, meromictic sub-basins.

Bottom morphology in distal areas of most lakes is flat because sediments have covered the original topography having more irregular karstic features (sinkholes). In active karstic lake systems, such as Lake Banyoles, lake bed morphology is more complex. Several distal, flat platforms (ca. 20 m water depth) occur between the main sinkholes (>30 m deep) where fluidized fine-grained sediments of varying densities are dominant. These sinkhole areas are characterized by flat bottom in seismic surveys (Canals et al., 1990; Morellón et al., in review) that are the uppermost surface of suspensate sediment clouds sustained by upwards phreatic inflow of warmer waters.

5. Discussion: The carbonate factory in Iberian karst lakes

5.1. Sources and Processes.

Carbonates are the main sediment component of Iberian karst lakes, except those located in glacial/periglaciar settings. Carbonate minerals are formed in most depositional environments in the lake systems as: i) tufa deposits associated with springs ii) coatings in macrophytes and aquatic vegetation in palustrine and littoral settings, and iii) endogenic precipitates in the epilimnion. Carbonate particles are also transported into the lake as iv) alluvial/fluvial and v) aeolian input. Finally, early diagenetic processes within the sediments (authigenic minerals) and internal re-working also contribute to carbonate deposition in lakes.

Carbonates in Iberian karst lakes have three main origins: chemical, biogenic and clastic (alluvial and aeolian)

i) Chemical formation. Carbonate precipitation as a consequence of direct chemical water concentration has been considered a main process in many freshwater and saline lakes (Eugster and Kelts, 1983; Last and Smol, 2001). Waters may become supersaturated in calcite (or other carbonate phases) because of changes in temperature and increased evaporation. However, even with supersaturated waters, microbial or algal activity in the epilimnion is necessary to trigger calcite formation (Stabel, 1986; Gierlowski-Kordesch, 2010). In littoral and palustrine settings, with larger changes in chemistry caused by lake level variations and stronger evaporation, direct precipitation could occur. However, precipitation of carbonate minerals in shallow marginal areas is also predominantly biochemical, mediated by microbes, macrophytes, algae or even fauna (Sanz-Montero et al., 2008; Gierlowski-Kordesch, 2010;). Some of the coatings and thin crusts in littoral vegetation in Lakes Estanya (Morellón et al., 2009a) and Arreo (Corella et al., 2013a) may respond to this process. Precipitation of carbonate nodules in mudflat – type environments with subaerial exposure and pedogenic processes have occurred in Lakes Estanya and Zoñar during low lake levels at the onset of the Holocene and between 4 – 2.5 ka BP, respectively. Aragonite formation in such ephemeral and saline settings (Lake Zoñar, Martín-Puertas et al., 2008) could be mostly chemically – controlled when waters reached a high (>1)

Mg/Ca ratios (Hardie et al., 1978). Occurrence of high magnesium calcite and dolomite in laminated intervals in Lake Estanya could reflect the effect of evaporation and chemical water – enrichment during periods of increased aridity (Fig. 11). However the association with microbial mats suggests that biomediation plays a significant role as a whole; direct chemical precipitation is a minor process in carbonate formation in Iberian karst lakes, and most likely microbe activity could be responsible for most of the endogenic carbonate formation.

ii) Biogenic. Biogenic - mediated carbonate precipitation occurs in all depositional environments in karst lakes. In littoral areas, shells (bivalves, gastropods, ostracods) are a significant fraction of massive and banded facies in all lakes. Charophyte remains are a particularly significant component in Lakes Taravilla, Estanya, Banyoles and Arreo where *Chara* meadows extend to deeper waters. Carbonate coatings around plants and nearshore vegetation are major contributions in lakes with a relatively large littoral zone (Lakes Estanya and Arreo). Although old tufa buildups are present in some of the watersheds (Lakes Taravilla, and Banyoles), and subaerial and subaqueous springs occur in all of them, no spring – related deposits have been found in any of the lakes. The absence of carbonate accumulations associated to seepage of spring zones could be caused by the similar hydrochemistry of groundwaters and lakewaters.

Calcite laminae in varved facies demonstrate the widespread precipitation of calcite in epilimetic waters. Whitings have only been observed in La Cruz (Romero et al., 2006; Romero-Viana et al., 2008; Romero-Viana et al., 2011). Sediment traps in Lakes Estanya, Zoñar and Banyoles became quickly covered with algal and microbial mats encrusted with calcite. Varve microstructure and composition indicate a clear connection with biological activity in Lakes Montcortès (diatom blooms) (Scussolini et al., 2011; Corella et al., 2012;) and Zoñar (*Botryococcus* blooms) (Martín-Puertas et al., 2008). Laminated facies composed of irregular organic (microbial mats) and calcite layers as those in the Holocene in Lake Estanya also suggest calcite formation in shallower, saline settings associated with microbial activity (Morellón et al., 2009a).

iii) Clastic. Lake sediments greatly reflect the geology of the watershed. Karst lakes are developed in carbonate terrains and, consequently, the erosion of surface and bedrock formations is responsible for the observed dominance of carbonates in these lake sediments. However, the amount of carbonate reaching the lake from the catchment depends on several factors: i) the size of the watershed, ii) the availability of erodible materials and iii) the existence of an organized drainage network. The availability of sediments in the catchment area is determined by the size of the watershed, geology, climate, vegetation cover, and in more recent times, land uses and human impact. In Lake Taravilla, the large tufa build-ups in the catchment are one of the main suppliers of carbonate particles to the lake. Lakes with small watersheds and no surface drainage network, such as Lakes Tejo and La Cruz, have reduced clastic input, mostly as coarse materials derived from the littoral zones. Lakes of similar size but with a relatively larger watershed and a small ephemeral inlet like Lake La Parra, have more clastic coarser facies. Lakes with intermediate watersheds (Lakes El Tobar and Montcortès) have more clastic facies, particularly fine-grained. Lakes with larger watersheds (Lakes Banyoles, Zoñar and Taravilla) have the highest percentages of clastic facies. Evidence of flood events and their sedimentological signature (turbidite- type facies) are found in the distal facies associations of all Iberian karstic lakes.

A unique characteristic of Iberian lakes is the large increase in clastic input during historical times, particularly since the Medieval epoch, caused by deforestation and changes in land uses in the watershed (Valero Garcés et al., 2009).

Silt-size particles transported by wind are likely an input in karst lakes located in areas with strong prevalent winds. However, the identification of such particles in the lacustrine or marine sediments by optical or chemical techniques is not easy (Moreno et al., 2002). One of the areas where aeolian processes are very significant is the Central Ebro Valley, where a number of saline lakes occur (Valero-Garcés et al., 2000; Moreno et al., 2004). The origin of these lakes includes dissolution and karstification of the Miocene carbonates and evaporites and also aeolian activity (Gutiérrez et al., 2013). In this setting, aeolian processes are responsible for the erosion and transport of large amounts of sediments: erosion of Holocene terraces suggests a specific rate of $30m^3$/ha/yr (Gutiérrez et al., 2013). However, most Iberian karst lakes are located in relatively well-vegetated areas where wind erosion and deflation processes are likely to be secondary.

5.2. Controls on carbonate deposition in karst lakes

Iberian karst lake sequences are characterized by a large variability of facies and depositional environments with abrupt lateral and vertical changes. As in most lakes (Valero-Garcés and Kelts, 1995; Renaut and Gierlowski-Kordesch, 2010), the main factor controlling sedimentation in Iberian karstic lakes is hydrology, influencing intensity of karstic processes, hydrochemistry, thermal regime and sediment delivery to the lake. We have identified five main parameters on facies distribution and carbonate deposition, all closely connected with hydrologic dynamics: intensity of karstification processes, basin morphology, hydrological balance and surface hydrology, watershed, and climate. Figure 16 summarizes some of the main physical and chemical characteristics of the selected lakes.

Karstification processes are not only responsible for the origin of the basins through collapse, subsidence, and dissolution of carbonate and evaporite formations, but they also effectively control the morphology of the basin and the dynamics of the hydrogeological system. Initial lake formation is directly related to mechanical and dissolution processes that generate the accommodation space for the lake (Kindinger et al., 1999; Gutiérrez et al., 2008). According to Kindinger et al.'s (1999) classification of progressive developmental phases of sinkhole lake formation, the Lake Banyoles with at least thirteen active springs and formation of dolines as recent as 1978 on the western shore (Brusi et al., 1990; Julià, 1980; Moner et al., 1987) could be considered the early stages of karst lake development. Most of the Iberian karst lakes are in a mature phase, when the sinkhole has been plugged with sediments. In larger karstic systems (Lakes Banyoles and Estanya), a number of small sinkholes have been filled with sediments and have reached the "polje" stage. Dry sinkholes with steep walls occur in several karst areas in the Iberian Range.

A different category for lake basin origin are the tufa – dammed lakes like Taravilla, and barrage lake systems in the Guadiana River (Tablas de Daimiel

National Park (Pedley et al., 1996), and in the Piedra River (Arenas et al., 2013). They have steep margins associated with the barrage, with gradual margins closer to the river inflow and flat bottoms. They are hydrologically open and connected to the fluvial drainage. The regional hydrology and the topographic location in the landscape control the formation of tufa-barrage lakes (above the regional springline) or sinkhole lakes (below the regional springline).

Lake morphology. Once karst lakes have reached a mature stage, the morphology and bathymetry of the lake is only altered by sedimentary infilling and lake level changes. Lake morphology determines the surface extent of depositional environments, - particularly littoral versus distal – and the maximum depth. Three main categories occur:

a) Elongated, relatively steep margins and flat bottoms in tufa – barrage lakes (Lake Taravilla)
b) Circularly- shaped, sinkhole, funnel-shaped morphologies. Lakes develop in single sinkholes with steep margins and very restricted littoral areas (Lakes El Tejo, La Cruz, La Parra, Montcortès).
c) Sinkholes with a relatively large littoral realm (Lakes Arreo, Tobar, Enol, Marboré, Basa de la Mora); or double sinkholes (Lake Estanya) or more complex sinkhole coalescence patterns (Lakes Zoñar and Banyoles).

Changes in basin morphology occur during the lake history. For example, currently, Lake Montcortès does not have a large platform bench; however, during the mid-Holocene, carbonate littoral facies developed most likely as a result of lake level changes induced by hydrologic fluctuations that altered the shape of the littoral and facilitated carbonate formation.

In all lakes, carbonates are more abundant in the littoral and transitional areas than the deepest areas. Carbonate particle size decreases from shore to distal areas, as a reflection of distance to the main sources of carbonate: detrital component from the watershed and endogenic component from the littoral zone. The organic matter content decreases from the platform towards the slope of the depression, but increases again in the distal areas. The main organic components in the sediments are different in proximal and distal environments: a mixture of terrestrial, submerged macrophytes and algal material in the littoral zone, and a higher contribution of algal sources in the distal facies. In all cases, distal organic matter has lower TOC/TN ratios suggestive of a higher contribution of algal sources (Meyers, 1997).

Hydrologic balance and surface hydrology. The hydrological balance and lake level fluctuations are main factors controlling facies distribution and composition. Lake water input occurs through rainfall, surface drainage, surface runoff and groundwaters; outputs are through evaporation, surface drainage and groundwater fluxes. Changes in lake level occur more rapidly in hydrologically – closed lakes as a response to moisture fluctuations (Hardie et al., 1978). The presence of an active inlet determines the intensity of the clastic input to the lakes (Renaut and Gierlowski-Kordesch, 2010). Although conceptual hydrogeological models and some water balances indicate a large groundwater contribution for all lakes (except Lake Taravilla), few of the studied lakes (Lakes Banyoles and Zoñar) have a quantified water balance. In spite that surface hydrology is not a sure indication of the global water balance, open or closed surface drainage is a key characteristic of the lake basin, defining the water and sediment input to the lake. The variety of surface drainage in Iberian karstic lakes includes: i) no inlets, only seasonal surface run-off and no surface outlets (Lakes Tejo and La Cruz) ii), only ephemeral inlets and no surface outlets (Parra, Estanya, Zoñar), iii) seasonal outlets and inlets (Lakes Tobar, Basa and Arreo), iv) permanent outlets (Lakes Montcortès, Enol, and Marboré), v) permanent inlets and outlets (Lakes Banyoles and Taravilla). We grouped them into the following types (Fig. 16C and 17):

1. Open (through – flowing) lakes, with a permanent surface outlet. It includes lakes with tufa dam like Lake Banyoles and Taravilla, and lakes without tufa dams, developed in glaciated terrains (Lakes Enol and Marboré) and non-glaciated terrains (Lakes Montcortès and El Tobar)
2. Intermediate, with an ephemeral or seasonal outlet: Examples are Lake Arreo and Basa de la Mora.
3. Closed lakes, with no surface outlet: Lakes El Tejo, La Cruz, La Parra, Estanya and Zoñar.

Watershed. The geology of the watershed influences the clastic supply to the lake and the hydrochemistry of the waters. Lakes developed in terrains with more evaporite formations (Lakes Arreo, El Tobar and Estanya) have both, more saline waters and more abundant gypsum formation. The size of the catchment also exerts a large influence in the sediment delivered to the lake: lakes with larger catchments (Lakes Banyoles, Tobar, Zoñar and Taravilla) have higher carbonate and siliciclastic contribution and higher sedimentation rates during the last millennia. Figure 17 illustrates a lake classification based on surface hydrology and sediment supply indicated by the watershed surface area.

Changes in main watershed characteristics strongly control lake sedimentation. Lakes in glaciated areas during the Late Quaternary (Lakes Marboré, Enol and Basa de la Mora) show clear depositional changes associated to the dynamics of the glaciers in the watershed and changes in the vegetation cover, both controlled by climate and hydrologic changes during the Pleistocene and Holocene (Moreno et al., 2010). Deforestation and increased population in the watersheds during Medieval times resulted in higher sedimentation rates and increased frequency of turbidity processes in most lakes. A flood frequency increase during the Little Ice Age is detected in Lake Taravilla, and it has been associated with higher rainfall (Moreno et al., 2008). The impact in sedimentation rate caused by decreasing human pressure in rural Spain after the 1950s has also been recorded in several lakes: Lake Zoñar; (Martín-Puertas et al., 2008); Lake Arreo (Corella et al., 2011a) and Lake Montcortès (Corella, 2011b).).

Climate. Iberian karst lakes are located in regions with Mediterranean, continental and high altitude climates. Precipitation ultimately controls the lake hydrology so its influence is paramount in lake dynamics. Aquifers and groundwater dynamics may introduce a time lag in the response of the lake system although observations during the last decades demonstrate a rapid transfer to rainfall signal to lake dynamics: Lake Zoñar (Valero-Garcés et al., 2006), Cañada del Hoyo lakes (López-Blanco et al., 2011), and Lake Banyoles (Brusi et al., 1990).

