Local formation of varved sediments in a karstic collapse depression of Lake Banyoles (NE Spain)

Formación local de sedimentos varvados en una depresión de colapso kárstico del Lago Bañolas (NE España)

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ABSTRACT

Banyoles is the largest and deepest lake of karstic-tectonic origin in the Iberian Peninsula. The lake comprises several circular sub-basins characterized by different oxygenation conditions at their hypolimnions. The multiproxy analysis of a > 5 m long sediment core combined with high resolution seismic stratigraphy (3.5 kHz pinger *and multi-frequency* Chirp *surveys), allow a precise reconstruction of the evolution of a karstic depression (named B3) until present times. Local meromictic conditions in this sub-basin have been conducive to deposition and preservation of ca. 85 cm of varved sediments since the late 19th century. The onset of these conditions is likely related to lake waters eutrophication caused by increasing farming activities in the watershed. Increasing clastic input and organic productivity during the second half of the 20th century have also been recorded within the laminated sediments, revealing an intensification of human impact and warmer water temperatures.*

Key-words: *Karstic lake, meromixis, varves, late 19th century, eutrophication.*

RESUMEN

*Banyoles es el lago con origen kárstico-tectónico más extenso y profundo en la Península Ibérica. El lago incluye varias subcuencas circulares caracterizadas por diferentes condiciones de oxigenación en sus hipolimnions. El análisis multidisciplinar de un testigo de sondeo de más de 5 m de longitud combinado con sísmica de alta resolución (*pinger *de 3,5 kHz y* Chirp *multifrecuencia) permiten reconstruir de forma precisa la evolución de esta depresión kárstica (llamada B3) hasta la actualidad. Las condiciones locales de meromixis en esta cubeta han dado lugar al depósito y preservación de ~ 85 cm de sedimentos varvados desde finales del siglo XIX. El comienzo de estas condiciones está relacionado, probablemente, con la eutrofización de las aguas del lago causada por el aumento de las prácticas agrícolas en la cuenca. Durante la segunda mitad del siglo XX se han registrado también un aumento del aporte detrítico y de la productividad orgánica dentro de estos sedimentos laminados, que revelan una intensificación del impacto humano y un aumento de la temperatura de las aguas.*

Palabras clave: *Lago kárstico, meromixis, varvas, final siglo XIX, eutrofización.*

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Introduction

Lake sediments provide long, continuous archives of past environmental changes related to natural, climate variability, human impact or a combination of both (Last and Smol, 2001) in continental areas. However, these paleoenvironmental reconstructions are often characterized by a variable chronological control, limited by the availability of material to be dated by different radiometric techniques (mainly radiocarbon). This issue is particularly important in Mediterranean settings, where vegetation cover is scarce.

Varved, lacustrine sediments of different types (clastic, biogenic and evaporitic) (Brauer, 2004; Zolitschka, 2007) are only preserved in a limited range of depositional conditions and constitute continuous, high-resolution records with an annually resolved chronology, able to provide information about seasonal variability or to accurately date past natural or human-induced catastrophic events (Ojala *et al.*, 2012).

In this paper we provide evidence of the preservation of a ca. 100 year long an-

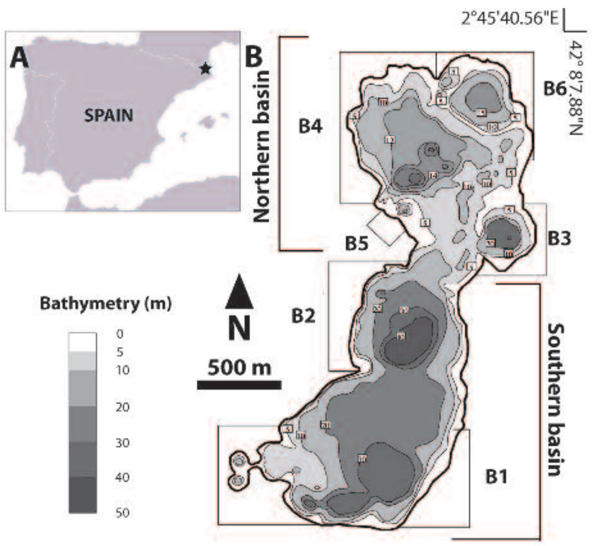

Fig. 1.- A) Location of the Lake Banyoles within the Iberian Peninsula; B) bathymetric map, basins and sub-basins (modified from Soler *et al.*, 2009).

