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Fernando Barreiro Lostres

Evolución de los sistemas kársticos lacustres de la Serranía de Cuenca durante el Holoceno tardío: modelos de depósito e implicaciones climáticas y ambientales

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EVOLUCIÓN DE LOS SISTEMAS KÁRSTICOS LACUSTRES DE LA SERRANÍA DE CUENCA DURANTE EL HOLOCENO TARDÍO: MODELOS DE DEPÓSITO E IMPLICACIONES CLIMÁTICAS Y AMBIENTALES

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2016

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Research article 2

Barreiro-Lostres, F., Moreno, A., Giralt, S., Caballero, M., Valero-Garces, B., 2014. Climate, palaeohydrology and land use change in the Central Iberian Range over the last 1.6 kyr: The La Parra Lake record. The Holocene 24, 1177 – 1192. doi:10.1177/0959683614540960.

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El Doctor BLAS LORENZO VALERO GARCÉS, Profesor de Investigación del Consejo Superior de Investigaciones Científicas en el Instituto Pirenaico de Ecología

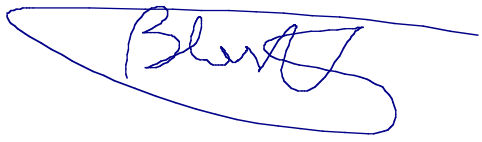
CERTIFICA:

Que Don Fernando Barreiro Lostres ha realizado bajo su dirección el trabajo que, para optar al grado de Doctor en Geología, presenta con el título:

"*Evolución de los sistemas kársticos lacustres de la Serranía de Cuenca durante el Holoceno tardío: Modelos de depósito e implicaciones climáticas y ambientales*"

Que el trabajo se ajusta a los objetivos establecidos en el Proyecto de Tesis Doctoral aprobado por el departamento de Ciencias de la Tierra y ratificado por la Escuela de Doctorado el 03/11/2014. Por consiguiente, autoriza la presentación de la misma en el formato "compendio de publicaciones", de acuerdo con la normativa vigente.

Y para que así conste, firmo la presente Certificación en Zaragoza el 23 de mayo de 2015 para los efectos que sean oportunos.



Fdo.: Blas Lorenzo Valero Garcés

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Por último, quiero resaltar que cada línea de esta tesis esconde la interpretación de un lugar, una vivencia, una sensación, un olor, un color de agua, una estación, un sol, una lluvia, una gota de sudor, una expectativa, una persona, un pensamiento, una emoción diferente. Disfrútenla.

A Fernando, María
y Sara

Resumen

Esta Tesis Doctoral se centra en el estudio de la variabilidad paleolimnológica, paleohidrológica y paleoambiental, durante los últimos 2000 años en tres lagunas kársticas situadas en la rama occidental de la Cordillera Ibérica, caracterizadas por un clima de montaña mediterránea con influencias continentales, a través del análisis multidisciplinar de su relleno sedimentario obtenido mediante sondeos largos en ambientes litorales y distales. Concretamente, se trata de las dos lagunas pertenecientes al complejo lacustre de Cañada del Hoyo (Cuenca), El Tejo y La Parra; y 100 km más al norte, de la Laguna del Tobar, próxima a la localidad de Beteta.

Los resultados de este estudio proporcionan tres nuevos estudios multi-indicador con una cronología robusta de secuencias lacustres kársticas, mostrando la variabilidad hidrológica y medioambiental de sus cuencas durante los dos últimos milenios, contribuyendo a completar el mapa paleoambiental entre el norte y sur de la Península Ibérica.

Además del estudio de visu y microscópico sedimentológico y de ambientes de depósito, se han realizado análisis geofísicos (susceptibilidad magnética, densidad de Rayos Gamma), mineralógicos (difracción de Rayos X), semicuantitativos y cuantitativos de geoquímica elemental (Fluorescencia de Rayos X, Espectrometría de Masas con Plasma Acoplado Inductivamente, LECO) y biológicos (diatomeas) para reconstruir variables hidrológicas y ambientales tales como fluctuaciones en el nivel de las lagunas mediante el análisis de facies, tasas de sedimentación y erosión, productividad orgánica, así como el impacto de las actividades humanas a lo largo de la histórica relacionadas con los cambios de los usos del suelo.

Los modelos cronológicos de las secuencias están basados en dataciones de ^{14}C y también en radiometría de $^{210}Pb/^{137}Cs$, permitiendo tener un mayor detalle en la sedimentación reciente. Esto a dado lugar a las cronologías lacustres más antiguas y robustas de la zona, aunque esta Tesis de centra en los últimos 2000 años.

Los lagos kársticos de la Península Ibérica suelen ser pequeños, con secuencias sedimentarias caracterizadas por una elevada variabilidad de facies, generalmente clásticas y carbonatadas con cambios laterales y verticales abruptos. Las casos aquí estudiados permiten ilustrar condiciones hidrológicas y limnológicas similares en una región dominada litología calcárea, aunque con una variación gradual en el tamaño de sus cuencas, y por tanto, una variación gradual del impacto humano a través de los cambios en el uso del suelo. Este hecho también permite comparar desde cuencas hidrológicamente desconectadas de las aguas superficiales (El Tejo), con conexión intermitente (La Parra), hasta cuencas permanentemente conectadas con el medio fluvial (El Tobar), lo que condiciona de forma importante la disponibilidad de sedimentos

capaces de llegar a las lagunas y por tanto, su tasa de sedimentación.

Aunque las tres lagunas tienen un origen kárstico, actualmente se encuentran en un estado ya maduro y los procesos kársticos ya no son muy activos. Por ello, al tratarse de dolinas inundadas, su geomorfología presenta forma de embudo, implicando que la sedimentación actual esté fuertemente condicionada por la batimetría y las condiciones hidrólogicas. Las propiedades sedimentológicas y geoquímicas de las tres secuencias ha permitido diferenciar han permitido diferenciar dos ambientes de depósito principales: i) litoral-sublitoral, que incluye la plataforma litoral con producción de carbonatos y la zona de talud, normalmente escarpado, constituida por facies clásticas gruesas y facies de limos masivas y bandeadas; y ii) la zona distal-profunda, que engloba la zona profunda proximal y la distal, constituida principalmente por facies masivas, bandeadas y laminadas ricas en carbonatos o materia orgánica, e incluso por intervalos varvados, permitiendo deducir la presencias de periodos anóxicos en el fondo de los lagos.

En general acordes con la mayoría de registros ibéricos y de otras zonas del Mediterráneo occidental a escala centenaria, las secuencias indican condiciones predominantemente áridas antes del 300 D.C., cuando La Parra era una dolina seca. Después de este periodo, los niveles lacustres han fluctuado dentro de un marco general más húmedo durante los últimos 1600 años. Durante esta nueva etapa, las condiciones más áridas tuvieron lugar al final de la Alta Edad Media, previamente a la Anomalía Climática Medieval, la cual también presenta niveles lacustres relativamente bajos; mientras que las condiciones más húmedas tuvieron lugar desde el 1200 hasta el 1600 D.C., coincidiendo con la Pequeña Edad del Hielo, aunque con importantes fluctuaciones hacia periodos cortos más áridos. Diferencias en la respuesta sedimentaria bajo un mismo cambio en las condiciones hidrológicas están relacionadas con la diferente configuración de las cuencas lacustres.

Además, los indicadores sedimentológicos y geoquímicos también han permitido identificar en las secuencias lacustres las interacciones más relevantes entre las lagunas, sus cuencas y el impacto antrópico a lo largo de la historia, manifestándose principalmente mediante el aumento de la producción de sedimentos en las cuencas y su aporte a las lagunas. En función de su intensidad y frecuencia, han podido diferenciarse además entre *eventos* (cortos e intensos) y *periodos* (prolongados en el tiempo y más difusos) de aumento de la sedimentación. Su interpretación conjunta con datos de las principales actividades económicas a lo largo de la historia ha permitido conocer que la mayor parte de los momentos con mayor aporte de sedimentos a las lagunas coincide con fases climáticas más húmedas y un aumento en la presión antrópica en sus cuencas.

Este estudio también se ha centrado en la búsqueda de una metodología que permita efectuar cálculos cuantitativos aproximados de una forma sencilla

y eficiente de esos momentos de mayor aporte de sedimentos a partir del estudio geofísico y geoquímico de los sondeos obtenidos. Concretamente se persigue el cálculo de la masa acumulada en los lagos, la masa mínima denudada que implica en las cuencas y la tasa de denudación total a lo largo del último milenio. Posteriormente, para comprobar su coherencia, los datos obtenidos se han contrastado con cuencas experimentales actuales del Pirineo aragonés, aportando conclusiones satisfactorias y abriendo nuevas vías de investigación experimental aplicando las técnicas de monitorización ya existentes a cuencas lacustres.