At millennial time-scales, the long-term trends reflect the large changes associated to glacial/interglacial dynamics. Deglaciation onset is commonly marked by an increase in organic and carbonate productivity in the lakes (Lakes Enol and Estanya, Figs. 11, 13). Some abrupt climate changes within these glacial periods are clearly identified as changes in texture and lamination of littoral facies in Lake Banyoles (Valero-Garcés et al., 1998; Höbig et al., 2012) and as an increase in carbonate content in the Enol sequence (Moreno et al., 2010). Carbonate and gypsum content also mark the rapid hydrological response of Lake Estanya during deglaciation (Fig. 11; (Morellón et al., 2009b)). Changes in the drainage and provenance area caused by glacier retreat could be responsible of some of the observed changes as documented in the Alps (L´Annecy (Nicoud and Manalt, 2001)) and the Pyrenees (Lake Tramacastilla, (García-Ruiz and Valero Garcés, 1998)).

Large Holocene moisture changes in the Iberian Peninsula have also been reflected in facies variability in the lake sequences. For example, Lakes Basa de la Mora (Fig. 7) and Estanya (Fig. 11) show more profundal facies during the relatively more humid early Holocene and more littoral and carbonate-rich littoral facies during the more arid mid-Holocene. Another clear example of climatically-driven evolution is the coherent trends identified in Iberian lakes during the more arid Medieval Climate Anomaly and the more humid Little Ice Age (Valero Garcés et al., 2009; Morellón et al., 2012; Moreno et al., 2012).

Climatic factors cannot be disregarded on the generation processes of clastic facies as an increase in storminess is directly related to higher run-off. Increasing aridity during some intervals (e.g., Medieval Climate Anomaly) may also play an important role in the sediment availability as dry soils are more easily eroded. In Lake Montcortès, the more abundant presence of clastic laminae in the varved intervals is linked to more precipitation events per year (Corella et al 2012). Temperature has a strong influence in biological activity, and in the timing of carbonate precipitation related to planktonic blooms. In both, Lake Zoñar and Lake Montcortès changes in water temperature have resulted in different textures of the calcite precipitated in the lakes during the Little Ice Age and the Iberian – Roman Humid Period (Martín-Puertas et al., 2008; Corella et al., 2012). Recent endogenic calcite formation (calcite lamina thickness) is correlated with winter rainfall in Lake La Cruz (Romero-Viana et al., 2008) and a similar mechanism could be in place in other Spanish lakes. Temperature also influences the solubility of carbonate (Deocampo, 2010) and may be the main reason for the low carbonate content of proglacial Enol and recent Marboré sedimentary sequences (Moreno et al., 2011). The preservation potential of carbonates in cold-water lakes could be diminished by preferential dissolution of fine-grained calcite (glacier flour) in these settings.

Water chemistry. Hydrological balance and watershed geology greatly determine water chemical composition. In our data set, lakes with functional outlets have lower TDS and conductivities and lakes with no surface outlets have the highest salinities (Fig. 16C, D). Sulfate is the most common anion in lakes developed over a dominantly evaporite substrate (Lakes Arreo and El Tobar) while carbonate- bicarbonate dominates in carbonate terrains. Ca^{2+} is the dominant cation in evaporite-rich watersheds while the dominance of Ca^{2+} or Mg^{2+} in carbonate-terrain lakes depends on the relative abundance of dolomite. El Tobar is a unique case because of the presence a hypersaline monimolimnion related to the input of saline springs (Vicente et al., 1993).

In hydrologically – open basins with short residence times as in Lakes Taravilla and Banyoles, chemical compositions of lake waters and surface waters is similar and do not greatly change through time. If lake level drops below the outlet, hydrologically – open lakes may become closed, evaporative basins, as it is the case in Lake Zoñar during several dry periods in the past (Martín-Puertas et al., 2008b) or Lake Taravilla in recent droughts in the 1990s (Valero-Garcés et al., 2008). Increased evaporation changes water salinity as reflected in deposition of other carbonate phases (aragonite, HMC) and sulfates (gypsum) (Fig. 9). Lakes depending almost exclusively on groundwater fluxes as those in Cañada del Hoyo react even more rapidly to water balances with changes in littoral and distal facies distribution (Romero-Viana et al., 2009; López-Blanco et al., 2011); however, changes in salinity are not large enough to precipitate more saline minerals. Saline water input plays a definitive role in Lakes El Tobar and Arreo water chemistry and mineral deposition because the presence of saline groundwaters.

Water chemistry is also key to carbonate preservation since hypolimnetic conditions may dissolve small calcite grains before deposition (Dean et al., 2007). Even lakes with high littoral and epilimnetic carbonate productivity and well-developed carbonate benches may have little accumulation of carbonates in the distal, deeper zones dominated by organic deposition (Gilbert and Lesak, 1981). Dissolution of carbonates in hypolimnetic waters is favored by lower temperatures and lower alkalinity and pH caused by organic matter decay (Deocampo, 2010) These processes could also contribute to the absence of some calcite layers in varve facies (Montcortès, Zoñar).

Dissolution also affects clastic carbonates. Rhythmites in Lakes Enol, Marboré and Basa de la Mora have very low carbonate content, in spite of the dominant carbonate composition of the rock formations and the main moraines in the catchment. Low temperatures during glacial times (Lake Enol) would have been conducive to dissolution of fine clastic carbonates delivered into the lake by the proglacial streams. In Lakes Marboré and Basa de la Mora, the Late glacial and Holocene moraines in the catchment are carbonate - rich (up to 11 % TIC) while the laminated sediments are carbonate-free (< 0.1 % TIC). Cold, low salinity surface waters in these high altitude settings (> 2500 m asl) could have dissolved some of the fine carbonate particles before entering the lake. Groundwater seeping into the lake could also contribute to further dissolve fine-grained carbonates.

Water stratification. Lake depth is the main parameter controlling thermal stratification and development of anoxic conditions (Wetzel, 2001) The development of seasonal or permanent thermal stratification requires a minimum water depth of 6 m (Shaw et al., 2002) and so thermal stratification occurs in all Iberian karst lakes, except Lake La Basa de la Mora (4 m max. water depth) (Fig. 16B, D). Lake Montcortès is the only lake with permanent anoxic waters due to thermal stratification. Recent monitoring and paleolimnological reconstructions based on short cores point to dominant meromictic conditions in Lake Arreo prior to the 1960s (Corella et al., 2011a), disturbed by water removal for irrigation. In Lake El Tobar the input of highly saline waters is responsible for hypersaline hypolimnion and permanent meromixis (Vicente et al., 1993).

The sedimentary sequences of the studied Spanish lakes show examples where changes from predominantly stratified to mixed water column conditions in distal areas are reflected in the alternation of banded/ massive and laminated facies (Lakes Arreo, Estanya and Zoñar).

Lake evolution. Iberian karstic lakes are small compared with large karstic lacustrine basins, but their facies associations and sequences serve as analogs for both Quaternary and pre-Quaternary lake basins. Our review shows a large spatial facies and depositional environment variability: in a < 100 m long transect we find littoral facies with evidences of subaerial exposure and profundal finely facies (Lakes Montcortés and Zoñar). Similar large variability occurs if time is considered. Only in Lake Montcortés, varved facies have been deposited during at least the last 5000 years in the deepest part of the lake basin. Most profundal areas have experienced rather abrupt changes in depositional environment conditions (depth, oxygen content) at a decadal or centennial scale.

Hydrology is clearly the paramount control on facies and depositional environment patterns distribution and evolution. The lake´s hydrological budget is greatly governed by the basin morphology and the water balance but at short time scales as those illustrated in this review (millennial scale), factors as tectonics, subsidence and karstic activity intensity are secondary to climate. Most Iberian karstic lake facies sequences indicative of lake level changes are reflecting the local and regional climate variability during the last millennia.

In large lakes, allogenic factors creating accommodation space (tectonics, karstic activity, volcanism, fluvial damming) and controlling water budgets (climate) determine sedimentation patterns (Bohacs et al., 2000). As we have shown in previous sections, the smaller Iberian karstic lakes, show similar interactions of the four main variables: sediment supply, water supply, basin-sill height (spill point), and basin floor depth. Our classification of Iberian Karstic lake basins based on surface hydrology and watershed surface area (Fig. 17) respond to the two main criteria in Bohacs et al (2000) classification of lake sequence stratigraphic patters: overfilled, balanced-fill and underfilled. Overfilled basins are characterized by water and sediment supply higher than accommodation rates, stable lake level, open hydrology and dilute waters. Lakes with open surface hydrology as Banyoles, Montcortès and Taravilla could be included in this type. Examples of underfilled basins, with smaller water and sediment supply than accommodation rates and closed surface hydrology are Lakes Zoñar and Estanya. Aggradations pattern are more common in Iberian lake sequences, and only in those cases with stronger fluvial influence (Lakes Taravilla and Banyoles), some progradational patterns occur in littoral sequences.

Our review illustrates how lake types evolve through the existence of a lake basin at centennial or even smaller time scales. In the absence of strong tectonic control, accommodation space and basin morphology are determined by surface (karstic and hydrologic) processes. Karstic processes generating new accommodation space are only active in Lake Banyoles; in most Iberian lake sequences, hydrology has determined changes in the surface drainage evolution. Lacustrine sedimentation may start much later than the basin was formed by karstic processes. This is clearly documented in Lake La Parra by the occurrence of an alteration zone between the substrate and the lake sediments. Profundal facies occurred early in the lake evolution (Lakes La Parra and Estanya), as an indication of the rapid flooding of the basin. At a Holocene- scale, the lake basins have not deepened much due to karstification processes, so the sedimentation pattern is comparable to volcanic crater lakes or dammed-lakes, starting with deep facies and gradually filled with sediment. Human activities have been a significant contributor to sediment input during the last millennium.

The variability of lake facies, depositional patterns and evolutionary trends envisaged in the geologic record of lake basins (Gierlowski-Kordesch and Kelts, 2000) is even more evident in extant and Quaternary lakes. Facies analyses from modern lake systems help to refine facies models for larger lake basins and to understand their dynamics at different temporal and spatial scales.

6. Conclusions

Iberian karst lakes are small lake systems with a large variability of facies and depositional environments. Carbonates are the main sediment components because of the geology of the watershed and the lake water hydrochemistry. Shallow littoral depositional environments with massive and banded facies are dominant because of the relatively small size of the lakes. Distal profundal facies are more spatially restricted but show a large variability of laminated facies. Slump and gravitational processes are more common in the lake basins with higher depth/surface ratio. Endogenic carbonate formation occurs in diverse settings and, although dominated by littoral processes, also includes epilimnetic calcite precipitation. Except in glaciated terrains, detrital carbonate input is a major contribution to the carbonate budget in these lakes. In spite of the complexity of the facies evolution in the Iberian karst lakes, the sedimentary sequences provide examples of evolutionary trends related to paleohydrological variability and also to changes in the watershed. Hydrology is the main control on facies and depositional environment patterns distribution and evolution. The large changes associated with glacial/interglacial cycles and the inherent large humidity variability of the Holocene Mediterranean climates have exerted a great control on lake deposition and climate has been an important forcing behind the hydrological/ depositional response of the lakes.

Human impact in the watersheds and the lakes has been documented since Iberian-Roman times and it has increased since the Medieval Ages with a much higher sediment delivery to the lakes. Several examples of the impact of historical land-use changes as the Medieval deforestation, the periods of higher population in the Pyrenees during the 19th century, or the abandonment of the rural areas in the mid-20th century are documented in several lake sequences.

Detailed sedimentary facies of these systems provide the framework to interpret past environmental changes and contribute to reconstruction of past hydrological and climate variability.

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Tables

Table 1. Main characteristics of selected Iberian karst lakes, including physical, limnological and hydrochemical parameters and main literature references.

Table 2. Facies and Facies Associations in Iberian karst lakes, including sedimentology, depositional processes, and environments

Figure captions

Figure 1. Simplified geological map of Spain (after Gibbons and Moreno, 2002) and location of the Iberian karst lakes sequences discussed (black dots) and reviewed (white dots) in this paper.

Figure 2. The diversity of karstic lakes in the Iberian Peninsula. Lake basins occur in fluvial drainages dammed by tufa buildups - Banyoles (A) and Taravilla (B) - in glaciated terrains - Enol (C) and Marboré (D) -and as simple – El Tejo (F),Montcortès (H) and Arreo (I) (Photo: Eugenio Rico) or multiple sinkoles – Estanya (E) and Zoñar (G). According to surface hydrology, lakes are open (through-flowing) as Banyoles (A), Taravilla (B), Enol (C), Marboré (D) and Montcortès H); closed with no surface outlet as Estanya (E) and El Tejo (F) or with a seasonal outlet in the recent past as Zoñar (G) and Arreo (I).

Figure 3. Core photographs of some diagnostic facies: A. Taravilla littoral facies association: Coarse clastic (LC) and Banded carbonate-rich silts and muds (LF) B. Zoñar varves (DLV(c) grading upwards to massive carbonate silts (LF) C. Varves with calcite laminae (DLV (c) with intercalated graded (DG) in Zoñar. D. Arreo Littoral Facies LF: Banded carbonate silts and muds. E. Arreo Distal Facies: Varves with calcite laminae DLV(c) (black), gypsum-rich laminites DLL(g) and massive DM distal facies. F. Arreo Distal Facies: Varves with calcite laminae DLV(c) (black) and graded DG distal facies. G. Montcortés distal facies: Varves with calcite laminae DLV(c) with intercalated graded DG distal facies. H. Varves with calcite laminae DLV(c) with intercalated graded DG distal facies. I. Organic varves DLV(o) in Montcorès. J. Enol Rhythmites (DLR facies). Scale bars: 10 cm

Figure 4. Littoral and palustrine facies in the sedimentary sequence of Lake Arreo: (modified from Corella et al., 2011a, 2013). From left to right, sequence includes depth, sedimentological units, core photograph, facies, magnetic susceptibility, TIC (Total Inorganic Carbon), TOC (Total Organic Carbon), TOC/TN ratio and selected mineralogy (Cl=clay minerals, Gy=Gypsum, Qz+Pl=Quartz + Plagioclases, Cc= calcite) and age model. Also shown, bathymetric map and location of the sediment core.

Figure 5. Clastic dominated littoral facies and massive/graded turbidites in the sedimentary sequence of Lake Taravilla (modified from Moreno et al., 2008). From left to right, sequences include depth, sedimentological units, core photograph,

facies, magnetic susceptibility, lightness (core 2A) and also TIC (Total Inorganic Carbon), TOC (Total Organic Carbon) and TOC/TN ratio (core 1A) and age model. Also shown, bathymetric map and location of the sediment cores.