Fig. 1.- A) Localización del Lago de Banyoles dentro de la Península Ibérica; B) Mapa batimétrico, cuencas y subcuencas (modificado de Soler et al.*, 2009).*

nually resolved record, extending to the present, in one of the deep, meromictic sub-basins of karstic Lake Banyoles (NE Spain). Our preliminary results demonstrate the potential of this recent varved sequence to test the impact of climate variability and human activities in the lake's catchment.

Regional setting

Lake Banyoles (42°1'N; 2°4'E, 173 m a.s.l.) is located in the NE of the Iberian Peninsula, 20 km west of the Mediterranean Sea (Fig. 1A). The lacustrine basin has a tectonic-karstic origin (Julià, 1980) and comprises several cone-like karstic depressions. The lake's bedrock is constituted by the mid Eocene Banyoles Formation (marine, organic- and pyrite-rich marls and mudstones), underlain by the mid Eocene Beuda Formation (massive gypsum), and the early Eocene Perafita Formation (dolostones) (Julià, 1980; Bischoff *et al.*, 1994). In the contact between these last two formations a 'de-dolomitization' process due to gypsum dissolution, a particularly intense karstification mechanism responsible for the formation and collapse of the Lake Banyoles depressions, occurred (Bischoff *et al.*, 1994). Karstic processes are still active in the lake catchment at present times as demonstrated by recent collapses, intermittent springs or karren fields (Julià, 1980; Canals *et al.*, 1990; Leroy, 1997, 2008; Höbig *et al.*, 2012).

Morphometry and limnology

The lake has a N-S elongated and lobe shape and a surface of 118 ha. The lake is formed by 6 main circular-shaped sub-basins (B1 to B6), with steep margins and water depths ranging from 7.5 to 44 m, connected by shallower, flat platforms (ca. 20 m and 5-10 m water depths in the southern and northern areas, respectively) (Fig. 1B) (Moreno-Amich and García-Berthou, 1989; Canals *et al.*, 1990).

The lake is hydrologically open and mainly groundwater-fed through subaquatic springs located in the deepest sub-basins of the southern basin (B1 and B2), providing ca. 85% of total water input (Casamitjana *et al.*, 2006). Periodic fluidization and re-suspension of sediments deposited at the bottom of the deepest sub-basins, led to the development of turbidity plumes and deposition of homogenites at the southern basin of the lake (Morellón *et al.*, 2014). These processes are related to particularly intense rainfall events in the recharge area of the aquifer feeding the lake.

Lake water in the southern basin is characterized by a lower residence time and higher oxygenation levels than water in the northern lobe. The northern basin has a lower groundwater input so that anoxic conditions and sulfide production at the hypolimnion occur in some sub-basins (Prat and Rieradevall, 1995). Thus, the 6 sub-basins are connected by their epilimnetic waters, but their respective hypolimnions are isolated and show different anoxic periods, ranging from 1 to 12 months/year (Prat and Rieradevall, 1995).

Surface lake waters are sulphate and calcium-rich ($[SO_4^{2-}] > [HCO_3^{2-}] > [Ca^{2+}] > [Mg^{2+}]$) (Bischoff et al., 1994), with electrical conductivity values of 1300 to 1400 µs/cm and a pH values between 7 and 8.1 (MAGRAMA, 2006). Water temperature ranges from 8 to 25 °C depending on the water depth and season (Rieradevall and Roca, 1995). Oxygenation conditions are also spatially variable and depending of groundwater input, ranging from oxic (0-7 m water depth), to one month of anoxia (sub-basin B1, >12 m water depth), and to long-lasting anoxia (sub-basins B3 and B4, >12 m). The lake is monomictic, with water stratification from April to October (Rieradevall and Roca, 1995).