Por último, esta Tesis Doctoral demuestra que los procesos de degradación, especialmente en cuencas lacustres de montaña e independientemente de su tamaño, están relacionados con la evolución medioambiental natural y el impacto antrópico a través de los cambios históricos en los usos del suelo, los cuales modelan incesantemente los paisajes culturales que heredamos tras años de historia.

Abstract

This Thesis memory focuses in the study of the paleolimnological, paleohydrological and paleoenvironmental variability during the last 2000 years on the karstic lakes located in the Western Branch of the Iberian Range by using a multidisciplinary methodology to investigate their sedimentary fill in recovered long cores at proximal and distal environments. They are characterized by a Mediterranean mountainous climate with continental influences. In particular, are studied two small lakes from the sinkhole-lake complex of Cañada del Hoyo (Cuenca): El Tejo and La Parra; and Lake El Tobar, located 100 km northwards close to Beteta locality.

The obtained results provide three new karstic lakes multiproxy studies with a robust chronology, showing the hydrological and environmental variability of their watersheds during the last two millennia. That tries to contribute the effort complementing the recent paleoenvironmental situation between the North and South of the Iberian Peninsula.

In addition to the *visu* and microscopic sedimentological and deposit environments study, different analyses have performed to reconstruct the hydrological and environmental variables as lake-level fluctuations, sedimentary and erosion rates, organic productivity and to infer the impact of historical anthropogenic activities related to land-use changes: geophysical (magnetic susceptibility, Gamma Ray density), mineralogical (X-Ray diffraction), semiquantitative and quantitative elemental geochemical (X-Ray Fluorescence, Inductively Coupled Plasma Mass Spectrometry, LECO) and biological (diatoms).

Sedimentary sequences chronological models are based in ^{14}C dates and in $^{210}Pb/^{137}Cs$ radiometric essays, which allow a higher detail in recent sedimentation. That has yielded the oldest and more robust lacustrine chronologies of the Iberian Range, although this Thesis memory is focused in the last 2000 years.

Iberian Peninsula karstic lakes are usually small, showing sequences characterized by high facies variability generally clastic and carbonatic with abrupt lateral and vertical changes. The studied cases illustrate similar hydrological and limnological conditions on a region dominated by carbonatic lithologies, although with a gradual change in their watershed sizes that implies also a gradual variation of the anthropogenic impact by land-use changes. That fact also allows comparing from hydrologically closed watersheds (El Tejo), with intermittent connected ones (La Parra) to permanently fluvial connected watersheds (El Tobar), a paramount control of sediment availability able to reach the lakes and therefore, their sedimentation rate.

The three lakes are in a mature karstic stage and karstic processes are not

very active at present. As they are flooded sinkholes, their geomorphology has a marked funnel-shape. Therefore sedimentation is mainly controlled by the bathymetry and hydrological conditions. The sedimentological and geochemical properties of the three sequences allowed to differentiate two main depositional environments: i) littoral-sublittoral, including the littoral platform with carbonate production and the usually steep talus zone, constituted by coarse clastic and massive and banded silty facies; ii) distal-profundal, containing the deep-proximal and deep-distal zones, constituted mainly by massive, banded and laminated facies rich in carbonates or organic matter, including varved intervals, which allow to deduce the presence of anoxic periods in lakes bottom.

The studied sequences are in general coherent with most of the Iberian and Western Mediterranean records. They indicate dominant arid conditions previous to 300 AD, when La Parra was a dry sinkhole. After that, lake levels fluctuated inside a wetter general frame along the last 1600 years. During that wetter stage, most arid conditions occurred synchronously with the Dark Ages, previously to the Medieval Climate Anomaly, which also presents relatively low lake-levels. Wettest conditions took place from 1200 to 1600 AD, synchronous to the Little Ice Age, although with noticeable short-term dry fluctuations. Differences in lake sedimentary response during same hydrological condition changes are related with differences in the configuration of lacustrine watersheds.

Besides, sedimentological and geochemical proxies also allowed identifying most notorious lake-watershed-human impacts along history, mainly expressed by the increment of sediment yield in the watersheds and reaching the lakes. Depending on the intensity and frequency of these increments, they can be differentiated between *events* (short and intense) and *periods* (extended in time and diffuse). Their interpretation joined with historical information of human activities showed that most stages of increment in sediment delivery to the lakes coincide with wetter climatic phases and the increment of anthropogenic impact in their watersheds.

This PhD Thesis also search for a simple and efficient methodology which allows to calculate quantitatively the increases in sediment inputs to the lakes from the geophysical and geochemical study of recovered cores. Particularly, the calculus of the mass accumulated in the lakes, the minimum mass of denuded sediments in the watersheds and the total denudation rate along the last millennia. After that, to test the coherence of the calculus, obtained data has been compared with current experimental watersheds located in the Aragonese Pyrennes, throwing satisfactory conclusions and presenting new experimental research routes by applying existing monitoring techniques to lacustrine watersheds.

At last, this PhD Thesis demonstrates that degradation processes,

especially in mountainous lake watersheds and independently of their size, are related to the environmental evolution and human impact through historical land-use changes, which permanently model the inherited cultural landscapes along years of history.

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1

Introduction

Concern about the degradation of Earth's environmental conditions, largely as a result of the impact of human activities, has leaded an increase in need for environmental assessments and the ability to manage anthropogenic activity in the environment. Studies focused on the natural development of environments are addressing issues such as global climate change and other related topics. A challenge arises in many instances in trying to discern which effects were caused by human activity and which were natural. Paleolimnology is the field of science that uses lake sediments to reconstruct past environmental conditions; therefore, paleolimnological studies can help distinguish between the two causing effects. In this PhD thesis, in order to decipher the interactions among past and recent climate, environment and human activities and the depositional dynamics, a multi-proxy paleoenvironmental study of three karstic lakes located in the Western Branch of the Iberian Range (Central-East Spain) has been conducted.

Panoramic view of Lake La Parra.
Vista panorámica de la Laguna de La Parra.

1.1 Motivation

Detailed observations and instrumental measurements have demonstrated that we live in a period of accelerated Climate Change (IPCC, 2013). Model projections, intended to reproduce at global scale the complex interactions among main climate variables and provide future scenarios remain yet imprecise. Modern observations and future predictions are of paramount relevance to evaluate the impact, vulnerability and the adaptation options for ecosystems and human societies to the challenges of future climate and environmental changes. A responsible and sustainable use of natural resources in a scenario of accelerating environmental and climate changes and increasing human pressure over the ecosystems is one of the main challenges for our societies in the 21st century (Smith and Zeder, 2013). Thus, a daunting task lies ahead for Science to guide society toward environmentally sustainable management policies (Crutzen, 2002), as the scientific community tries to disentangle the main mechanisms affecting recent global change and understand its dynamics at different time scales (Foley et al., 2013; IPCC, 2013).

There is no doubt about the important role that anthropogenic activities have played on environmental evolution since at least the Neolithic. During the last millennia and particularly since the Industrial Revolution (post-AD 1850), humans have become an integral part of the Earth system rather than a merely external factor. Therefore, one of the legacies of humankind is the creation of cultural landscapes, as environmental, climate and anthropogenic drivers interact (Birks et al., 2012). In this new period when mankind is a major environmental force – the Anthropocene –, human behavior at all scales becomes a main variable and a significant source of uncertainty, so we are treading on *terra incognita* (Crutzen, 2002).

Our knowledge of ecosystem responses to human and climate forcing is limited, both in current times and in the past. Available meteorological, monitoring and documentary records are not long enough to reveal the dynamics of surface processes and climate-anthropic interactions at decadal to centennial time scales (Dearing et al., 2010, 2006). Many areas worldwide --and the Mediterranean in particular-- are subject to extreme short-term hydrological events, especially droughts, creating difficulties for dry and irrigation farming and for domestic and industrial uses, but there is a large regional variability (Lionello et al., 2012; Seager et al., 2007; Roberts et al., 2004). We also need to know how climate and ecosystems –including human societies-- interacted in the past during hydrological crises before we can develop sound adaptation and mitigation policies to global changes.