Figure 6. Littoral facies in Lake La Parra (modified from Barreiro-Lostres, 2012). From left to right, sequence includes depth, sedimentological units, core photograph, facies, TIC (Total Inorganic Carbon), TOC (Total Organic Carbon), TOC/TN ratio and mineralogy (Dol+Qz+Pl= dolomite + quartz + plagioclase; Cc+Qz+CMg = calcite + aragonite + magnesium-rich calcite; Cl = clay minerals) and age model. Also shown, bathymetric map and location of the sediment core.

Figure 7. Littoral and distal facies in the sedimentary sequence of Lake La Basa de la Mora (modified from (Pérez-Sanz et al., 2013)). From left to right, sequence includes depth, sedimentological units, core photograph, facies, magnetic susceptibility, TIC (Total Inorganic Carbon), TOC (Total Organic Carbon) and TOC/TN ratio and age model. Also shown contour map and location of the sediment cores. Maximum water depth is 4 m.

Figure 8. Distal facies (varves, laminites and massive/graded) in Lake Montcortés (modified from Corella et al., 2011). From left to right, the sequence include depth, sedimentological units, core photograph, facies, magnetic susceptibility, TIC (Total Inorganic Carbon), TOC (Total Organic Carbon), TOC/TN ratio and mineralogy (Qz=quartz, Cc=calcite; Cl=clay minerals; Gy=gypsum) and age model. Also shown bathymetric map and location of the sediment cores.

Figure 9. Distal and littoral facies in Lake Zoñar (modified from Martín-Puertas et al., 2008). From left to right, both sequences include depth, sedimentological units, core photograph, facies, magnetic susceptibility, TIC (Total Inorganic Carbon), TOC (Total Organic Carbon), TOC/TN ratio and mineralogy (Qz=quartz, Cc=calcite; Ar= aragonite, Gy=gypsum; Cl=clay minerals) and age model. Also shown bathymetric map and location of the sediment cores.

Figure 10. Microphotographs of laminated carbonates. A. Varve sequences in Montcortès (XN light) and Zoñar (PN light). B. SEM photographs of endogenic and clastic carbonates. C. Fining-upward and coarsening-upward textures in calcite laminae from Zoñar varves.

Figure 11. Distal facies with gypsum-rich sediments (laminites) and littoral facies in Lake Estanya (modified from Morellón et al., 2010). From left to right, sequence includes depth, sedimentological units, core photograph, facies, magnetic susceptibility, TIC (Total Inorganic Carbon), TOC (Total Organic Carbon) and TOC/TN ratio and mineralogy and age model. Also shown bathymetric maps and location of the sediment cores.

Figure 12. Distal facies (laminites, varves, massive and graded) in Lake Arreo (modified from Corella et al., 2011). From left to right, sequence includes depth, sedimentological units, core photograph, facies, magnetic susceptibility, TIC (Total Inorganic Carbon), TOC (Total Organic Carbon), TOC/TN ratio and mineralogy

(Qz=quartz, Cl=clay minerals, Cc=calcite;Dol= dolomite; Gy=gypsum) and age model. Also shown bathymetric maps and location of the sediment core.

Figure 13. Rhythmites and laminated facies in the Lake Enol sequence (modified from Moreno et al., 2010). From left to right, sequences include depth, sedimentological units, core photograph, facies, magnetic susceptibility, lightness, bulk density, TIC (Total Inorganic Carbon) and TOC (Total Organic Carbon) and age model. Also shown contour map and location of the sediment cores.

Figure 14. Distal facies (laminites and homogeneites) in Lake Banyoles. From left to right, sequence includes depth, sedimentological units, core photograph, facies, Ligthness, TIC (Total Inorganic Carbon) and TOC (Total Organic Carbon) and age model. Also included bathymetric map and location of the sediment cores.

Figure 15. A. A 3-D model illustrating the hydrologic settings of Iberian Karstic lakes. The lines with numbers correspond with the possible location of the cross-sections on B. B. Depositional environments in Iberian karst lakes: palustrine environments are well developed in Taravilla (higher alluvial influence) and Arreo (lower alluvial influence). Littoral carbonates are well developed in Arreo, Estanya, and Banyoles and during the mid Holocene in Montcortès. Distal-profundal facies occur in most lakes, although significant development of varves only in Montcortès and Zoñar. Sinkholes with active groundwater input only occur in Banyoles.

Figure 16. Relationships among selected morphometric (lake and watershed surface area, maximum depth, lake surface/depth ratio), surface hydrology and salinity (electric conductivity) parameters of Iberian Karst lakes. A. Lake and watershed surface plot identifies single sinkholes (Tejo and La Parra) and complex large basins (Banyoles and Zoñar) at both ends of the spectrum; most lakes with smaller surface area have larger watersheds. B. Except for complex basin (> 30 ha lake surface), smaller lakes are usually deeper for both categories: lakes < 5 ha, and between 5-20 ha. C. Surface hydrology (1. Permanent outlet, 2. Ephemeral outlet; 3. No outlet) versus Electric Conductivity. High mountain lakes (Enol and Marboré) have the lowest EC values and lakes with no surface outlet (Estanya and Zoñar) the highest. However, high EC values occur in all hydrologic categories, and low EC values occur in lakes with no outlet but with strong groundwater input (La Parra, Tejo). D. Surface/Depth - EC plot does not show trends between morphometry and lake salinity although data are grouped in three categories: smaller and deeper lakes (low S/D ratios) have lower EC; lakes with intermediate values show a negative trend between S/D and EC; higher EC values occur in larger lakes.

Figure 17. A classification of Iberian Karstic lakes based on surface hydrology and sediment input.

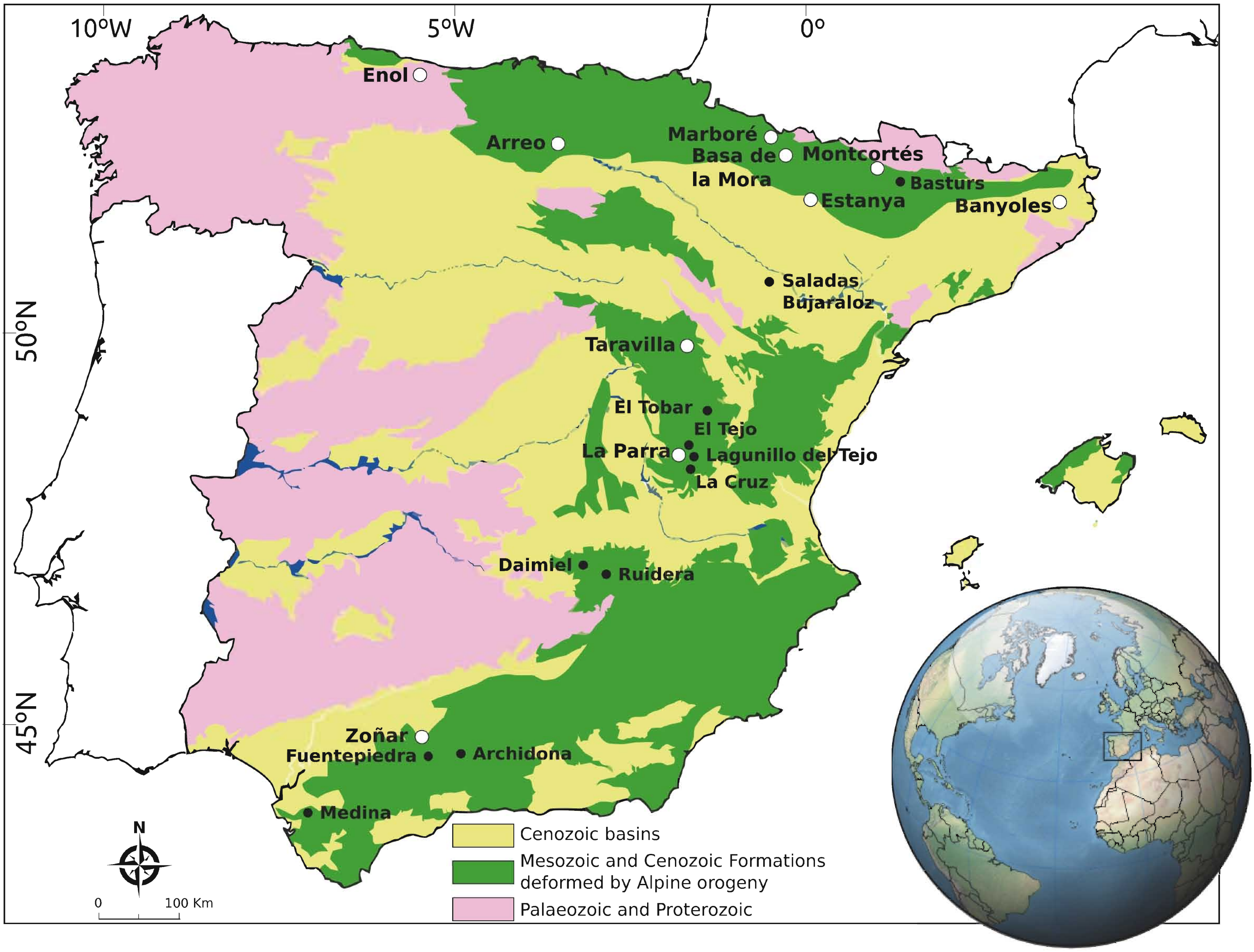
Table 1. Main characteristics of selected Iberian karst lakes, including physical, limnological and hydrochemical parameters and main literature references. Hydrology classification: 1. Open (through-flowing) lake (Water input >> Water output), permanent surface outflow; 2. Open lake (Water input > water output), seasonal outflow; 3. Closed lake (Water input < water output); no surface outflow. Geologic setting: 1. Glaciated terrain; 2. Fluvial environment with tufa dams; 3. Sinkhole in dominant carbonate formations; 4. Sinkhole in carbonate/gypsum formations

Lake	Geologic setting	Location	Altitude (m asl)	Surface Area (ha)	Maximum depth (m)	Watershed surface area (ha)	Hydrochemistry	Thermal regime	Surface Hydrology	Main References
Banyoles	3	42º1'N; 2º4'E	173	118	40 (80)	1142	Alkalinity: 3.87 meq L^{-1} pH = 7-8.2; $[SO_4^{2-}] > [HCO_3^{2-}] > [Ca^{2+}]$ EC = 900-2000 µS cm-1	Monomictic with meromictic sub-basins	1: Open; permanent inlet/outlet	Juliá, (1980) Valero-Garcés et al., (1998) Höbig et al. (2012)
El Tejo	3	39°N, 1°52'W	1000	1,5	27	4	Alkalinity= 3.05 meq L^{-1} pH = 8.7; $[HCO_3^{2-}] > [Ca^{2+}]$ EC = 540 µS cm-1	Monomictic to meromictic	3: Closed; Endorheic	This paper
El Tobar	4	40º32'N; 3º56'W	1200	16.2 ha	Holomictic: 12 (Meromictic: 20)	129	Alkalinity= 2.12 meq L^{-1} Mixolimnion: $([HCO_3^{2-}] > [Ca^{2+}]-[Mg^{2+}]$ pH = 8; EC=600 µS cm-1 Monimolimnion: Alkalinity= 4.33 meq L^{-1} $[NaCl^{1-}] > [Ca^{2+}] > [Mg^{2+}] > [SO_4^{2-}]$ EC = 2000 µS cm-1	Meromictic	2:Open; permanent inlet/outlet	Vicente et al. (1993)
La Parra	3	39º59'N, 1º52'W	1000	1.13	17.5	20	Alkalinity= 6.0 meq L^{-1} pH = 8.3; $[HCO_3^{2-}] > [Ca^{2+}]$ EC=335 µS cm-1	Holomictic	3: Closed; Endorheic	Barreiro-Lostres et al. (2011, 2013)
Taravilla	2	40°39' N 1°58' W	1100	2.11	12	550	Alkalinity = 2.92 meq L^{-1} pH = 7.8; $[Ca^{2+}] > [HCO_3^{2-}] > [SO_4^{2-}]$ EC =550 µS cm-1	Holomictic	1: Open; permanent inlet/outlet	Valero-Garcés et al. (2008)
Enol	1	43º11´N 4º09'W	1070	12.2	22	150	Alkalinity = 2.4 meq l-1; pH = 7.7–8.2 $([HCO_3^{2-}] > [Ca^{2+}] > [SO_4^{2-}]$ EC: 202 µS cm-1	Monomictic	Open; permanent inlet/outlet	Moreno et al., (2011)
Marboré	1	00º23´ E, 42º41´ N	2592	14.3	27	137	Alkalinity = 0.8 meq L^{-1}; pH = 7- 8.5 EC: 54.5 – 72.0 µS/cm;	Cool monomictic	1: Open; permanent inlet/outlet	Salabarnada, (2011)
Arreo	4	42º46´ N, 2º59´ W	657	6.57	24.8	287	Alkalinity = 4.18 meq L^{-1} ; pH= 7.6 – 8.2 $[Ca^{2+}] > [Mg^{2+}] > [Na^{+}] > [SO_4^{2-}]$ EC: 703-1727 µS/cm	Monomictic	2: Open; seasonal inlet/outlet	Corella, (2011)a, (2013)

Montcortés	3	42º 19´ N, 0º 59´ E	1027	9.3	30	300	Alkalinity = 2.5- 3.5 meq L^{-1} ; pH = 7-8.5 $[HCO_3^{2-}]>[Ca^{2+}]>[SO_4^{2}]$ EC = 372 µS/cm	Meromictic	1: Open; permanent inlet/outlet	Corella et al., (2011b; 2012)
Estanya	3	42°02' N, 0°32' E	670	18.83	20	106	Alkalinity = 2 -3.5 meq L^{-1} ; pH = 7.4 – 7.6 $[SO_4^{2-}]>[Ca^{2+}]> [Mg^{2+}]$ EC = 3440 µS/cm	Monomictic	3: Closed; Endorheic	Morellón et al., (2009)
Zoñar	3	37º29'00''N, 4º41'22'' W	300	37	14.5	876	Alkalinity = 3 – 5 meq L^{-1} pH = 7.1 -8.4 $[Cl^{-}]>[HCO_3^{2-}]> [SO_4^{2-}]>[Na^{+}]$ EC = 2500-3000 µS cm-1	Monomictic	3: Closed; Endorheic	Martín-Puertas et al. (2008)
Basa de la Mora	1	42º32' N 0º19' E	1914	5.5	3.5	462	Alkalinity= 0.6 meq $L^{-;}$ pH= 8.6 $[Ca^{2+}]>[SO_4^{2-}> [Mg^{2+}]$ EC = 215 µS cm-1	Holomictic	2: Open; seasonal inlet/outlet	Pérez-Sanz et al. (2013)