Materials and methods

A geophysical survey was carried out in April 2011 using a high-resolution, single-channel seismic system with a centre frequency of 3.5 kHz (GeoAcoustic pinger source) and a EdgeTech Chirp 3100-P multi-frequency profiler, covering 22 km and 14 km of seismic lines, respectively (Fig. 2A). Seismic processing workshop software was used for the processing of the pinger data (band-pass filter, flat gain) and the resulting seismic data set was interpreted using the Kingdom Suite software.

In May 2011, three pairs of overlapping sediment cores (BAN-11-1A, 2A and 3A) with lengths of ~13, 12 and 5 m, respectively, were recovered using a percussion coring equipment installed on a floating raft. This research focuses on core 3A, recovered in sub-basin B3, at ca. 23 m water depth (Fig. 2A). Two additional short, gravity cores were obtained to recover the uppermost part and the sediment/water interface of the sequence. The uppermost 40 cm of the BAN-11-3A sequence were sub-sampled in the field at 1 cm resolution for ^{137}Cs dating.

Physical properties as magnetic susceptibility (MS), gamma density and P-wave velocity were measured in core BAN-11-3A with a Geotek Multi-Sensor Core Logger (MSCL) every 1 cm. The core were subsequently split lengthwise in two halves and imaged with a digital camera. Sedimentary facies were defined after visual and microscopic smear slides observation, applying the methodology described in Schnurrenberger *et al.* (2003).

Core BAN-11-3A was sampled every 3 cm for Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC), measured with a LECO SC 144 DR elemental analyzer. The chronology of this lake sequence is based on: i) ^{137}Cs and dating by gamma spectroscopy at Eawag (Dübendorf, Switzerland) and ii) varve counting in the uppermost part of the sequence. Sedimentation rate estimated for this uppermost part has been extrapolated downcore to the lower 85 cm of sediment sequence. No terrestrial plant remains have been found for ^{14}C dating.

Results and discussion

Seismic stratigraphy and depositional evolution of sub-basin B3

A maximum seismic penetration of ca. 10 m was achieved in sub-basin B3. Seismic stratigraphic analysis of our 3.5 kHz survey allowed the identification of three major seismic units (SA-SD; Fig. 2B) and several seismic horizons, which have been tracked within this sub-basin. These horizons and units were correlated with the core lithostratigraphy. A constant acoustic velocity of 1500 m/sec based on the MSCL measurements has been used for the seismic-to-core correlation (Fig. 2B and C).

The oldest seismic unit (Unit SA) reaches more than 5 m thickness and is characterized by transparent seismic facies, with few irregularly shaped short and discontinuous reflections towards the upper part. This unit correlates with reworked travertine facies at the base of the sequence.

Seismic unit SB is ca. 1 m thick and is characterized by transparent seismic facies, suggesting a homogeneous lithology, and limited by a higher amplitude reflection at the top.

Seismic unit SC corresponds to the uppermost ca. 2 m of the sequence and is characterized by a high density of higher amplitude reflections at the lower half leading to progressively more homogeneous and chaotic reflections at the upper part. These seismic features suggest distal, fine grained, lacustrine deposits characterized by highly variable density values.

The sedimentary sequence of sub-basin B3

The sedimentary sequence of Lake Banyoles sub-basin B3 has been divided into two different units (Fig. 3):