A look at the interconnected nature of hydrologic, ecologic, and socioeconomic systems shows that they are all vulnerable to predicted changes in Earth's climate (IPCC, 2013). To evaluate how natural resources —water in

particular— will respond to future climate scenarios, scientists need a robust understanding of the interactions between the land surface, atmosphere and oceans at a large scale and between land ecosystems and resource availability on a small scale. Dynamic models of these natural systems can inform management and regulatory tactics that optimize trade-offs between ecosystem resilience and human economic activity. In that sense, late Holocene paleoclimate and paleoenvironmental reconstructions are key to improve our understanding of how current climate variability and future climate challenges will affect ecosystems and natural resources (Mann et al., 2009; Mayewski et al., 2004; Bradley et al., 2003).

The last two millennia period is particularly important for characterizing the natural variability of the climate and framing recent global warming in a general context; recent paleoclimate variability will help to assess the extent to which recent climate changes are anomalous and the extent to which these changes are likely related to anthropogenic impacts on climate (Mann, 2007). A considerable body of scientific research in recent decades has sought to characterize the nature of climate variability over the last two millennia by using multi-proxy data and theoretical sophisticated models to reconstruct the evolution of large-scale changes in temperature, precipitation, droughts and atmospheric circulation (Mann and Jones, 2003; Briffa et al., 2001; Bradley and Jones, 1993). From these studies, it is known that climate in past millennia has been characterized by a complex pattern of regional and temporal variations, as responses to changes in radiative forcing of climate (volcanic eruptions, solar irradiance variability) summed with internal chaotic oscillations of the climate system and the characteristic patterns of reorganization of the atmospheric and oceanic circulations over time (mainly related to El Niño-Southern Oscillation, ENSO, or the North Atlantic Oscillation, NAO, between others; Mann, 2007; Kirov and Georgieva, 2002; Shindell et al., 2001).

Over the last two millennia, although with some inconsistencies due to the complex regional pattern of climate variability, it is accepted that at least in the Northern Hemisphere two main climatic periods took place (Mann, 2007): The Medieval Climate Anomaly (MCA, 11th-14th centuries) with warmer conditions, and the Little Ice Age (LIA, 15th-19th centuries) with cooler conditions. Although their worldwide impact has been clearly documented (Osborn, 2006; Valero-Garcés et al., 2006; Mann and Jones, 2003; Verschuren et al., 2000), at a regional scale (e.g. the western Mediterranean), the exact temporal and spatial patterns of climatic variability during those periods is more complex, showing indeed controversial behaviors (Mann, 2007). They have been related to variations in solar activity (Bard et al., 2000), but this linkage between climate and solar activity remains controversial (Bard and Frank, 2006; Corella et al., 2014). Furthermore, studies at global or hemispheric

scales, suggest that late 20th century climate change is anomalous in the context of at least the past millennium (Mann, 2007).

The Iberian Peninsula, located west of the Mediterranean Basin, is a key location for understanding climate connections between the eastern and western Mediterranean (Roberts et al., 2012) and interactions with North Atlantic climate dynamics (Lacey et al., 2015). The understanding of past climate variability across continental Iberia itself has improved considerably over the last two decades, employing a range of proxy methods and sources, including sequences from peatbogs (González-Sampériz et al., 2008), speleothems (Stoll et al., 2013), cave sediment (Fernández et al. 2007), palaeo-floods (Moreno et al., 2008; Benito et al., 2003) and lacustrine sediment (Valero-Garcés and Moreno, 2011; Reed et al., 2001). During the last 2000 years, Iberian paleoclimate records show broad similarities, with significant climatic fluctuations occurred at centennial and decadal scales in the Iberian Peninsula accompanied by several phases of intensified human impact. Periods such as the Iberian Roman Humid Period (IRHP, 650 BC-AD 350), the Dark Ages (DA, AD 500-900), the Medieval Climatic Anomaly (MCA, AD 900-1300) and the Little Ice Age (LIA, AD 1300-1850) were accompanied by cycles of strong hydrological and environmental impacts, particularly in the Mediterranean mountain areas (García-Ruíz et al., 2013; Moreno et al., 2012; Morellón et al., 2011; Martín-Puertas et al., 2008). These periods coincide roughly chronologically with the North Hemisphere 'MCA' and 'LIA' climate phases, although with regional trends which underline timing discrepancies in paleohydrological shifts. These discrepancies, due to the different intensities of the climate signature recorded in the natural archives, the significant regional geographic variability in the Iberian Peninsula and the complex interplay of intense human impact, create difficulties to precisely identify the timing and dynamics of wet and dry stages and to disentangle anthropic and climatic signal.

To contribute to the effort of understanding climate-human-ecosystems interactions at a longer time scales and to complement some of these knowledge gaps about past climate changes more high-resolution, multi-proxy and accurately dated records are essential. In the Mediterranean region, lake sediments have demonstrated to be exceptional archives at a regional scale of past environmental and human evolution (Magny et al., 2013; Lionello, 2012; Roberts et al., 2012). Usually, high sedimentation environments occurred in lake systems, and the sedimentary sequences, reflect the changes occurring in the watershed and the depositional environment (Last and Smol, 2001). That information stored in the sediments can be recovered by a multi-disciplinary study of the sedimentary sequences.

In the Iberian Peninsula, lakes have provided excellent lacustrine systems

highly sensitive to past environmental and human impacts (Valero-Garcés and Moreno, 2011). Karstic lakes, although small, present variable salinity conditions, variable water stratification and water inlets and outlets, variable hydrological behavior from closed to open lakes, and variable clastic input from the watershed caused by rainfall and anthropic use of the watersheds. The small size relatively to their depth allows a good connection to the surrounding aquifer, making karstic lakes very sensitive to regional hydrological balances, experiencing considerable lake level, water chemistry and biological fluctuations in response to changes in effective moisture (Cohen, 2003).

The occurrence of karstic lakes in the Iberian Range provides a unique opportunity to test the interactions of climate, environmental change and human impacts during the last millennia. The lakes have been influenced with the same climatic conditions and a similar regional human impact, allowing to study the sedimentary processes in each lake and to infer cultural-climate interactions.

1.2 Thesis objectives

This PhD dissertation focuses on the multi-proxy sedimentary study of three karstic lakes (El Tejo, La Parra and El Tobar), located in the Western Branch of the Iberian Range, in order to decipher the interactions among climate, environment and human activities and the depositional dynamics in these lakes.

The overarching objective of this PhD is to understand the depositional, hydrological and geochemical evolution these three karstic lake systems during the last 2000 years, and how the lakes history was drove by the interactions with various controls at different time scales, focusing mainly on climate variability and anthropogenic impacts. To achieve this main objective, firstly we need establishing an accurate chronology for the lake records and secondly, the paleoenvironmental conditions of the watershed and the limnogeological evolution of the lake systems have to be reconstructed from those lacustrine sedimentary sequences.

In particular, the following objectives are pursued:

1. **Limnogeological evolution of karstic lakes.**
    - 1.1. To understand the facies deposition in karstic lakes and how sedimentological and chemical properties record fluctuations in limnological conditions (depth, anoxic conditions, bioproductivity).
    - 1.2. To investigate how water mixing conditions, hydrological changes and variations in source contribution (runoff, groundwater, direct precipitation) affect the limnochemical evolution of these karstic lakes, and particularly, the

development of annual laminations.

1.3. To identify the patterns of depositional changes during the last 2000 years.

2. **Lakes and climate variability**.
   2.1. To describe accurately and date the main climatic phases in the Iberian Peninsula during the last 2000 years and to find out whether the patterns of climatic change are consistent with NAO variation, solar variability, or other proposed climate-forcing mechanisms for the last millennia.
   2.2. To investigate the hydrologic response of the lakes to changes in regional climates.
   2.3. To compare the lake reconstructions with the regional and global teleconnections between the reconstructed climate from these lake records and other climatic records from within and beyond the region.
3. **Lakes and human activities.**
   3.1. To investigate the relationship between historical changes in the watershed caused by human activities (deforestation, grazing, water use), climate fluctuations and lake dynamics.
4. **To quantify past erosion rates and sediment delivery.**
   4.1. To describe and quantify the erosion rates from the watershed and the sediment input into the lakes associated to extreme events provoked by those sedimentary events and consequently, estimate the denudation needed from the watershed.
   4.2. To compare reconstructed past erosion rates with data from monitoring catchments in mountain areas.
5. **To investigate the synergetic relationship between human activities and regional climate and to provide tools to discriminate between geochemical changes representing local (lake and watershed) from regional (environmental, climate) variability.**

1.3 Research strategy

Our knowledge of the complex climate-human-ecosystem dynamic interactions is limited. To obtain a better understanding of the response of terrestrial ecosystems and the hydrosphere to climate and anthropogenic forcings, is critical to: i) improve our knowledge of the different climate periods during the last two millennia, which is the closer time period to actual time, with similar boundary conditions; ii) understand the depositional dynamics of the selected paleo-archives; iii) assess the variability of the human impact at regional and local scales and at different time scales.