Table 2. Facies and Facies Associations in Iberian karst lakes, including sedimentology and depositional processes and environments

FACIES	*Sedimentological features*	*Depositional Processes and Environments*
PALUSTRINE FACIES ASSOCIATION (P)		
P.C. Coarse clastic.	Up to 25 cm thick gravel beds organized in fining-upwards sequences, composed of bedrock and/or tufa clasts embedded within a carbonate and quartz sandy matrix with abundant plant remains	Wetland, strong alluvial influence
P.F. Fine clastic.	Cm to dm thick carbonate-rich coarse silts with edaphic textures, bioturbation and evidences of subaerial exposure	Wetland, low alluvial influence
P.O. Organic- rich.	Cm to dm thick, massive organic-rich silts with abundant plant remains	Wetland
LITTORAL FACIES ASSOCIATION (L)		
L.C. Coarse clastic.	Meter thick fining upward sequences composed of carbonate-rich silty-sand to coarse sand; massive to faintly laminated carbonate silt and massive to faintly laminated, dark grey carbonate silt and mud. Occasionally centimetre-thick silt layers with abundant organic rests are also deposited.	Littoral, high energy, variable alluvial influence
L.F. Massive to banded carbonate-rich silts and muds.	Dm- to cm thick layers with variable amounts of silicates and carbonates, and significant content of biogenic carbonate (*Chara*, gastropods) and plant remains. Subfacies defined by banded textures with biogenic carbonate content	Littoral, low energy, low alluvial influence
L.F (s). Massive to banded carbonate-rich silts and muds with mottling and evaporite nodules.	. Gypsum nodules and bioturbation features (root traces, coarse plant remains, mottling, mixed sediment textures) are common. Abundant gastropods and large mm to cm-size terrestrial plant remains	Littoral with subaerial exposure and saline stages
DISTAL FACIES ASSOCIATION (D)		
D.B. Banded to laminated carbonate silts.	Dm- thick layers with silty fraction composed of carbonates, quartz and abundant clay-rich matrix. Minor amounts of feldspars, high-magnesium calcite (HMC) and gypsum. Common biogenic components as aggregates of amorphous lacustrine organic matter, macrophyte remains and diatoms	Distal, variable bottom conditions (bioturbation, oxygenation)
D.L. Finely laminated		
D.L.V. Varves		
D.L.V (c). With calcite laminae.	Sets of dark-brown laminae (lacustrine organic matter, diatoms), yellowish mm-thick laminae (authigenic carbonates (calcite, aragonite, dolomite)), and rare grey carbonate silt laminae.	Distal, moderately deep, meromictic conditions
D.L.V (o). Without calcite laminae	Sets of mm-thick, brown to greenish, organic-rich laminae and mm-thick terrigenous grey silt layers.	Distal, Moderately deep, anoxic meromictic conditions
D.L.L. Laminites		
D.L.L(g). Gypsum- rich.	Sets of cm-thick alternating yellowish bands of gypsum with reworked biogenic carbonates, dark brown diatom ooze with lacustrine organic matter and lenticular gypsum and grey massive clays.	Distal, deep saline with anoxic bottom conditions
D.L.L (o). Organic-rich.	Organic laminites are composed of amorphous lacustrine organic matter, diatoms and some macrophyte remains, with minor amounts of clay minerals, calcite, dolomite and quartz. In some cases (Zoñar, Estanya) includes laminated microbial mats.	Distal, shallow saline
D.L.R. Rhythmites.	Carbonate-poor, dm- to meter thick layers composed of laminae defined by grain size, from clay to coarse silt and sand.	Distal, periglacial to pro-glacial environments
D.M/G/H. Massive to Graded.	Cm- to dm- thick layers with high magnetic susceptibility, graded textures and mixed carbonate and silicate composition. Presence of biogenic components and common plant remains	Distal, floods and turbidite currents
D.G. Graded	. They occur as: dm-thick, laminated to banded intervals with regular, sharp contacts, and ii) cm to mm-thick laminae with diffuse and irregular contacts, constituted by massive, graded sediments.	
D.M. Massive	They occur as cm- thick, massive layers with sharp and erosive basal contacts.	Distal, floods and mass wasting processes
D.H. Homogeneites.	Cm to dm thick, grey, massive layers composed by fine-grained carbonate-rich silts	Distal, Resuspension of sediments from active spring discharge in sinkholes
GRAVITATIONAL FACIES (G)		
- G.F. **Convoluted.**	Thin intervals of laminated facies with convoluted, folded and distorted textures	Distal, slumps and gravitational deposits
- G.C. **Chaotic**.	Heterometric coarse facies with gravel size-clasts and heterometric sandy matrix	



10ºW
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Enol
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Marboré
Basa de
la Mora
Montcortés
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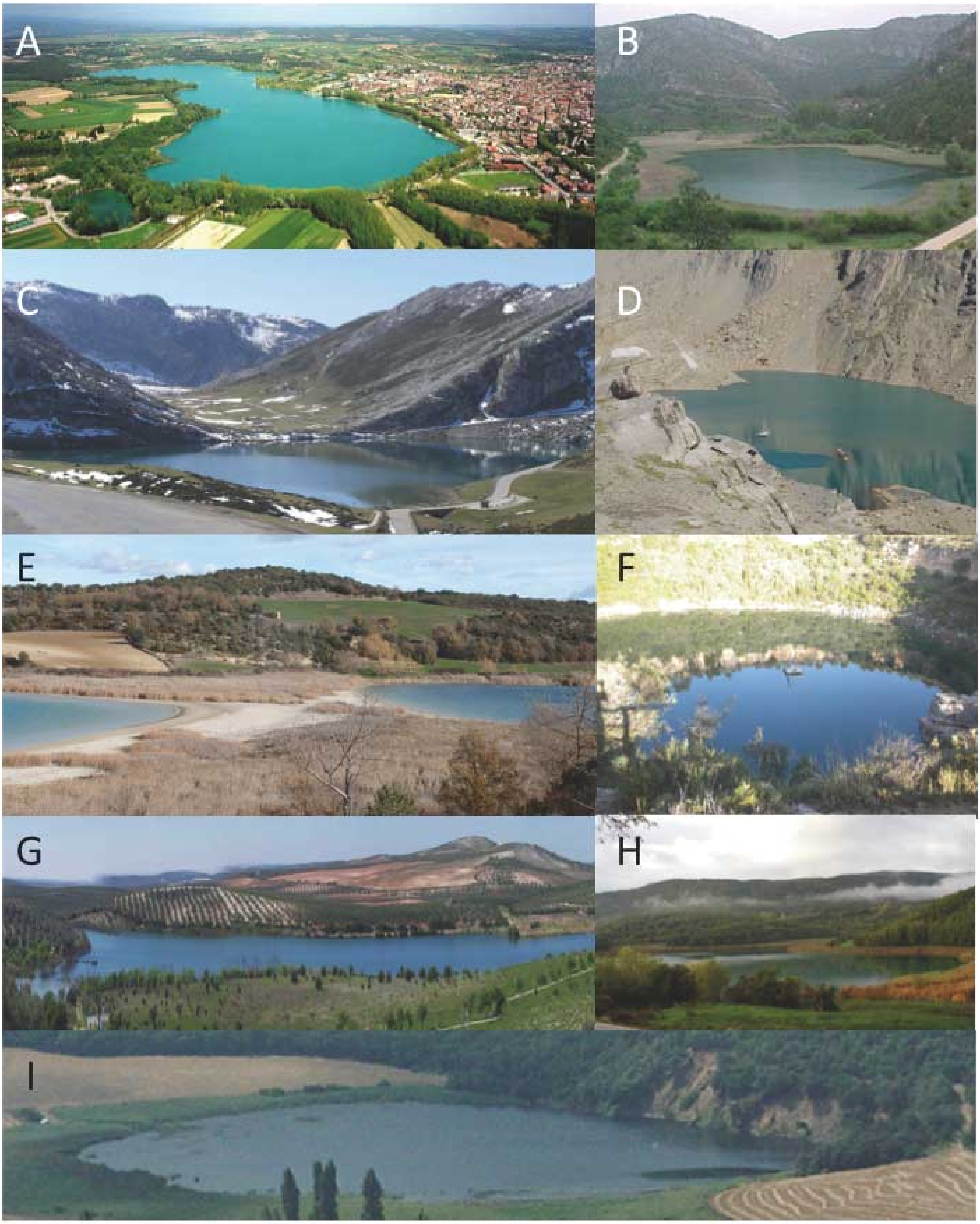
Estanya
Banyoles
Saladas
Bujaraloz
Taravilla
El Tobar
El Tejo
La Parra
Lagunillo del Tejo
La Cruz
Daimiel
Ruidera
Zoñar
Fuentepiedra
Archidona
Medina
N
0
100 Km
Cenozoic basins
Mesozoic and Cenozoic Formations deformed by Alpine orogeny
Palaeozoic and Proterozoic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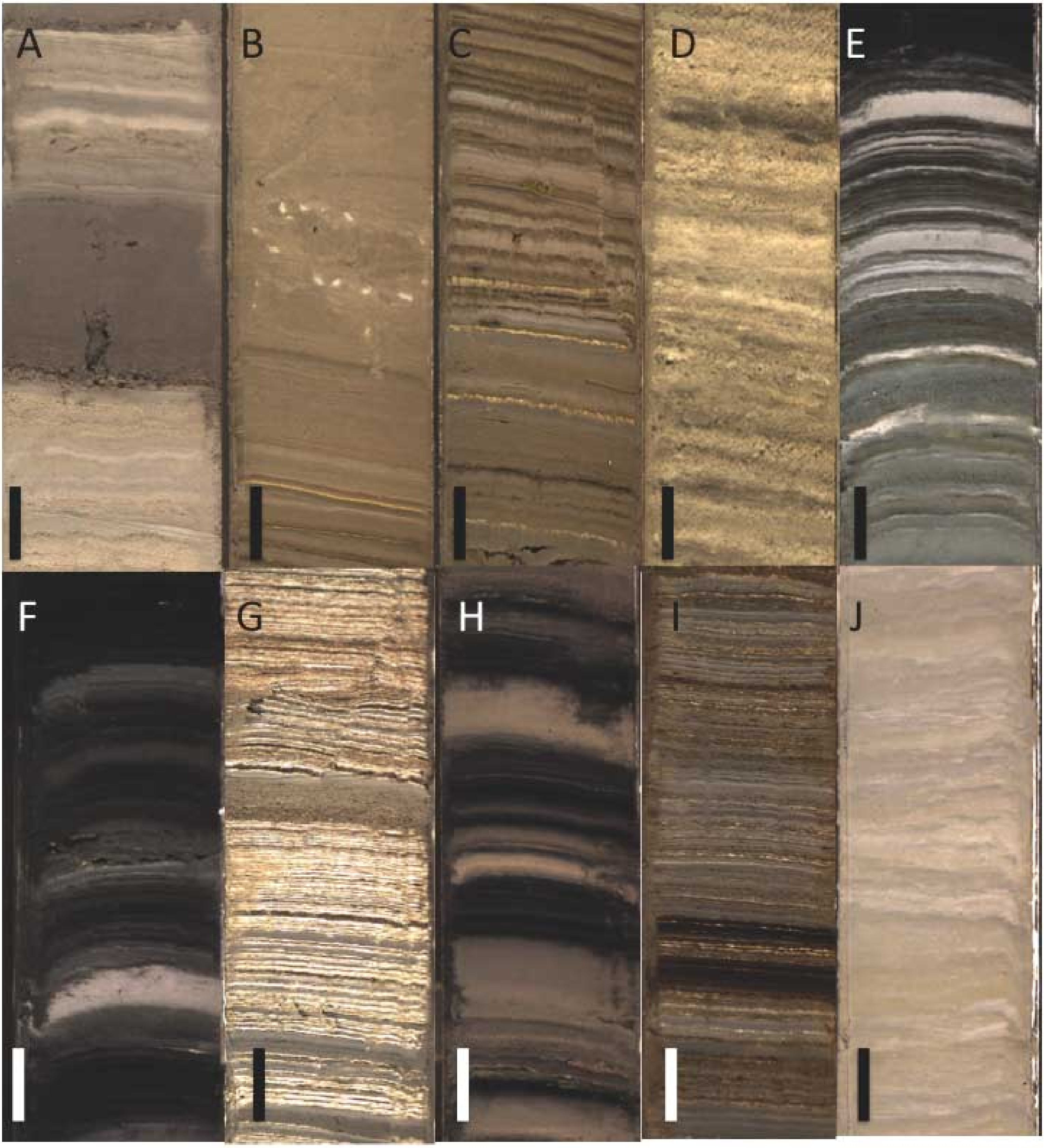
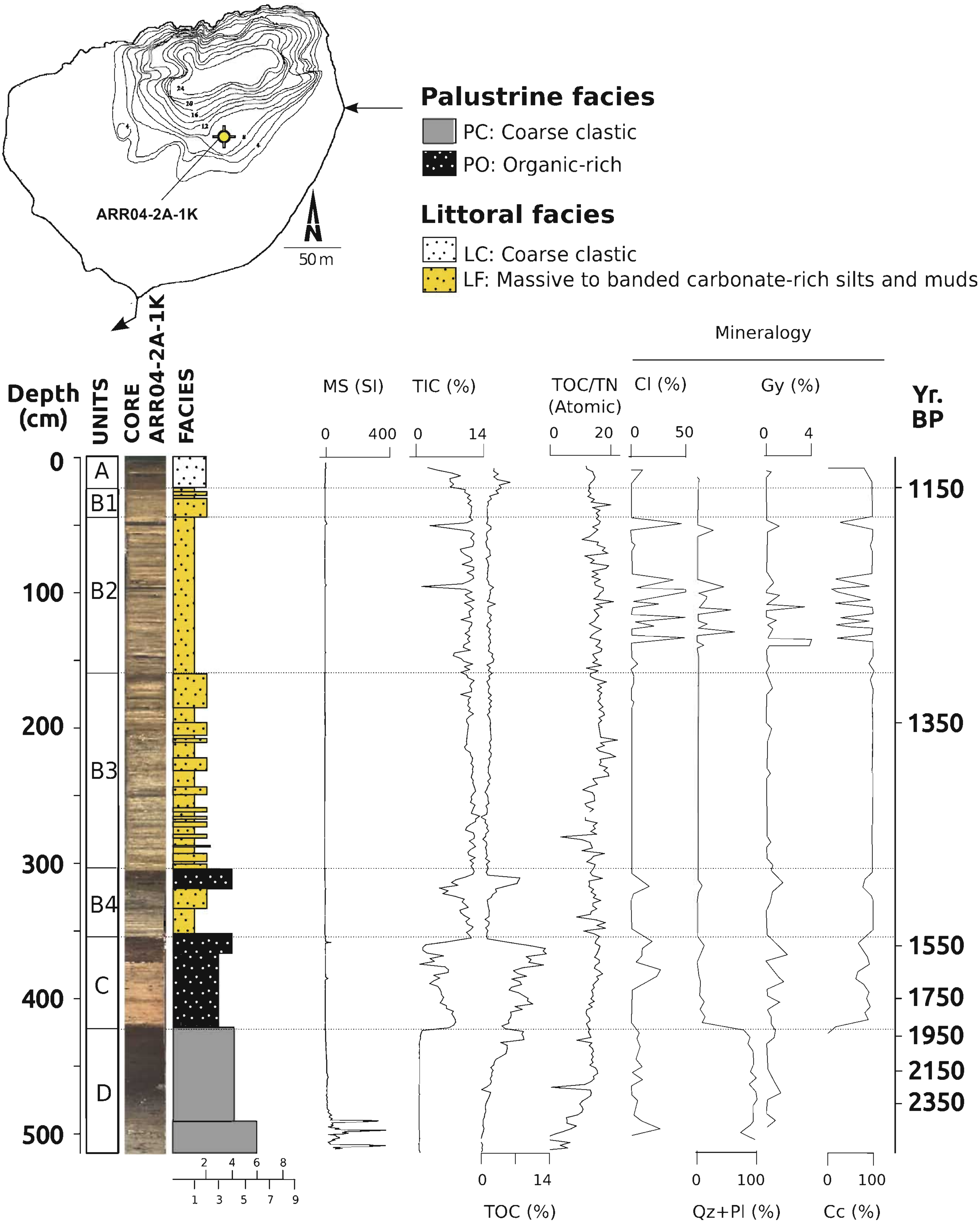
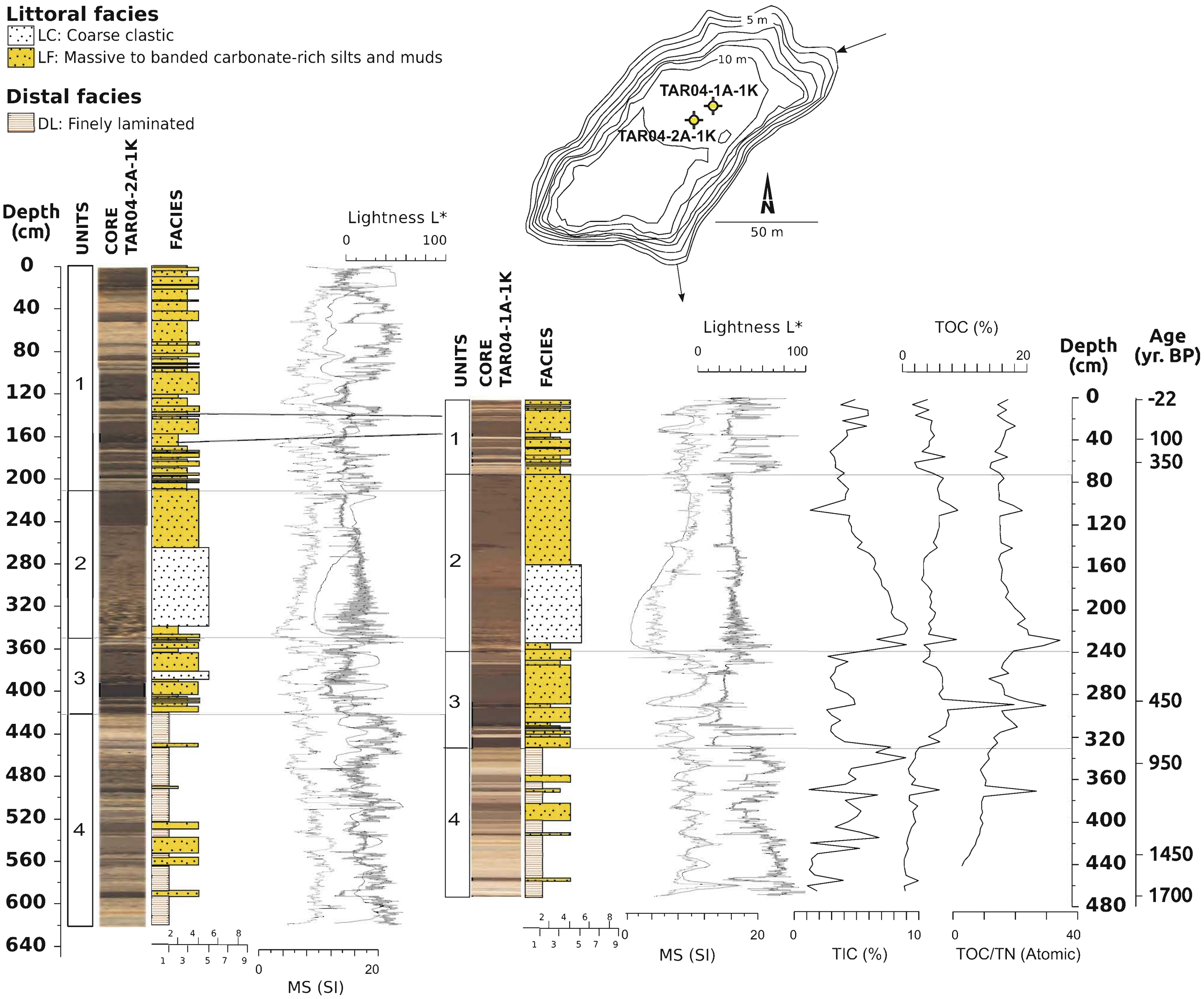
H
I