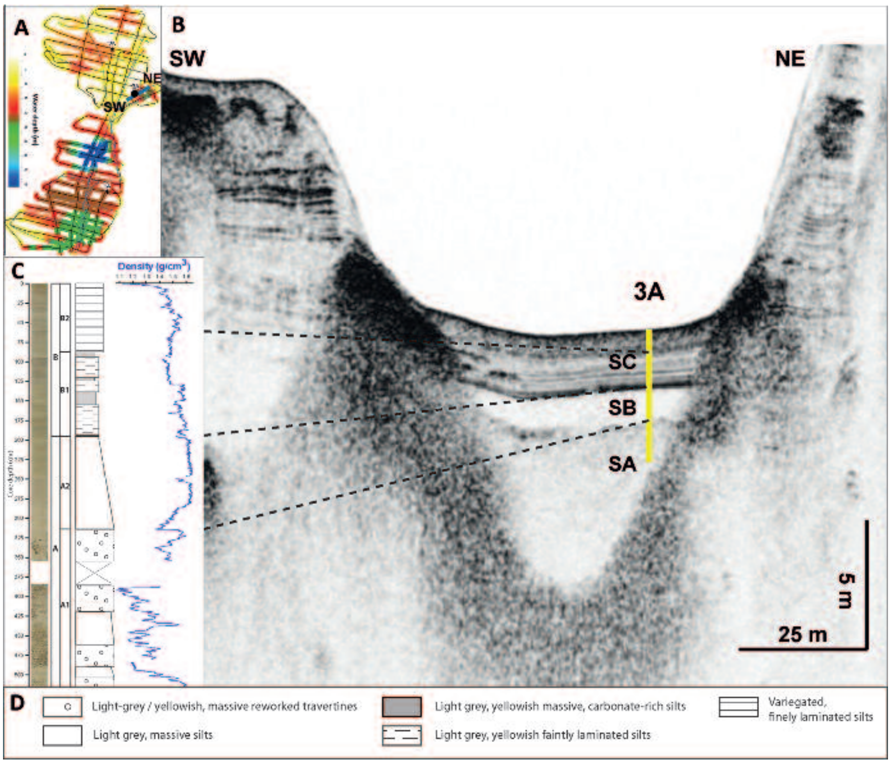

Fig. 2.- A) Seismic grids obtained with the Pinger 3.5 kHz source (yellow) and Edgetech profiler (red), with indication of bathymetry (see color-coded scale on the left) the seismic profile displayed in (B) (SW-NE) and sediment core (black dot) displayed in (C). B) SW-NE seismic profile and correlation with core BAN-11-3A (C) with dashed lines and seismic units (SA-SB) indicated next to the core location. C) core BAN-11-3A image, sedimentological profile and density core log. D) lithological legend. (Colour figure on the web).

Fig. 2.- (A) Red de líneas sísmicas obtenidas con el Pinger 3.5 kHz (amarillo) y el perfilador Edgetech (rojo), con la batimetría (ver escala de color a la izquierda), el perfil sísmico mostrado en (B) (SW-NE) y el sondeo BAN-11-3A indicados; (B) perfil sísmico SW-NE y correlación con el sondeo BAN-11-3A con líneas discontínuas y unidades sísmicas (SA-SB) indicadas junto a la localización del sondeo; (C) imagen del sondeo BAN-11-3A, perfil sedimentológico y curva de densidad; (D) leyenda litológica. (Figura en color en la web).

Unit A (520-195 cm core depth). This interval is composed of: i) alternating sequences of reworked travertines and light, grey, massive, fine grained silts, likely related to the collapse of this doline (Subunit A1), and ii) a > 1 m thick fining-upwards turbidite sequence with a sandy lower part topped by a black, thin, massive clay lamina (Subunit A2). This turbidite deposit represents the deposition of fine-grained material suspended after a mass-wasting process. The lower travertine and massive silts corresponds to seismic unit SA and the turbidite layers to seismic unit SB. Chronology of Unit A is unconstrained, although correlation with other cores in Banyoles (Morellón *et al.*, 2014) suggests a Late Holocene onset.

Unit B (195-0 cm) also comprises two different subunits. Subunit B1 (195-85 cm) is composed by light grey to yellowish, faintly laminated carbonate and organic-rich silts with intercalations of 10 to 20 cm thick levels of light grey to yellowish, massive carbonate-rich silts. The uppermost 85 cm of the sequence (subunit B2) are characterized by variegated, finely laminated silts. These laminated sediments are formed by couplets of yellowish calcite lamina, identified by petrographic microscopy, and light grey, massive clayey lamina, with the occasional presence of a reddish lamina formed by reworked plant remains. Unit B correlates with uppermost seismic unit SA.

The 1963 AD maximum peak of ^{137}Cs activity was found at 30 cm depth. The annual character of lamination is demonstrated by the number of couplets yellow-grey laminae from this point to the top of the core (49). Extrapolation of this sedimentation rate (ca. 0.65 cm/year) to the base of this laminated sequence indicates that this type of sedimentation started at ca. 1878 AD.