These goals can be achieved with multidisciplinary paleoclimate and paleoecological studies of detailed lake sedimentary records (Pardo et al., 2013). Lake records allow the reconstruction of climate dynamics, hydrology and vegetal communities into the past, including the recent abrupt changes (González-Sampériz *et al.*, 2010; Moreno *et al.*, 2010; Mayewski et al., 2004; Valero-Garcés *et al.*, 2000) and the ecological resilience of the environmental system (Gil-Romera *et al.*, 2010, Corella et al., 2014; Currás et al., 2012; Martín-Puertas et al., 2008; Morellón et al., 2011; Moreno et al., 2008; López-Blanco et al., 2011a,b; Romero-Viana et al., 2009).

In this research we used a multidisciplinary approach to investigate at watershed and lake scales, the paleohydrological and geochemical response to human and climate impact of three karstic lakes from the Castillian –Western – Branch of the Iberian Range during the last 2000 years. The methodologies include: field surveys, sedimentary facies analyses at micro-scale, geophysics, geochemistry, and biological (diatoms) multi-proxy studies based on core sediments. The research strategy includes four main aspects: i) depositional evolution of lakes (*1.3.1*); ii) climate variability (*1.3.2*); iii) human impact (*1.3.3*) and iv) quantification of sediment delivery and erosion rates (*1.3.4*). These aspects are then integrated in a general frame including human, climate and landscape processes interdependencies (*1.3.5*).

1.3.1 Sedimentological and stratigraphic reconstruction

Lake sediments are composed of materials originated both within the lake basins themselves, and in their watershed. Lake sediments therefore represent a mixture of a very wide range of particles, most of which experience a complex history of formation, mobilization, transport and deposition (O'Sullivan and Reynolds, 2004). The material that contributes to the formation of lake sediments, and the processes by which it reaches the lake bottom, are very diverse and at same time are also modulated by climate and environmental variability and by anthropogenic impacts. Then, material entering the lake from its catchment, or generated in the water column, still passes through many processes before it deposited at the lake floor (O'Sullivan and Reynolds, 2004) and even experience post-depositional (early diagenetic) changes. Thus, lake sediments reflect both their depositional history and their original composition and place of origin within the lake-watershed system.

The information that lake sediments contain therefore records not only the ontogeny of lakes themselves, but also of the terrestrial areas that drain into them, and of atmospheric deposition over the lake and its watershed. Lake sediments also provide an important time perspective on a vast range of surface and environmental processes, enabling to infer their onset, their physical, chemical and biological manifestations, and, ideally, their causes or

consequences. That also may allow reconstructing past conditions of a lake system and its watershed, information that is invaluable when restoring practices are needed. Paleolimnological techniques help to reconstruct the evolution of lake systems themselves and of their watershed, and analyze the interactions between lakes, their drainage basins and environmental conditions, especially those promoted by human action and climate variability (O'Sullivan and Reynolds, 2004).

Therefore, the first required task of this research is to reconstruct the depositional evolution of the three lakes that comprise this study in order to disentangle what are the main controls of depositional processes in karstic lakes during the last 2000 years. Karstic lake sediments are mixtures of endogenic minerals (carbonates, sulphates, sulphures), organic matter (diatoms, algal mats, littoral macrophytes, reworked terrestrial plants, invertebrate remains) and detrital mineral fraction from the watershed (mostly carbonates and silicates of variable grain sizes). Particularly, in these kinds of lakes questions about facies distribution, geochemical composition and lake level fluctuations are very important, and they have been addressed through the analyses of three main components: clastic input, endogenic mineral formation and meromictic conditions development.

For Lake La Parra, the results and discussion about the sedimentological study, facies analysis and limnogeological evolution are in the *Result* chapter, *subsections 4.3, 4.4*; and for Lake El Tobar in *subsection 4.5*. A sedimentological description for Lake El Tejo is provided in the *Annex 3* of the supplementary material in the *subsection 4.6*. Also in *subsection 4.6* the main sedimentary events recorded in each lake sequence for the last 2000 years are characterized by using sedimentological evidences and the geochemical information stored in the sediments.

1.3.2 Palaeoclimatic reconstruction and landscape evolution

Lake sediments represent an archive of environmental change and variability unrivaled in the geological record (Lionello, 2012; O'Sullivan and Reynolds, 2004). The timescales over which sediments accumulate in lakes make themselves very adequate for the study of surface processes in the continents, including human impact on nature, during the pre- and post-industrial society. Long sequences of lacustrine sediments are the only continental records which rival polar and tropical ice-caps as archives of long-term climatic variability, in terms of continuity, precision and detail (O'Sullivan and Reynolds, 2004).

Once characterized the depositional evolution from the lacustrine sequences, some climate-related parameters as lake level fluctuations along time are inferred from a detailed facies and geochemical analysis.

Development of fine lamination is one of the main sedimentary features of karstic lakes and it is related to paleohydrology. But, what is meaning of the development of fine laminated facies? Why do not they occur in all the karstic lakes under similar forcing conditions? It is possible to extrapolate conceptual sedimentary models among different Mediterranean karstic lakes? A key question in paleolimnology research applied to paleoclimatology is if it is possible to discriminate watershed-scale cycles from regional changes by analyzing spectra of multiple sediment parameters; or if human impact (farming activities, increased erosion, water use) can be isolated from the climate variability.

Applying a multiproxy methodology, the paleohydrological evolution of the three lakes will be assessed and the inferred paleoclimate implications both at local (*Results subsection 4.5*) and regional scale for the last 2000 years will be discussed (*Results subsection 4.4*). The timing and variability of dry/humid periods will be compared with local, regional and also global records in a wider Mediterranean context, describing their frequency and spatial extent and looking for possible latitudinal/longitudinal gradients within the Iberian Peninsula.

1.3.3 Human impact through historical land use

Recent interdisciplinary research in many different world areas has convincingly shown that human land-use within the last 10,000 years has significantly impacted regional geomorphological histories, ranging from soil erosion, hillslope processes, fluvial sedimentation, and stream development in both humid and semi-arid, temperate, and tropical regions (Bauer, 2014 and references therein). On a more local view, human agricultural and stock-breeding activities, historical events, land-use changes and engineering projects have dramatically impacted the watershed landscape, natural hydrology, and environmental setting of many lakes throughout the world. It remains a pressing concern to improve our knowledge of the timing and magnitude of previous human impacts in order to place their effects into an appropriate context (Hillman et al., 2016). Lake sediment records from locations with long periods of human settlement within the lake catchment can provide insight into the nature, scale, and scope of these activities.

In Mediterranean areas where water resources are scarce, historical human activities have been a decisive factor in the lake hydrology and, particularly, agricultural practices a main forcing in the depositional dynamics of the lake systems (e.g. Estaña Lake, Pyrenees; Salada de Chiprana, Ebro Basin, Valero-Garcés *et* al., 2000; Lake La Cruz, Iberian Chain, Julià et al., 1998; Lake El Tobar, Iberian Chain, López-Blanco et al., 2011). Lake watersheds located at low and intermediate altitude were affected by increased grazing during

medieval times, and deforestation, changes in land use, and increasing farming after the 19th century. Mechanization during the 1950s increased erosion and changed some limnological properties in lakes. Management of hydrological resources greatly affected some of the lake systems. In El Tobar, waters were diverted from a nearby reservoir in the 1960s and the impact had implications for the lake dynamics and limnological functioning (López-Blanco et al., 2011). Disentangling human and climate impact is key to accurate reconstructions of past global changes. Besides it is needed to understand the response of lake ecosystems and exploring their resilience to increasing human pressure and to design conservation and restoration policies.

In sum, worldwide studies underscore the notion that archaeological and historical context is fundamental to produce rigorous interpretations of paleoenvironmental variability, particularly in regions where humans historically have settled for thousands of years. In such a setting, where environmental geochemistry can be influenced by a myriad of factors, a multi-proxy approach is essential for disentangling the impacts of anthropogenic changes from natural climate variability (Hillman et al., 2016).

The Iberian Ranges form part of a cultural landscape since at least Neolithic times. Historical events and land-use changes compilations using local and regional historical documents have been included in this research along the different *Results subsections*. They provide an independent account of landscape and land use changes during the last 2000 years that can be compared with the lacustrine records of watershed evolution. This line of research provides a history of past global changes reconstructed from lake records and also helps to investigate how lake systems have reacted to such variable human impact.