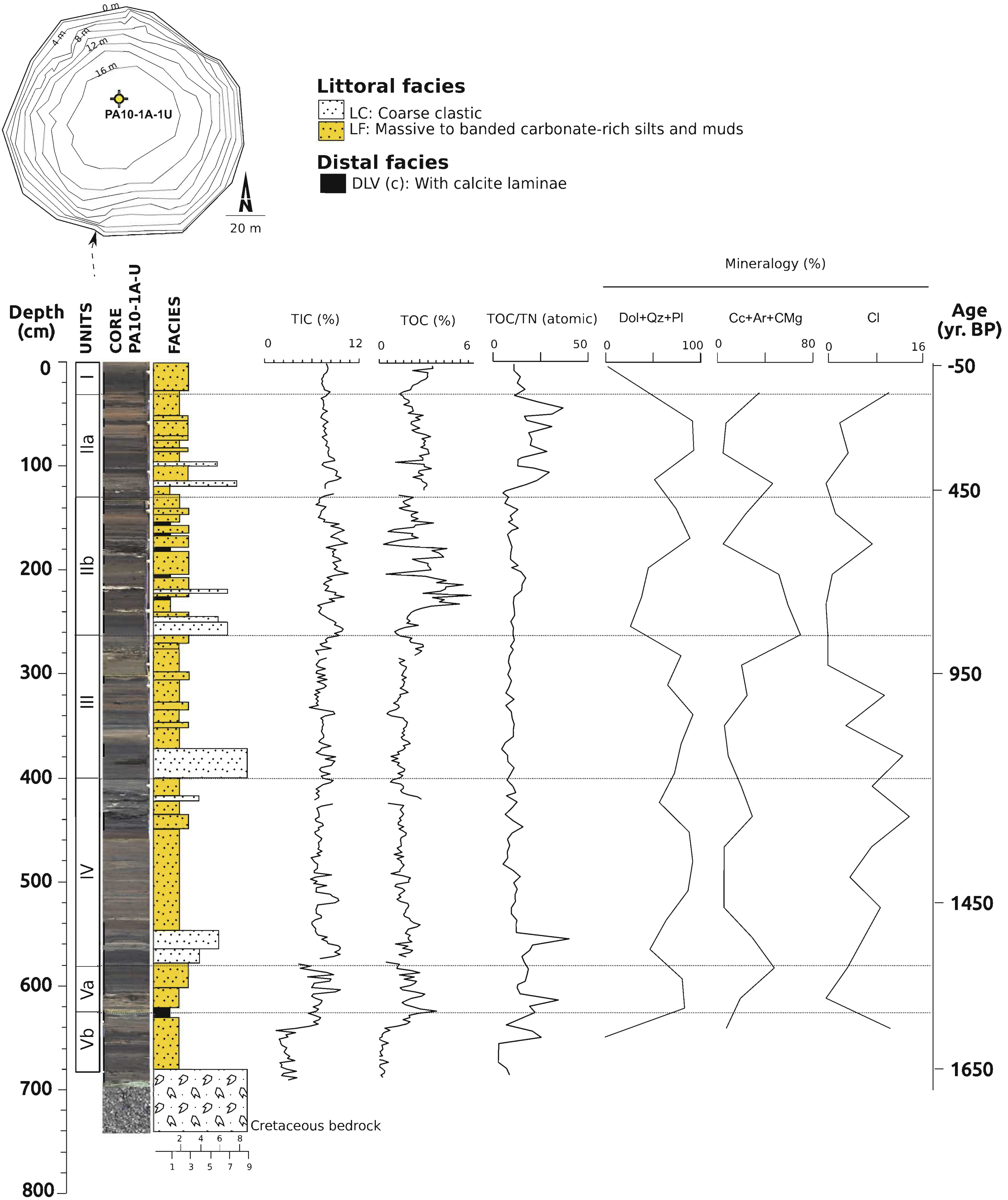

A
B
C
D
E
F
G
H
I
J



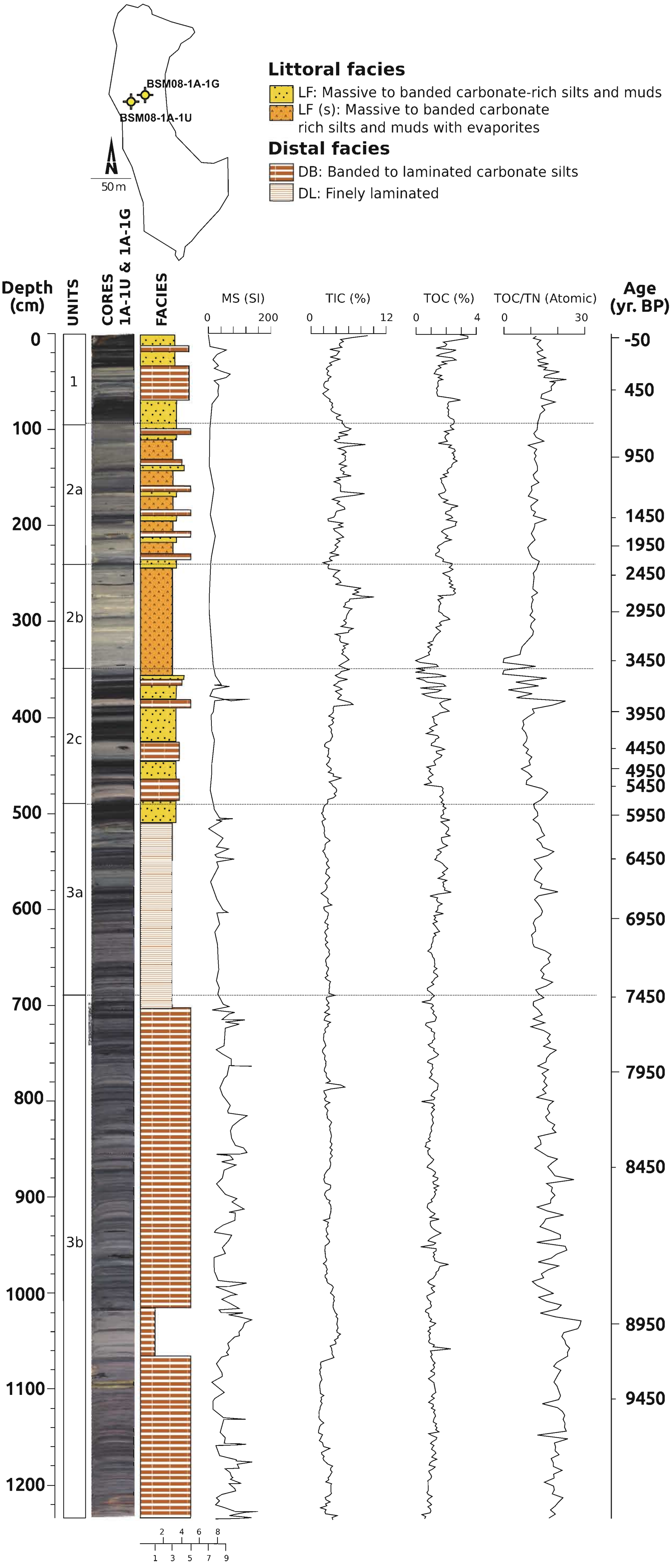
ARR04-2A-1K
50 m
Palustrine facies
PC: Coarse clastic
PO: Organic-rich
Littoral facies
LC: Coarse clastic
LF: Massive to banded carbonate-rich silts and muds
Mineralogy
Depth (cm)
UNITS
CORE ARR04-2A-1K
FACIES
MS (SI)
TIC (%)
TOC/TN (Atomic)
Cl (%)
Gy (%)
Yr. BP
A
B1
B2
B3
B4
C
D
1150
1350
1550
1750
1950
2150
2350
TOC (%)
Qz+Pl (%)
Cc (%)