Assuming no significant lake level changes in Banyoles during recent times, the onset of varve formation, indicative of predominant meromixis might be related with

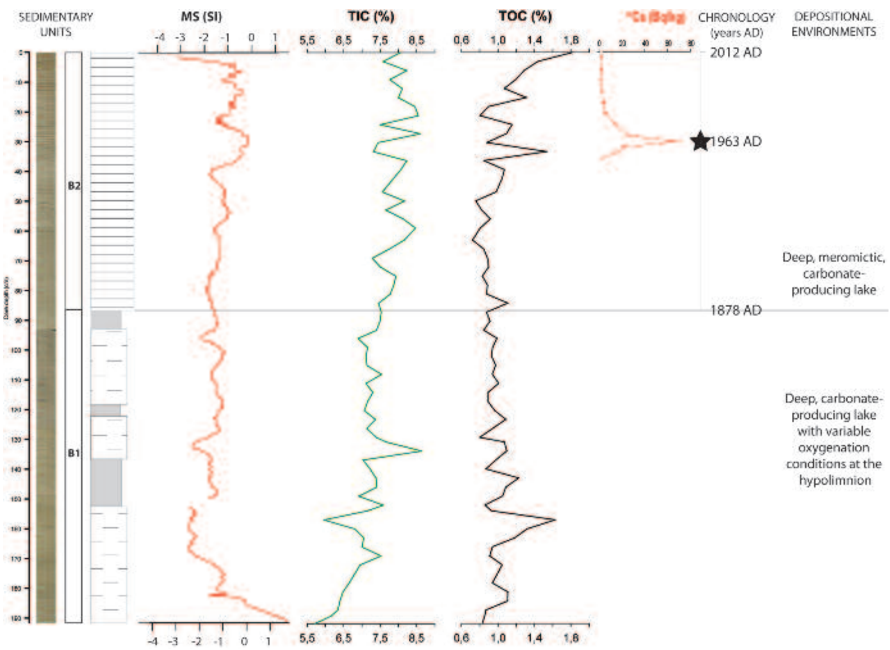

Fig. 3.- Detail of the uppermost 190 cm of core BAN-11-3A, including: core image, sedimentary units (B1-B2), sedimentological profile (see legend in figure 2D), Magnetic Susceptibility (MS), Total Inorganic Carbon (TIC), Total Organic Carbon (TOC) and ^{137}Cs core logs. Chronology (in years AD) and reconstructed depositional environments are indicated on the right side.

Fig. 3.- Detalle de los 190 cm superiores del sondeo BAN-11-3A, incluyendo: imagen del sondeo, unidades sedimentarias (B1-B2), perfil sedimentológico (ver leyenda en la figura 2D) y perfiles de Susceptibilidad Magnética (MS), Carbono Inorgánico Total (TIC), Carbono Orgánico Total (TOC) y ^{137}Cs. La cronología (en años AD) y los ambientes de depósito reconstruidos están indicados en el lado derecho de la figura.

eutrophication due to more intense farming activities conducive to higher nutrient input into the lake. This change in sedimentation correlates with a decrease in chironomid littoral taxa (García-Soler, 2013).

Fluctuations in MS, TIC and TOC values within this laminated sequence reveal a slight increase in clastic input (higher MS values, thicker grey clayey laminae) and organic matter (higher TOC), during the second half of the 20th century, consistent with sedimentological changes. This increase in organic matter might be due to increasing productivity caused by warmer water temperatures and/or higher input of pollutants related to farming activity in the lake catchment.

Conclusions

The seismic stratigraphy and sediment sequence at Lake Banyoles sub-basin B3 allows reconstructing its depositional evolution since late Holocene times, likely formed after a karstic collapse.

The onset of varve deposition started at ca. 1878 AD according to our varve chronology, supported by the maximum 1963 AD ^{137}Cs activity peak, and continued up to present times, likely due to the onset of local, meromictic conditions likely related to eutrophication.

Increasing TOC during the second half of the 20th century might be related to higher organic productivity related to warmer water temperatures and/or increasing farming activities in the catchment. Further research on this laminated sequence will clarify the recent evolution of Lake Banyoles.

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