1.3.4 Quantification of watershed erosion and sediment input

At global scale, the evolution of the Earth's surface occurs through the erosion of rock and soil formations and redistribution of mass. This is ultimately driven by energy from two sources: tectonics, which contributes to erosion indirectly through uplift; and climate, which influences erosion and weathering via temperature and precipitation (Willenbring and Jerolmack, 2016). Both factors have the potential to produce global changes in the rate of landscape evolution, although their sedimentary signal may be obscured between climate, tectonics, geomorphology or, more recently, human impact feedbacks. Recently, that led to important debates in paleoclimatology science, as e.g. is the hypothesized positive feedback mechanisms between climate and erosion during the Cenozoic, supporting (Herman and Champagnac, 2016) or refuting that premise (Willenbring and Jerolmack, 2016).

At its simplest, the sedimentary system can be split into three

components, an upland production “erosional engine” (Whittaker et al., 2009), transfer of sediment, and deposition in a basin or store. However, basin response to external forcings is complex and strongly contingent upon the internal basin processing (autogenic processes) of these forcings, which moreover may be distorted by the anthropogenic intervention. At large spatial and time scales, some researchers suggest that sedimentary records more faithfully represent climate forcings than those from tectonic variability (Bonnet and Crave, 2003; Densmore, 2000). Other studies have shown how climate changes can also change or increase sediment delivery through mechanisms such as the extension of the stream network and increased stream powers (Coulthard et al., 2002; Tucker and Slingerland, 1997). Contrarily, some studies found that sediment response was relatively insensitive to short-term climate variability (Armitage et al., 2013). Therefore, there is clearly a need to disentangle the relative impacts of climate, tectonics, autogenic processes and human impact on sediment delivery and how these may manifest themselves in the sedimentary record.

At shorter spatial and time scales, watershed processes, particularly sediment delivery and denudation, are also key players in lake dynamics within small watersheds, and they seem to be more closely related with higher frequency environmental changes (events from floods, storms, decadal-centennial climate variations as solar irradiance or NAO). Specifically, alpine catchment areas characterized by steep and usually bare slopes, are particularly sensitive to erosion processes during heavy precipitation events. As consequence, both climate and soil cover evolution influence erosion/deposition rates and patterns. Therefore, lake sediments in such environments represent interesting archives to reconstruct past environmental changes through detrital sequences (Giguet-Covex et al., 2011). At last two millennia scale, the forcings can be simplified because tectonic or bedrock erosion activity is limited and except specific cases, may be omitted (Romans et al., 2015). However, in this context, places with human settlements since oldtimes are usually characterized by extensive grasslands landscapes, created in response to grazing pressure (Pascua Echegaray, 2012; Van der Post et al., 1997; Trimble and Mendel, 1995; Esteban Cava, 1994; Montserrat Martí, 1992), sometimes making difficult to discern the effect of land use from climate impact (Dearing and Jones, 2003). Therefore, human factor is key in the disturbance of the climate-vegetation-soil equilibrium (Giguet-Covex et al., 2011).

But, in that complex context, how clastic sediment influx can be quantified in a simple, feasible and reproducible manner from lake sequences? How is it related to watershed denudation processes? Is it comparable with actual measurements in mountain experimental catchments? And how both

human and climate impacts interplay in the sedimentary delivery during the last 2000 years? These questions have been addressed on *Results subsection 4.6*, following the simple conceptual approach of Einsele and Hinderer (1998): from known sedimentation rates the average denudation is found and compared with experimental catchments (García-Ruíz et al., 2010).

1.3.5 Human impact, climate and watershed dynamics synergies

The reasons behind the documented environmental change are one of the main controversies in the interpretation of the Holocene environmental paleorecords (Riera et al., 2004). One important problem of paleoecology not yet resolved is to differentiate between human and natural reasons for the environmental changes. The concept of the Anthropocene recognizes that humankind has become one of the many factors capable of affecting global geological processes. However, the questions of when, where and how human societies became such a geological force remain to be solved (Giguet-Covex et al., 2014). One suitable approach is the use of present-day analogues and crosschecking paleoecological with historical data (Lamb, 1995).

Usually, policy-related quantification of human influences on climate has focused largely on changes in atmospheric composition. However, a large body of work has demonstrated that land-cover change provides an additional major forcing of climate, through changes in the physical properties of the land surface (Pielke et al., 2002 and references therein). Landscape shaping, which affects erosion, is most likely the oldest human-caused geological process. In particular, the domestication of animals has long been a determinant of the modification of landscapes (Giguet-Covex et al., 2014; Trimble and Mendel, 1995). Globally, landscape modifications change the surface albedo radiative forcing, which may be comparable with that due to anthropogenic aerosols, solar variation and several of the greenhouse gases. Moreover, in regions of intensive human-caused land-use change such as North America, Europe and southeast Asia, the local radiative-forcing change caused by surface albedo may actually be greater than that due to all the well-mixed anthropogenic greenhouse gases together (IPCC, 2001).

Atmospheric and ocean circulation patterns and their subsequent involvement within the planet's climate are dynamic, variable and difficult to predict. This limits the ability to predict the impact of land-use change and landscape dynamics on global climate dynamic patterns. A more complete indication of human contributions to climate change will require the climatic influences of land-surface conditions and other processes to be factored into climate-change-mitigation strategies. Many of these processes may have strong regional effects that actually cannot be contemplated in a global worldwide perspective due to scale differences. This concept gives the idea

that local-scale environmental changes potentially could influence on larger regional scales. Thus, relatively small local changes should be taken into consideration when trying to explain broader environmental landscape dynamics. The land surface is an important part of the climate system, above all in considering local-scale. Since its beginnings, during societal evolution humans have substantially altered land cover type, ecosystem structure, natural disturbance regimes, and caused a fragmentation of the landscape. The resulting surface cover is both the legacy of past actions and a constraint on current options. Consequently, actions taken today will, in the same way, have effects that reach far into the future (Marland et al., 2003).

In the case of Mediterranean Europe, due to its particular climatic and physical conditions and historical anthropogenic pressure, the landscape is a complex mosaic. It is a product of the occurrence of intense rainstorms and prolonged droughts, the presence of steep slopes, topographic diversity, high evapotranspiration, recent tectonic activity, and the long and intense history of human activity, mainly reflected in the recurrent use of fire, overgrazing and farming. Thus, Mediterranean landscapes can be considered to be anthropogenic (García-Ruíz et al., 2013). Therefore, these areas need to be considered as part of a delicate equilibrium between nature and the long history of human occupation (Lasanta et al., 2015). Environmental consequences of changes in human behavior (mainly intensification or abandonment of agricultural systems) may be considered as pernicious in both cases because of the gradual decrease in landscape diversity and complexity and the increase of vulnerability to certain hazards such as forest fires, floods, and droughts (Serra et al., 2008). That, combined with natural processes occurred into the watershed of a lacustrine system may give to a number of human-environmental interactions that can increment or decrease geoecological processes (erosion, transport, deposition) and their linked consequences. As consequence, the continuous anthropic-environment synergistic effects and their variability can be stored in the lake sediments, making lacustrine records ideal to study and disentangle main human-nature bidirectional feedbacks.

The present-day environmental status of the Iberian Range karstic lakes-watersheds systems here investigated is the result of the natural variability and the evolution of historical management during the last 2000 years including the recent progressive decline in human activity in the half-20th century. Livestock tracks, small-populated villages, agricultural terraces, water channels, etc., are common in the contemporary landscapes. These indicate that in the past landscapes were intensively managed and more densely populated. In contrast to its economic backwardness today, the region enjoyed an important political and economic status in the Medieval Ages because of its strategic position at

the border between the Muslim and the Christian kingdoms (Esteban Cava, 1994). Multidisciplinary paleoenvironmental reconstructions corroborated by historical data are useful in accounting for lacustrine ecosystem responses to climatic and human activities.

The human-environment interactions and their relationship with the lakes-watersheds systems are described mainly in the *Results subsections 4.5* and *4.6*.

1.4 PhD candidate contribution

The global objectives for this PhD only can be addressed with a wide multidisciplinary approach, including a number of experts in different research-fields (sedimentologists, mineralogists, geochemists, geophysicists, diatomologists, palinologists, field surveyor, etc.; see *Results*, *subsection 4.1*, *Table 4.1*).