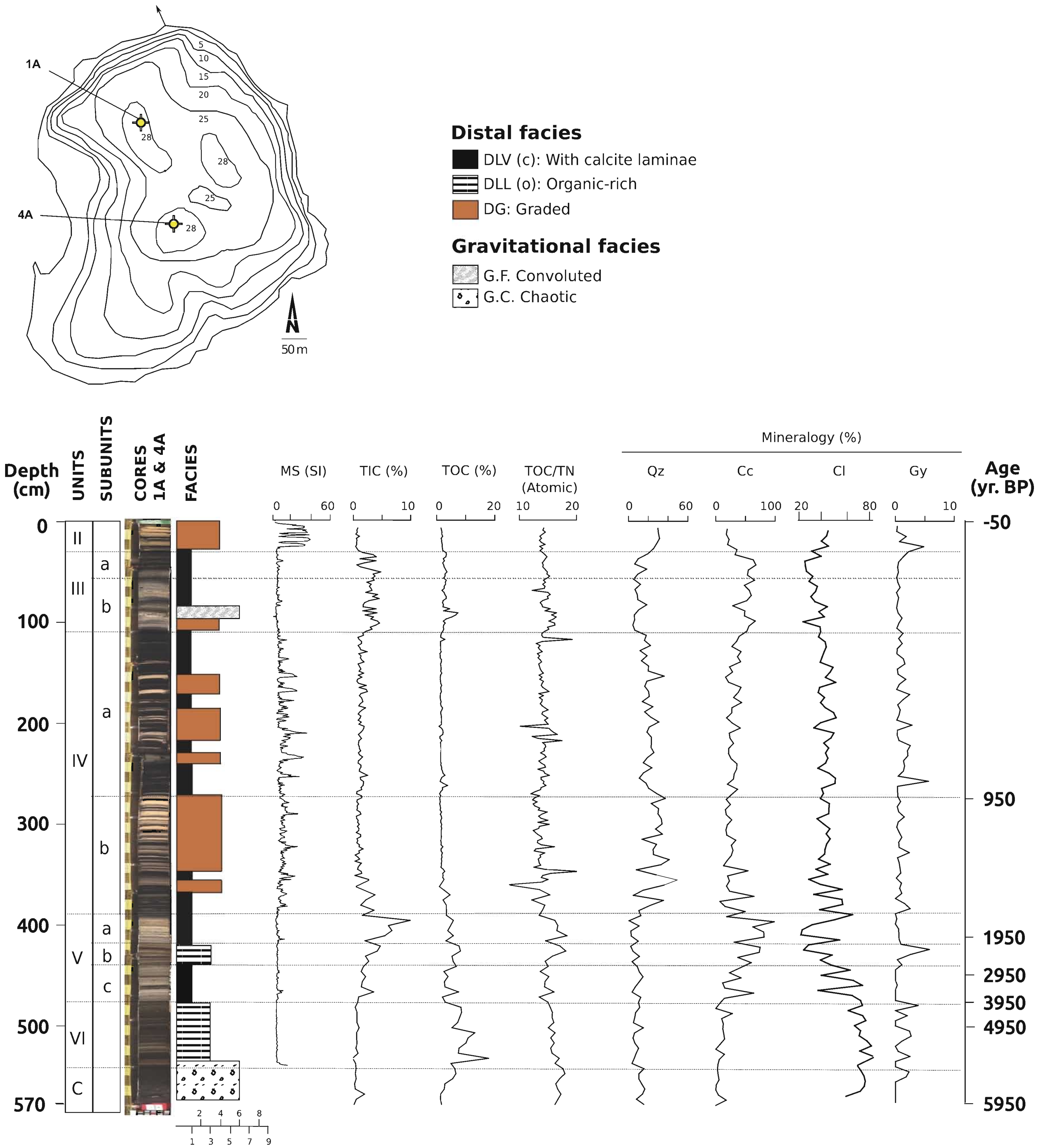


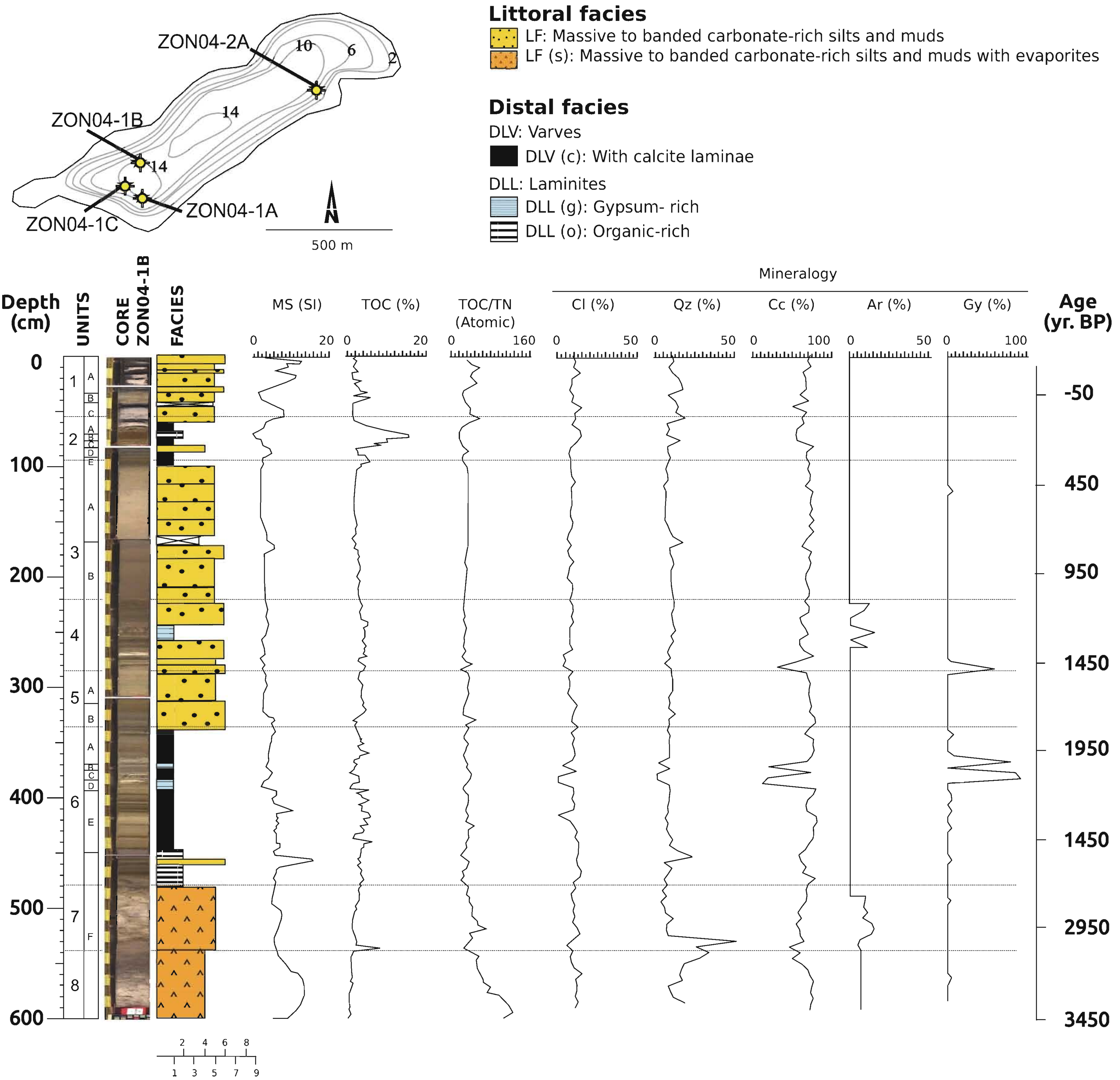
Littoral facies
LC: Coarse clastic
LF: Massive to banded carbonate-rich silts and muds
Distal facies
DL: Finely laminated
5 m
10 m
TAR04-1A-1K
TAR04-2A-1K
50 m
Depth (cm)
UNITS
CORE TAR04-2A-1K
FACIES
Lightness L*
MS (SI)
CORE TAR04-1A-1K
TOC (%)
TIC (%)
TOC/TN (Atomic)
Age (yr. BP)
-22
100
350
450
950
1450
1700



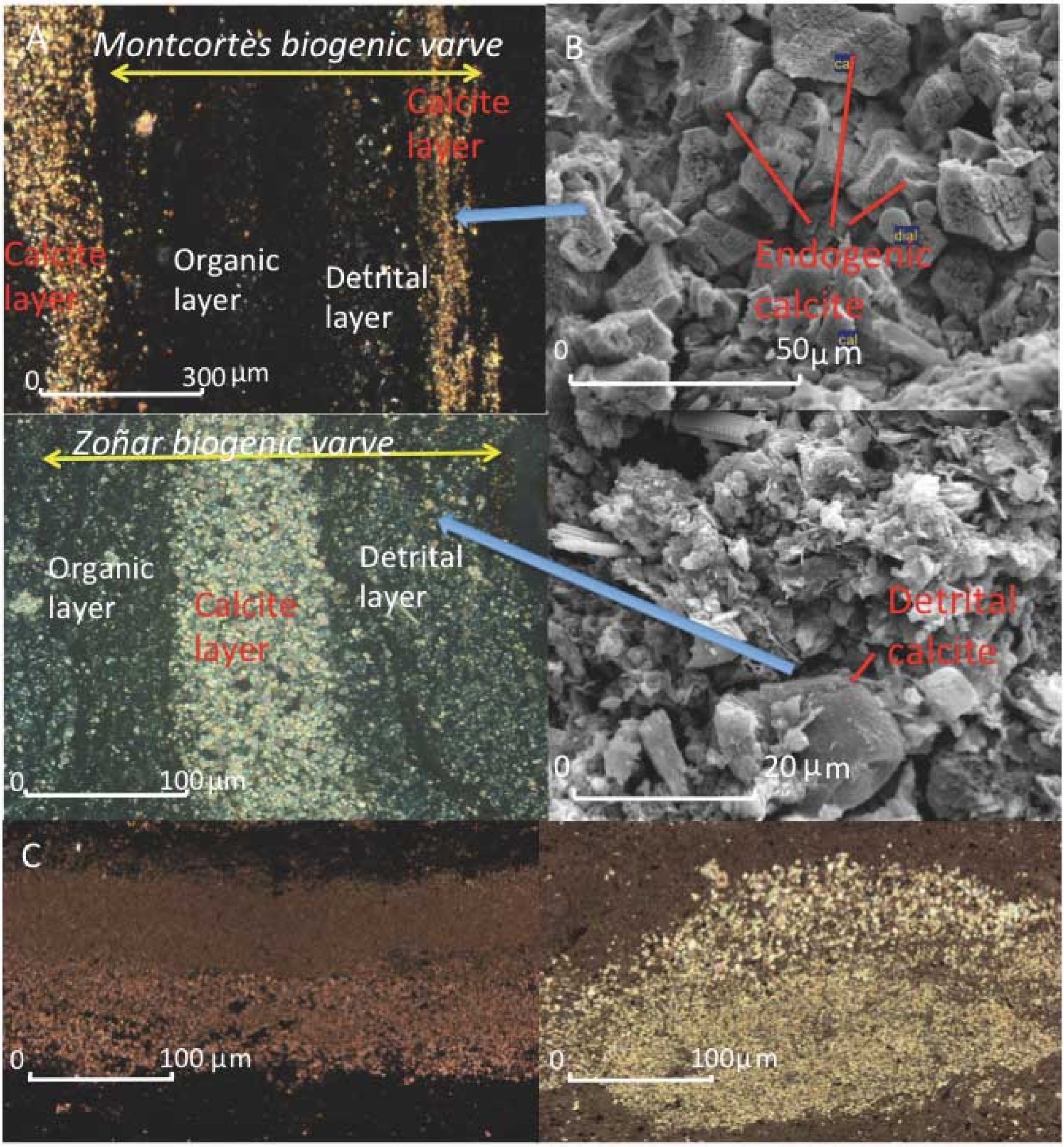
0 m
4 m
8 m
12 m
16 m
PA10-1A-1U
N
20 m
Littoral facies
LC: Coarse clastic
LF: Massive to banded carbonate-rich silts and muds
Distal facies
DLV (c): With calcite laminae
Mineralogy (%)
Depth (cm)
UNITS
CORE PA10-1A-U
FACIES
TIC (%)
TOC (%)
TOC/TN (atomic)
Dol+Qz+Pl
Cc+Ar+CMg
Cl
Age (yr. BP)
I
IIa
IIb
III
IV
Va
Vb
Cretaceous bedrock

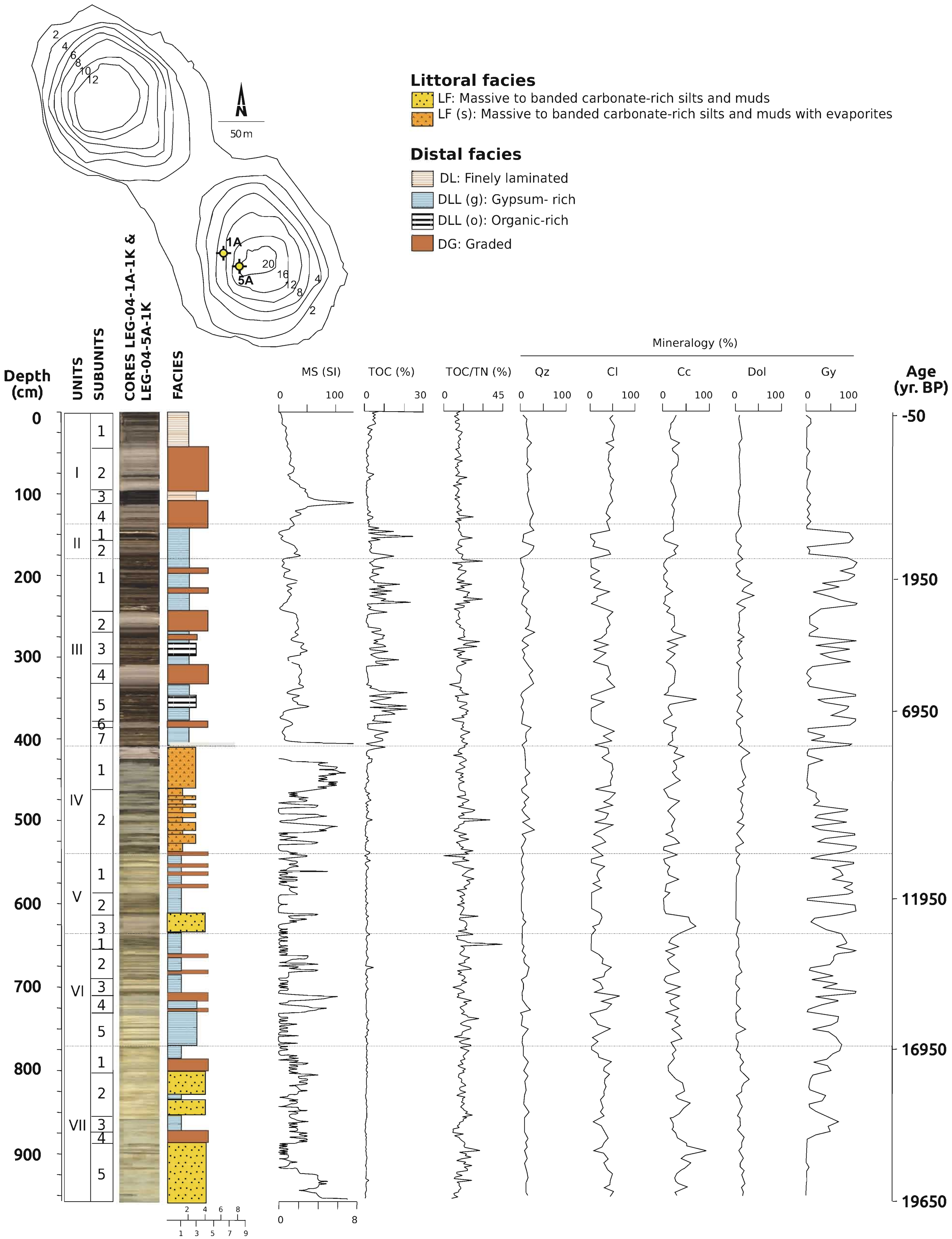

BSM08-1A-1G
BSM08-1A-1U
N
50 m
Littoral facies
LF: Massive to banded carbonate-rich silts and muds
LF (s): Massive to banded carbonate rich silts and muds with evaporites
Distal facies
DB: Banded to laminated carbonate silts
DL: Finely laminated
Depth (cm)
UNITS
CORES 1A-1U & 1A-1G
FACIES
MS (SI)
TIC (%)
TOC (%)
TOC/TN (Atomic)
Age (yr. BP)
1
2a
2b
2c
3a
3b
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
-50
450
950
1450
1950
2450
2950
3450
3950
4450
4950
5450
5950
6450
6950
7450
7950
8450
8950
9450