My personal contribution to the published research articles that form this PhD memoir ranges from the participation in field campaigns with the collection of long and short sediment cores, the physical surveys (bathymetries, seismic profiles, water sampling) to the laboratory preparation of the cores (splitting, imaging, description, packaging and storing), the description of the sedimentary sequences (*visu* and microscopic), the sampling processes and sample preparation for mineralogical and geochemical analysis realized with different techniques (semiquantitative, quantitative), the sampling and preparation of biological samples and the radioisotope dating. I also compiled main historical information from the area of study and organized it. I was responsible for data treatment to ensure the quality of the long-term series from the different proxies, and the interpretation of the main results after statistical treatment and/or calculus. Then I synthesized and combined the results and detailed interpretations provided by the expert collaborators, to extract and highlight the main conclusions relevant for this research, concerning human and climatic impacts on watershed and lake dynamics.

2

Area of study

The research developed during this PhD thesis has been focused on the study of two small sinkhole karstic lakes (El Tejo and La Parra) and a larger karstic lake (El Tobar), located in the Western Branch of the Iberian Range. Although sharing similar geomorphogenetic characteristics, climatic evolution and human impact, each lake has different watershed configurations, from small closed to large open basins. By comparing their evolution along time, interesting conclusion has been reached.

View of Lake El Tejo.
Vista de la Laguna de El Tejo.

2.1 Regional setting: The Castilian Branch of the Iberian Range

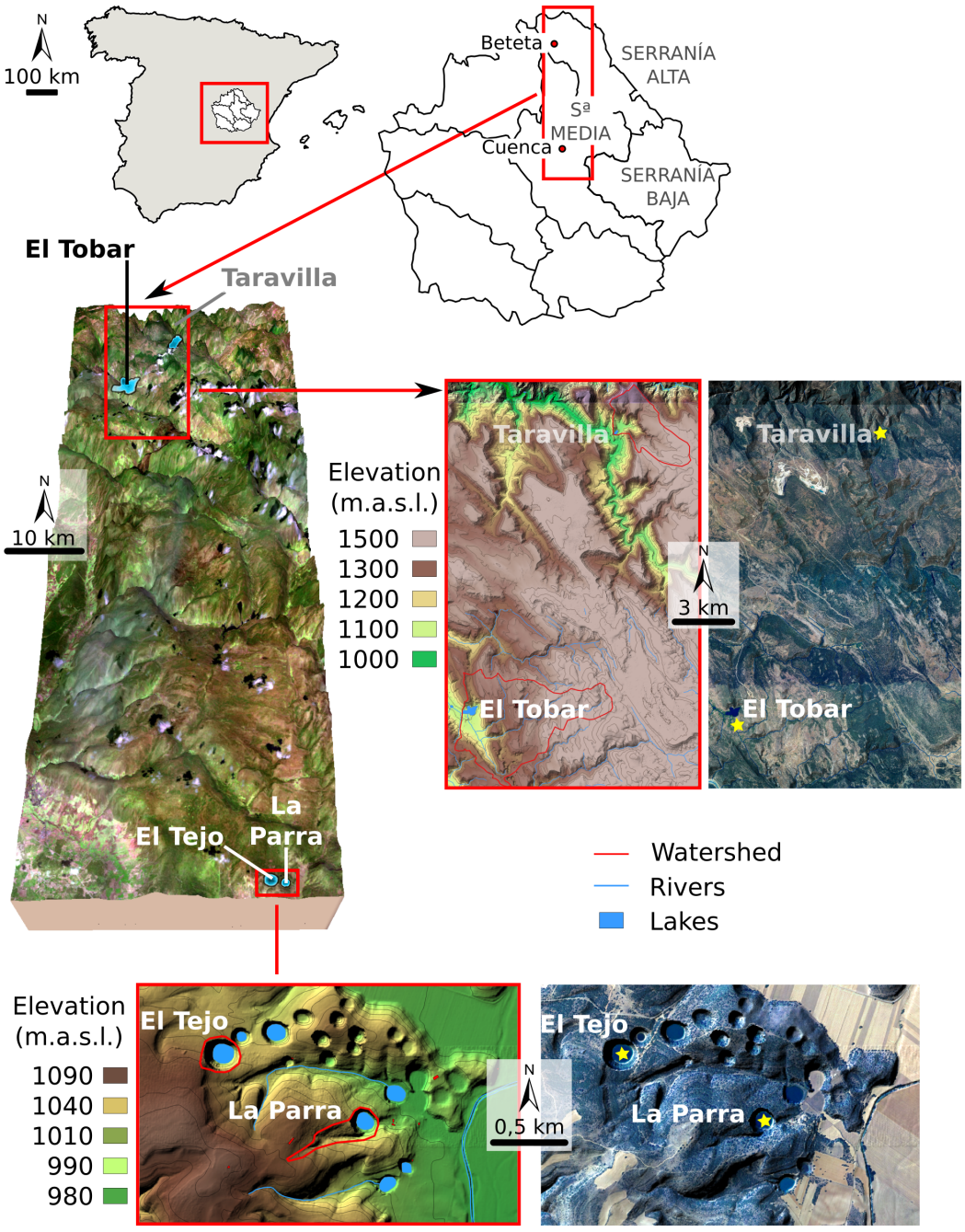


Figure 2.1. Top: *Iberian Peninsula with the location of Castilla-La Mancha autonomous region and main Iberian Range administrative subdivision: Serranía Alta, Media and Baja.* ***Center-left:*** *Respective location of lakes in the northern and southern part of the área of study.* ***Center-right:*** *Topographical elevation map and orthoimage of the northern site, comprising Lake El Tobar (and Taravilla).* ***Bottom:*** *Topographical elevation map and orthoimage of the southern site, with lakes El Tejo and La Parra.*

The area of study is located in the Serranía de Cuenca, at the Central-Northeast of the Iberian Peninsula in the Western Branch of the Iberian Range, also called the Castilian Branch (*figure 2.1*). One of the sites (El Tobar) is located at the northern part, called the Serranía Alta, and the other two sites are located about ca 100 km southwards, in the Serranía Media. The landscape is a carbonatic, relatively flattened topography reaching 1600 m a.s.l. at the northern part and about 1000 m a.s.l. at the southern zone. The Tajo, Guadiela and Cuervo rivers in the Serranía Alta and the Júcar, Cabriel and Guadazaón rivers in the Serranía Media have originated deep incised features in this landscape.

2.1.1 Geologic context

The Iberian Range has a NW-SE orientation, with a Paleozoic basement of quartzites and shales, and a mainly calcareous Mesozoic cover constituted by limestones and dolostones with intercalated levels of marls.

The tectonic phases that followed the main chain uplift, mainly during the Upper Oligocene and Lower Miocene, led to the formation of a horst and graben relief, with Neogene continental sediments filling the depressions and Paleozoic materials in the tectonically uplifted reliefs. A new tectonic pulse at the end of the Pliocene created new grabens, which have been infilled by Plio-Quaternary and Quaternary alluvial fans. This tectonic activity has continued until the Holocene (Gutiérrez et al., 1998).

From a geomorphological perspective, the most important characteristic of this area is the development of an extensive erosive event, named the Main Erosion Surface of the Iberian Range (Gutiérrez Elorza and Valverde, 1994; Peña et al., 1984) that mainly affected the large Mesozoic carbonate-dominated areas of the Range. This erosive phase took place during the lower Pliocene, and as a consequence, in the Iberian Range up to four erosive surfaces can be distinguished. They appear as stepped plains starting from the areas of Paleozoic relief with a gentle slope towards the Neogene continental basins, showing a typical piedmont outline (Gutiérrez et al., 1998). The development of these Neogene erosion surfaces of the Iberian Range is linked to a number of large-scale geological and environmental factors such as time, climate, lithology and tectonics (Gutiérrez et al., 1998).

These erosion surfaces provided the favorable framework in which very intense endo- and exo-karstic processes modeled large areas of carbonatic rocks during the Quaternary. As a consequence, a number of polje valleys, and other exo-karstic features as dolines and tufa-dammed valleys developed. Particularly, in the area of study, thick dolomitic Jurassic and Middle and Upper Cretaceous dolomitic formations have been affected by intense karstic processes (Alonso, 1986; Gutiérrez-Elorza and Valverde, 1994; Carmona and

Bitzer, 2001; Peña and Lozano, 2004) originating small funnel-shaped depressions, relatively deep that sometimes intercept the surrounding aquifers, developing karstic lakes (Valero-Garcés and Moreno 2011).

2.1.2 Modern climate and vegetation

The climate of the Iberian Peninsula is influenced by both, subtropical and mid-latitude climatic dynamics. The area of study is located in a mountainous Mediterranean climatic context, although modulated by continental influences with sharp daily and seasonal temperature fluctuations and prone to intense convective storms during summer and at the beginning of the fall. Average annual precipitation is relatively high (500-1000 mm) and is mostly controlled by the westerly winds associated with cold fronts in late fall and winter, but inter-annual variability is large.

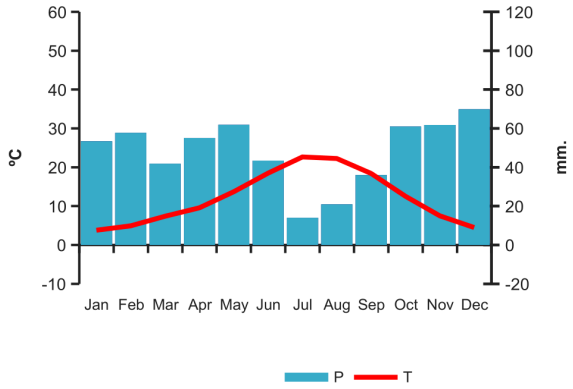
According to nearby meteorological stations (Beteta, 4 km NW, for the rainfall period 1945–2011 and Cañizares, 20 km SW, for the temperature period 1951–2010), the northern site of study (El Tobar) presents harsh long winters (3 °C mean monthly temperature) and hot short summers (19 °C). Average annual precipitation is relatively high (956 mm, *figure 2.2*), being July and August the driest months and December the wettest. Meteorological records show a small mean annual temperature increase (~ 2 °C) and a significant mean annual precipitation decrease since 1980s Current Era (CE), from 1600–1200 to 1000–800 mm. Vegetation type belongs to the supra Mediterranean sub-humid type with Central Europe tendency (Peinado-Lorca and Martínez-Parras, 1987). Pine trees dominate, with *Pinus nigra salzmannii*, *Pinus sylvestris* and *Pinus pinaster* as the main species; *Quercus ilex rotundifolia, Quercus faginea, Juniperus faginea* and *Juniperus communis* are also present as secondary species in the sunny slopes. Cereal fields and *Salix* crops - used in the past for an artisan industry - occur at valley bottoms, although some of them are currently abandoned.

The southern sites (El Tejo and La Parra, *figure 2.2*) present a mean annual precipitation of 542 mm, while the mean annual temperature is 14,6 ºC, ranging from 4 ºC (January) to 23 ºC (July) (Cuenca Meteorological Station, 12 Km NW, for the rainfall period 1956-2011). An increase of the mean annual temperature from about 11 ºC in 1956 to about 14 ºC in 2011 is also clear, indicative of a warming of the region in 55 years of ~ 3 ºC. Mean rainfall indicates that July is the driest month (15,7 mm) and October the wettest (59,4 mm). Meteorological records show a lineal decrease in rainfall from 1956 until 2011, ranging from 600 to 490 mm. Local vegetation is dominated by *Pinus nigra, Quercus faginea, Quercus ilex rotundifolia, Juniperus thurifera, Buxus sempervirens* and *Quercus coccifera*. Cereal crops occupy depressions and lowlands.

El Tejo

Elevation: 1049 m
Latitude: 39,99
Longitude: -1,88

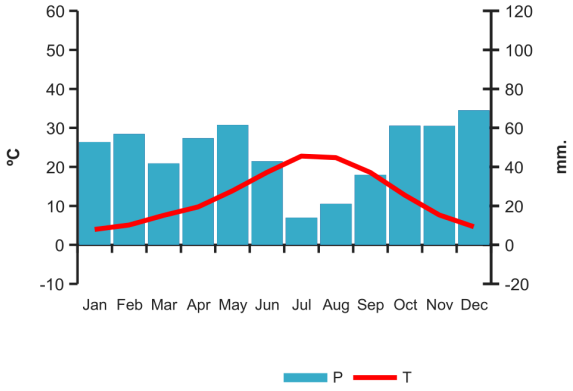
	T	P
Jan	3,8	564
Feb	4,9	487
Mar	7,4	256
Apr	9,5	513
May	13,7	205
Jun	18,5	487
Jul	22,7	538
Aug	22,2	462
Sep	18,4	949
Oct	12,5	609
Nov	7,5	77
Dec	4,5	462
Annual	**12,1**	**576,5**



La Parra

Elevation: 1018 m
Latitude: 39,98
Longitude: -1,87

	T	P
Jan	3,9	527
Feb	5,1	569
Mar	7,6	418
Apr	9,7	547
May	13,9	615
Jun	18,6	429
Jul	22,8	139
Aug	22,4	210
Sep	18,6	359
Oct	12,7	611
Nov	7,7	609
Dec	4,6	690
Annual	**12,3**	**572,6**



El Tobar

Elevation: 1228 m
Latitude: 40,54
Longitude: -2,05

	T	P
Jan	1,9	564
Feb	3,2	923
Mar	5,7	692
Apr	7,8	256
May	11,9	026
Jun	16,8	436
Jul	20,9	128
Aug	20,4	266
Sep	16,4	333
Oct	10,6	615
Nov	5,6	641
Dec	2,8	333
Annual	**10,3**	**856,7**

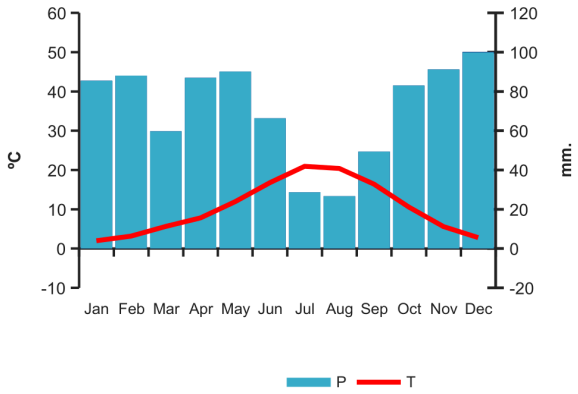


Figure 2.2. *Climographs with monthly and annual temperature and precipitation from the three lakes from provided by the Climatic Atlas from the Iberian Peninsula (Ninyerola et al., 2005).*

2.2 The lakes

This research has been carried in three karstic lakes. La Parra and El Tejo are located at the southern area of study in the Serranía Media, at the right margin of the polje excavated by the Guadazaón River, in the locality of Cañada del Hoyo, 25 km from the city of Cuenca. El Tobar is located in the valley excavated by the Masegar River, 5 km from the locality of Beteta in the Serranía Alta.

2.2.1 La Parra

2.2.1.1 Geology

Lake La Parra (39.982557, -1.866921, 1014 m a.s.l.) forms part of the karstic lake complex of "Las Torcas", in Cañada del Hoyo (*figure 2.3 and 2.5*), developed by intense karstic processes on Upper Cretaceous limestones and dolostones (Cenomanian-Turonian) and Late Jurassic carbonate formations (Alonso, 1986; Gutiérrez-Elorza and Valverde, 1994; Carmona and Bitzer, 2001; Peña and Lozano, 2004). The Middle-Upper-Cenomanian green marls (Margas de Chera Formation, Segura et al., 1988) are the local low permeability base level for karstic flows. The origin of this complex is probably structural, following the NE-SW trace of the known Guadazaón polje, which follows the orientation of the Valdemoro fault (Eraso et al. 1979). More recently some authors (Carmona and Bitzer, 2001) argued that the regional NW-SE syncline affecting the Cretaceous has been a main factor in the development of these sinkholes by collapse as consequence of karstic dissolution. That process, continued in time, led to the formation of small funnel-shaped depressions, relatively deep that intercepted the surrounding karstic aquifer and therefore permanent lakes developed (Valero-Garcés and Moreno, 2011).

Figure 2.3: *View of sinkhole Lake La Parra with the Uwitec floating platform ready to core.*

Lake La Parra has a circular morphology (113 m diameter, 0.01 km^2 water surface, 14 m maximum water depth) and steep margins, with 10 m high

vertical scarps composed of Upper Cretaceous dolomites surrounding the lake from W to SE margins.

2.2.1.2 Hydrology and limnology

The lakes of Las Torcas karstic system are hydraulically connected to the regional carbonate aquifer, and the lake levels reflect the regional groundwater levels. The main aquifer-recharge area (60% total water influx) is located in a 25 km^2 karstic area 15 km north of the Las Torcas Complex. The groundwater flux is estimated as 300l/s (Carmona and Bitzer, 2001) and follows N-S trend fractures and karstic conduits towards the south and only floods the sinkholes located topographically at <~1000 m a.s.l. From the sinkholes, groundwater drains towards the Guadazaón River fluvial aquifer.