1A
4A
5
10
15
20
25
28
50 m
Distal facies
DLV (c): With calcite laminae
DLL (o): Organic-rich
DG: Graded
Gravitational facies
G.F. Convoluted
G.C. Chaotic
Depth (cm)
UNITS
SUBUNITS
CORES 1A & 4A
FACIES
MS (SI)
TIC (%)
TOC (%)
TOC/TN (Atomic)
Mineralogy (%)
Qz
Cc
Cl
Gy
Age (yr. BP)
II
III
IV
V
VI
C
a
b
c
-50
950
1950
2950
3950
4950
5950
0
100
200
300
400
500
570

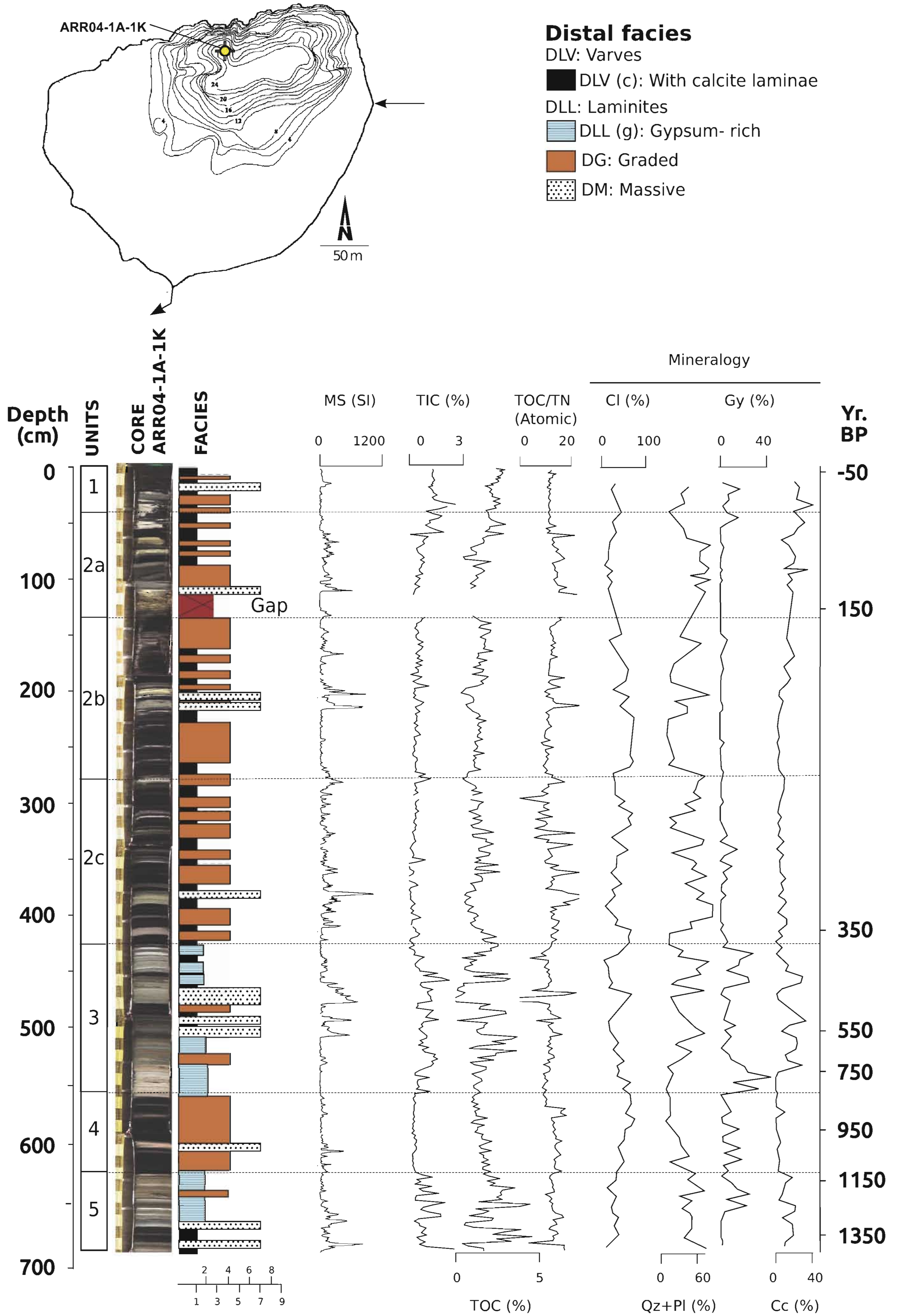


ZON04-2A
10
6
2
14
ZON04-1B
14
ZON04-1C
ZON04-1A
N
500 m
Littoral facies
LF: Massive to banded carbonate-rich silts and muds
LF (s): Massive to banded carbonate-rich silts and muds with evaporites
Distal facies
DLV: Varves
DLV (c): With calcite laminae
DLL: Laminites
DLL (g): Gypsum- rich
DLL (o): Organic-rich
Mineralogy
Depth (cm)
UNITS
CORE ZON04-1B
FACIES
MS (SI)
TOC (%)
TOC/TN (Atomic)
Cl (%)
Qz (%)
Cc (%)
Ar (%)
Gy (%)
Age (yr. BP)
0 20
0 20
0 160
0 50
0 50
0 100
0 50
0 100
0
100
200
300
400
500
600
1 2 3 4 5 6 7 8
A B C A B C D E A B A B A B C D E F
-50
450
950
1450
1950
1450
2950
3450
2 4 6 8
1 3 5 7 9

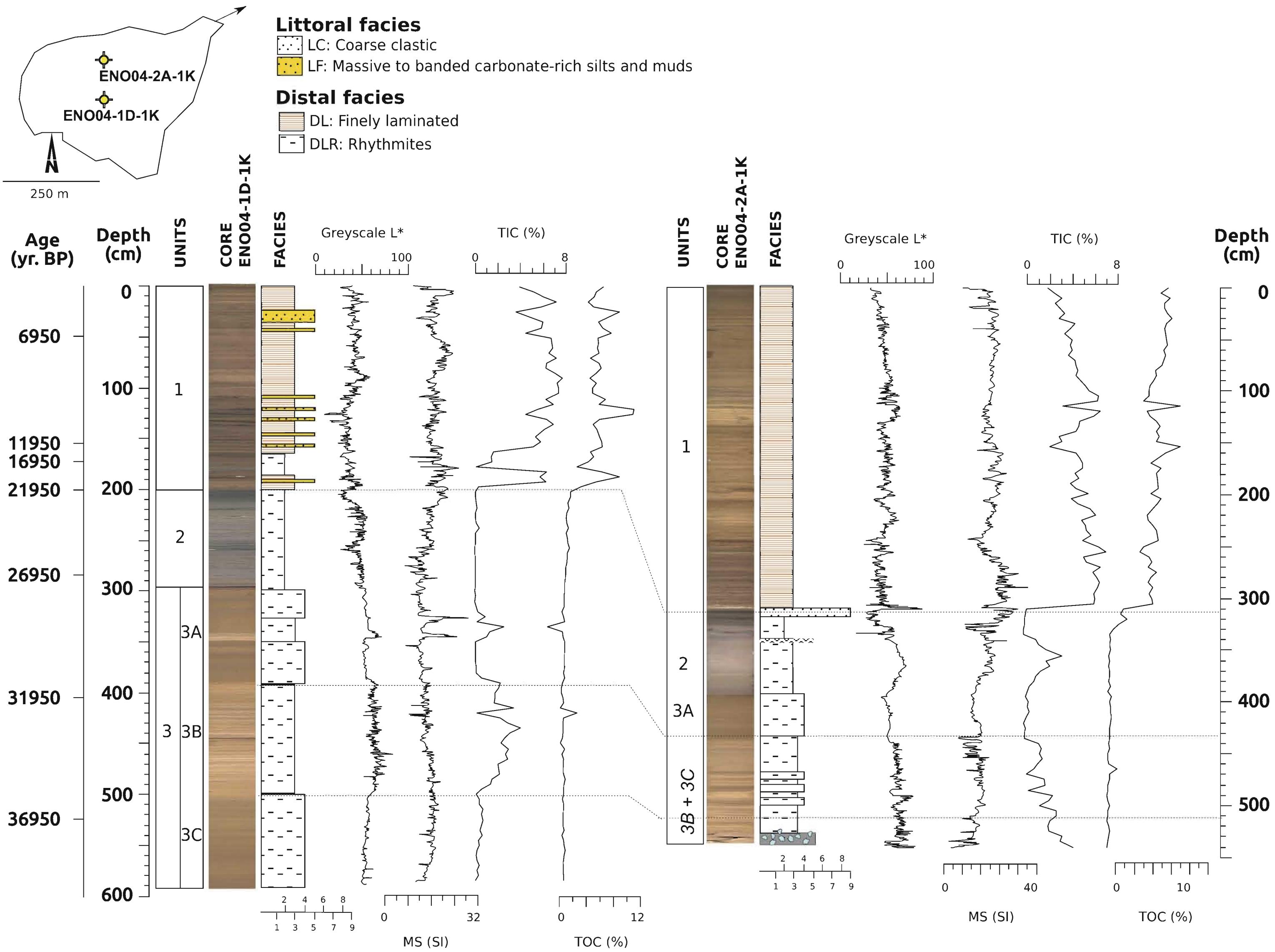

A
Montcortès biogenic varve
Calcite layer
Calcite layer
Organic layer
Detrital layer
0
300 µm
B
Endogenic calcite
0
50µm
Zoñar biogenic varve
Organic layer
Calcite layer
Detrital layer
0
100µm
Detrital calcite
0
20µm
C
0
100µm
0
100µm



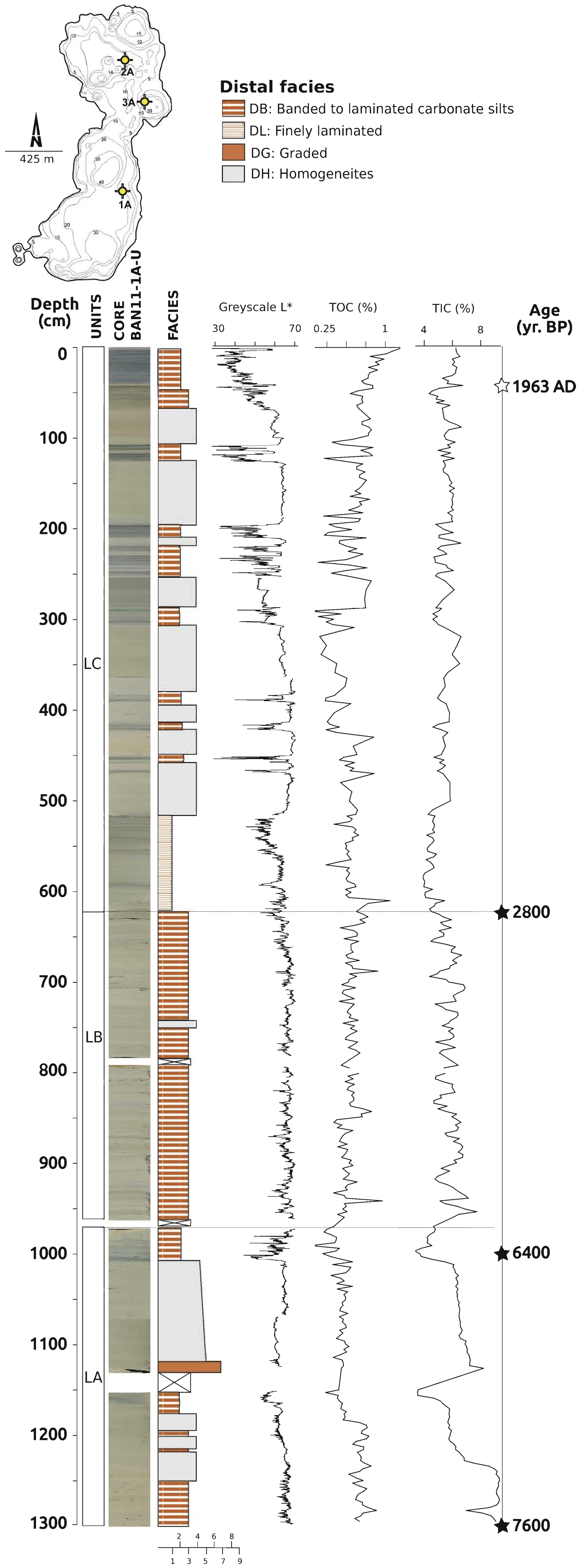
Littoral facies
LF: Massive to banded carbonate-rich silts and muds
LF (s): Massive to banded carbonate-rich silts and muds with evaporites
Distal facies
DL: Finely laminated
DLL (g): Gypsum- rich
DLL (o): Organic-rich
DG: Graded
50 m
1A
5A
Depth (cm)
UNITS
SUBUNITS
CORES LEG-04-1A-1K & LEG-04-5A-1K
FACIES
MS (SI)
TOC (%)
TOC/TN (%)
Mineralogy (%)
Qz
Cl
Cc
Dol
Gy
Age (yr. BP)
-50
1950
6950
11950
16950
19650



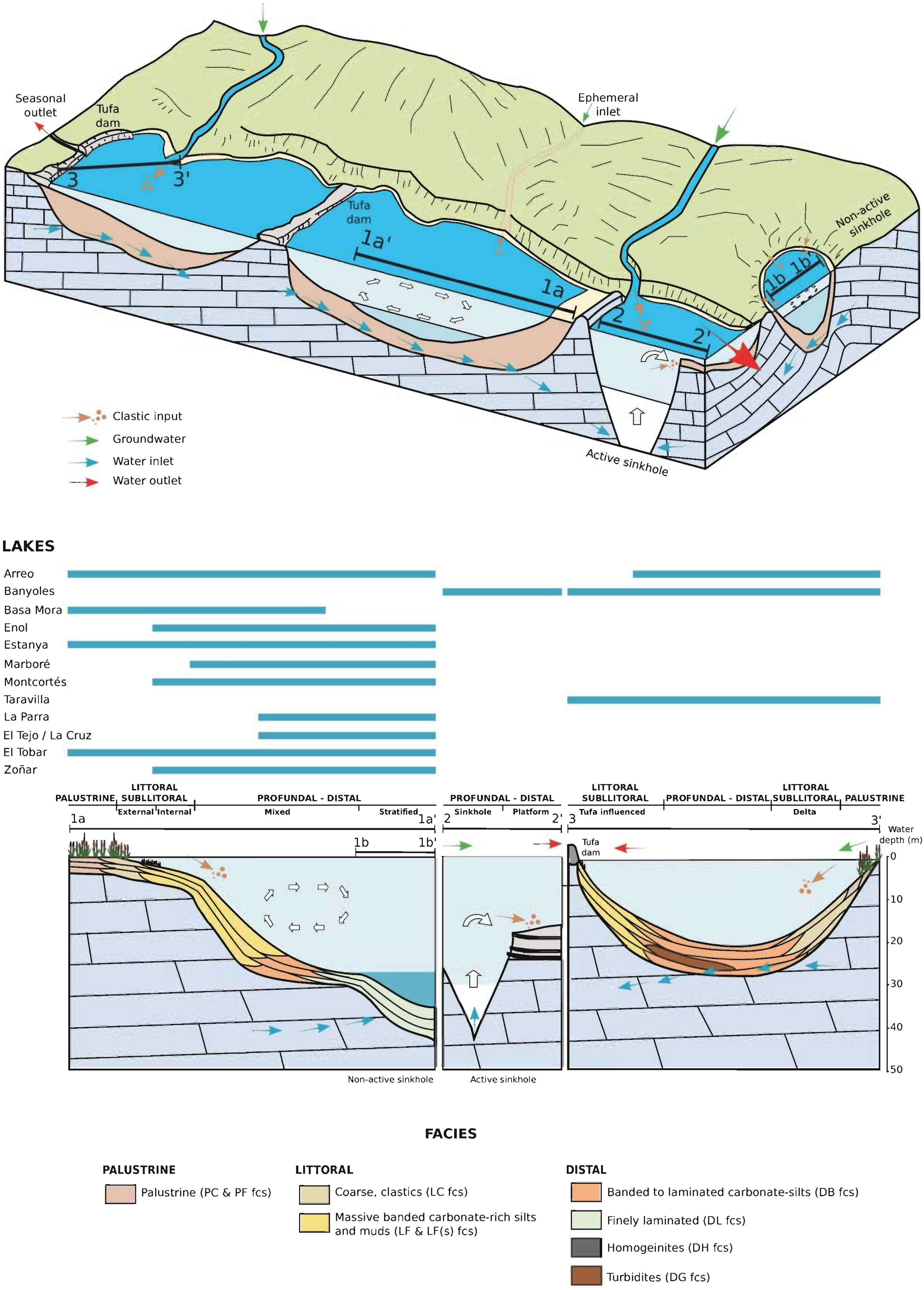
ARR04-1A-1K
50 m
Distal facies
DLV: Varves
DLV (c): With calcite laminae
DLL: Laminites
DLL (g): Gypsum- rich
DG: Graded
DM: Massive
Depth (cm)
UNITS
CORE ARR04-1A-1K
FACIES
MS (SI)
TIC (%)
TOC/TN (Atomic)
Mineralogy
Cl (%)
Gy (%)
Yr. BP
Gap
1
2a
2b
2c
3
4
5
TOC (%)
Qz+Pl (%)
Cc (%)

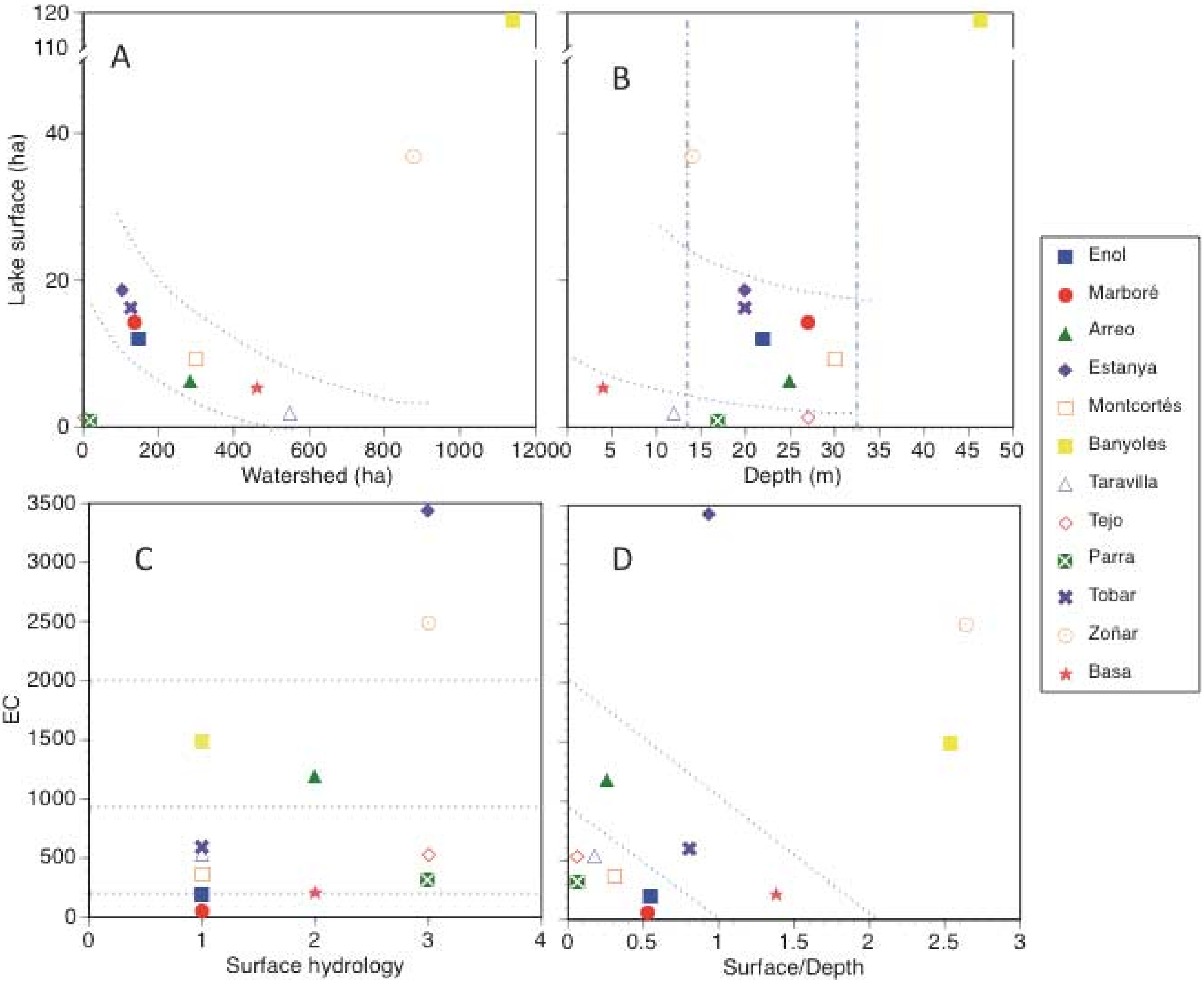


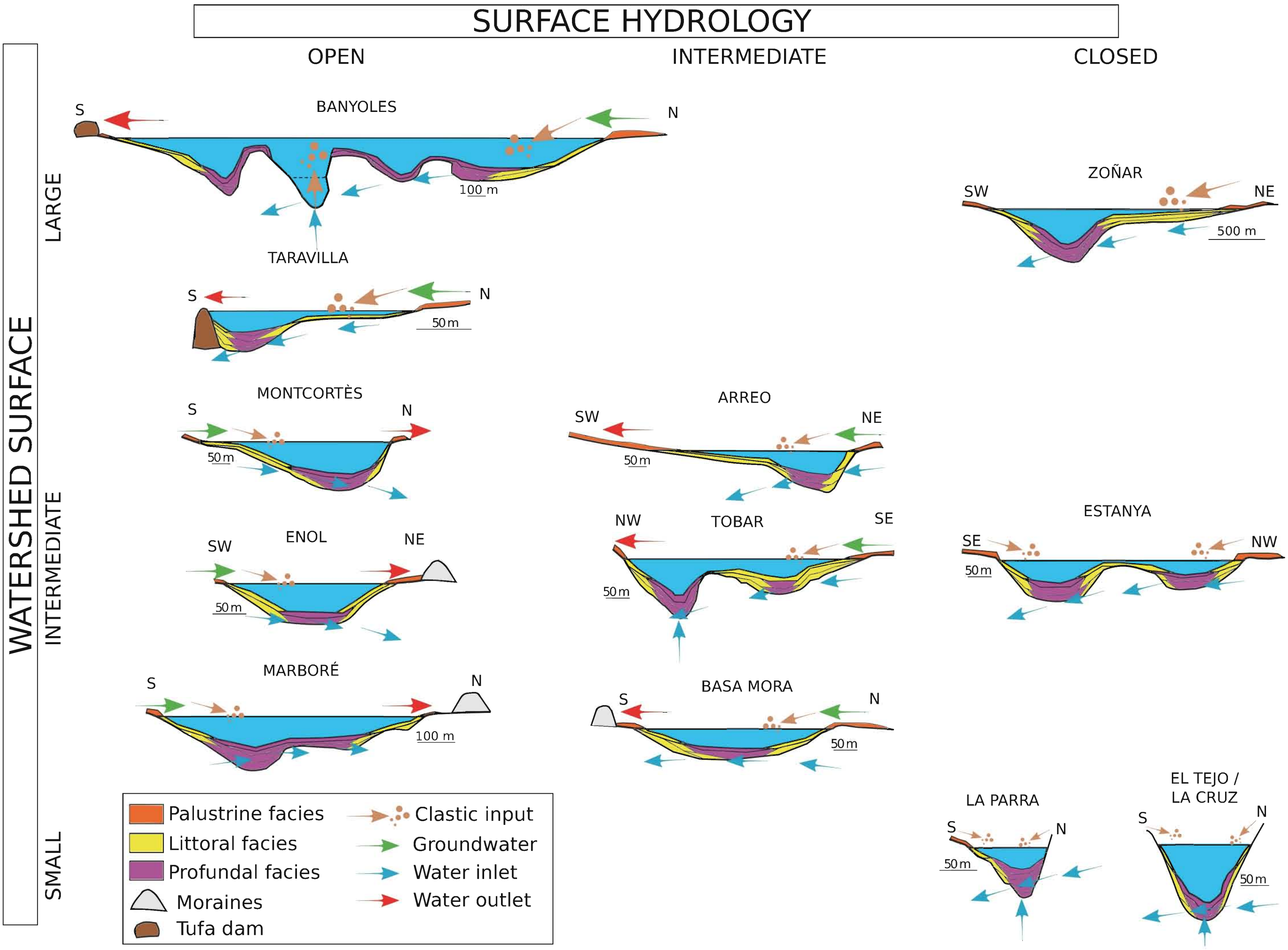
Littoral facies
LC: Coarse clastic
LF: Massive to banded carbonate-rich silts and muds
Distal facies
DL: Finely laminated
DLR: Rhythmites
ENO04-2A-1K
ENO04-1D-1K
250 m
N
Age (yr. BP)
Depth (cm)
UNITS
CORE ENO04-1D-1K
FACIES
Greyscale L*
TIC (%)
MS (SI)
TOC (%)
CORE ENO04-2A-1K
6950
11950
16950
21950
26950
31950
36950
3A
3B
3C
3B + 3C



2A
3A
1A
425 m
Distal facies
DB: Banded to laminated carbonate silts
DL: Finely laminated
DG: Graded
DH: Homogeneites
Depth (cm)
UNITS
CORE BAN11-1A-U
FACIES
Greyscale L*
TOC (%)
TIC (%)
Age (yr. BP)
LC
LB
LA
1963 AD
2800
6400
7600


Seasonal outlet
Tufa dam
Ephemeral inlet
Tufa dam
Non-active sinkhole
3
3'
1a'
1a
2
2'
1b
1b'
Active sinkhole
Clastic input
Groundwater
Water inlet
Water outlet
LAKES
Arreo
Banyoles
Basa Mora
Enol
Estanya
Marboré
Montcortés
Taravilla
La Parra
El Tejo / La Cruz
El Tobar
Zoñar
PALUSTRINE
LITTORAL SUBLLITORAL
External
Internal
PROFUNDAL - DISTAL
Mixed
Stratified
PROFUNDAL - DISTAL
Sinkhole
Platform
LITTORAL SUBLLITORAL
Tufa influenced
PROFUNDAL - DISTAL
LITTORAL SUBLLITORAL
Delta
PALUSTRINE
Water depth (m)
0
10
20
30
40
50
Tufa dam
Non-active sinkhole
Active sinkhole
FACIES
PALUSTRINE
Palustrine (PC & PF fcs)
LITTORAL
Coarse, clastics (LC fcs)
Massive banded carbonate-rich silts and muds (LF & LF(s) fcs)
DISTAL
Banded to laminated carbonate-silts (DB fcs)
Finely laminated (DL fcs)
Homogeinites (DH fcs)
Turbidites (DG fcs)


A
B
C
D
Lake surface (ha)
Watershed (ha)
Depth (m)
EC
Surface hydrology
Surface/Depth
Enol
Marboré
Arreo
Estanya
Montcortés
Banyoles
Taravilla
Tejo
Parra
Tobar
Zoñar
Basa



SURFACE HYDROLOGY
OPEN
INTERMEDIATE
CLOSED
WATERSHED SURFACE
LARGE
INTERMEDIATE
SMALL
BANYOLES
S
N
100 m
TARAVILLA
S
N
50 m
ZOÑAR
SW
NE
500 m
MONTCORTÈS
S
N
50 m
ARREO
SW
NE
50 m
ENOL
SW
NE
50 m
TOBAR
NW
SE
50 m
ESTANYA
SE
NW
50 m
MARBORÉ
S
N
100 m
BASA MORA
S
N
50 m
LA PARRA
S
N
50 m
EL TEJO / LA CRUZ
S
N
50 m
Palustrine facies
Littoral facies
Profundal facies
Moraines
Tufa dam
Clastic input
Groundwater
Water inlet
Water outlet