The Lake La Parra has a relatively large ephemeral inlet and lacks of surface outlet. Although no hydrological balance is available, the recent lake level fluctuations are controlled by (1) the small watershed (~ 10 ha) with reduced run-off input, (2) the low transmissivity of local and regional aquifers, (3) a high-seasonally driven rainfall regime with high evaporation in summer and (4) recent use of regional aquifers by agriculture wells. The enriched $\delta^{18}O$ values in lake water (ca −4 per mil) compared with aquifer and surface waters $\delta^{18}O$ values (−8.5 to −7 per mil, Carmona and Bitzer, 2001) demonstrate a strong impact of evaporation processes in lake hydrology.

Lake basin comprises mainly four modern depositional environments: a narrow littoral platform, a steep talus area, an offshore transitional area and a small offshore distal area. Current conditions show a low-energy environment with small lake level fluctuations (2–3 m) related to the water levels of the main regional aquifer and the fluctuations of the Guadazaón River.

Influenced by a dolomite-rich watershed, the La Parra waters are dominated by HCO_3^- (4.78 meq/L) anions and Mg^{2+} (3.96 meq/L) cations, and present a basic pH of 8. The lake is holomictic and with low sulphate (Miracle et al., 1992) as shown by chemical (Electrical Conductivity from 305 µS/cm to 356 µS/cm at 16 m depth) and isotopic measurements (from −4.01 to −4.20 per mil $\delta^{18}O$, and from −38.11 to −37.46 per mil δD at surface and 16 m water depth, respectively from surveys in 2012).

2.2.1.3 Land uses

Depressions and lowlands in the Cañada del Hoyo area are occupied by cereal crops. Historically, the most important land uses have consisted on pasturelands for the livestock economy of the region developed during 13th-16th centuries and also the exploitation of the Mediterranean forest for building and coal production along 16th-18th centuries. During the last decades, the regional government promoted an intense pine reforestation and currently the area is protected as a Natural Park, leading to increasingly touristic interest

due to its exceptional geomorphological features. The current watershed of La Parra is covered mainly by shrubs (14 %) and woodland (77 %) (*figure 2.5*). The lake area represents the 16 % of the total watershed area. The ephemeral inlet of Lake La Parra is occupied by shrubs and pine trees, leading to a rapid vegetal recolonization of the zone, so the inlet appears to be only seasonally functional.

Figure 2.4: Top: *Panoramic view of sinkhole Lake El Tejo.* ***Bottom:*** *Special logistics to put he Uwitec platform in the water due complex lake access and platform ready to core.*

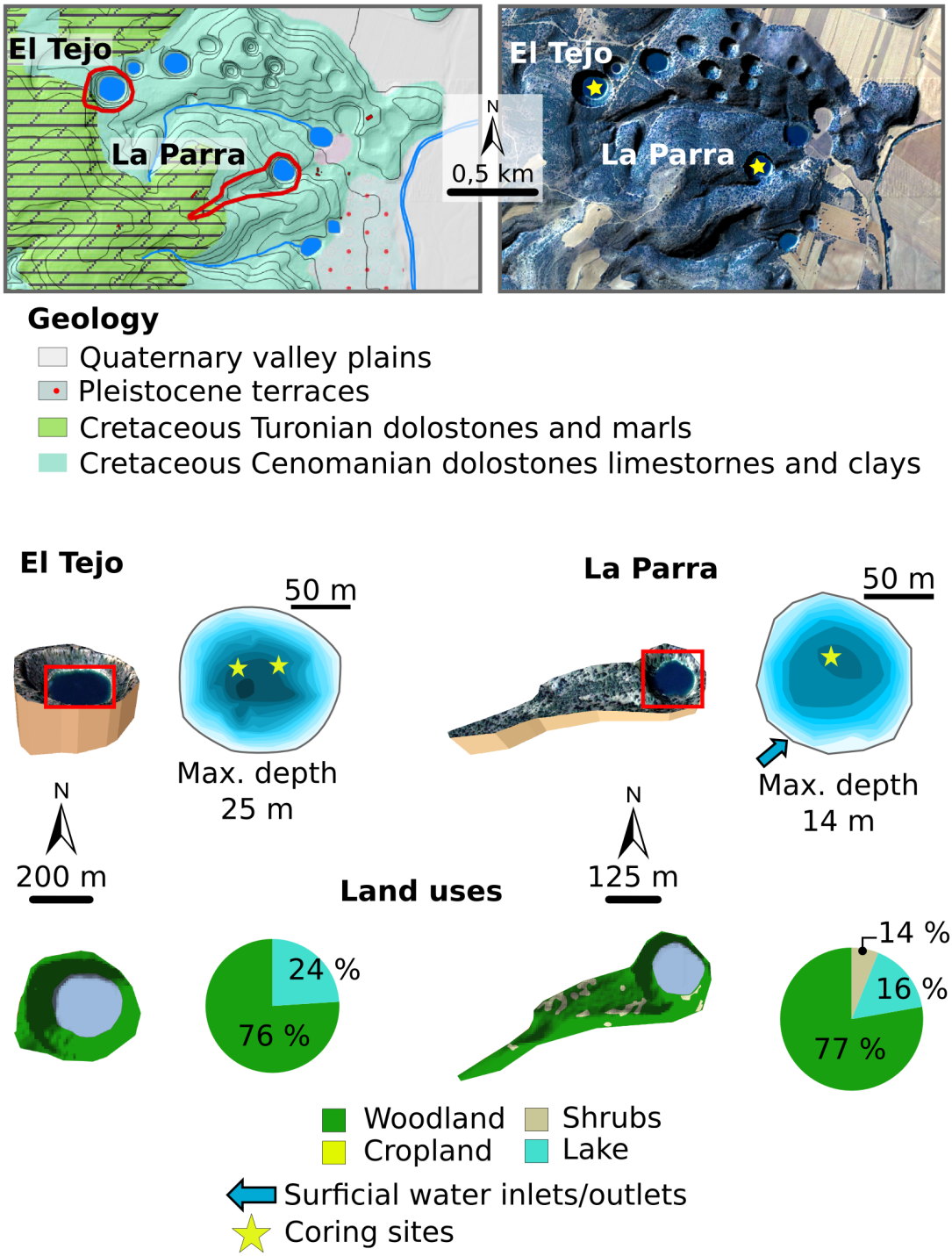


Figure 2.5. Top: *Geological map and orthoimage of lakes El Tejo and La Parra. Red lines limit the watershed drainage area.* ***Center:*** *3D-otrhoimtage diagrams of both lacustrine watersheds and the bathymetric map in which yellow stars indicate the long-cores sites.* ***Bottom:*** *Today land-uses map from aerial otrhoimages of the watersheds and surface percentage from total.*

2.2.2 El Tejo

2.2.2.1 Geology

Lake El Tejo (39.986618, -1.877637, 1000 m a.s.l.) also forms part of the flooded sinkhole complex of Cañada del Hoyo as La Parra and they are only 1.3 km apart (*figure 2.4 and 2.5*). The Lake has marked funnel-shape morphology with a surface of 0.02 km^2 with a maximum depth of 25 m. The catchment is very small (0.09 km^2), and basically consists of the very steep dolostone scarps of the doline, covered by dense vegetation in the north-facing slope and shrubs in the south facing one. Some rock blocks accumulations and screes occur at the base of the scarps reaching in some areas the littoral zones.

2.2.2.2 Hydrology and limnology

El Tejo Lake has not surface outlets or inlets and therefore, main water input is only by groundwater. The El Tejo lake levels would mostly reflect the regional aquifer groundwater level changes. Contrary to La Parra, El Tejo has no surface inlet, no extraction of lake waters for farming and the human impact inside the watershed has been minimal.

The chemistry of El Tejo waters is similar to La Parra, and is dominated by HCO_3^- (4.5 meq/L) anions and Mg^{2+} (5.8 meq/L) cations, and presents a high basic pH of 8.7. El Tejo lake is relatively well mixed, as shown by chemical composition (Miracle et al., 1992), Electrical Conductivity (from 537 µS/cm to 548 µS/cm at 25 m depth, surveys in 2012) and isotopic measurements (from 2.83 to 2.47 per mil δ18O, and from −3.85 to −0.65 per mil δD at surface and 25 m water depth, respectively from surveys in 2011). Evaporation plays a paramount control over El Tejo waters, as preliminary $\delta^{18}O$ values are around 2.7 per mil in relation to the values for the aquifer waters (-8 per mil, Carmona and Bitzer, 2001).

2.2.2.3 Land uses

The lake covers the 24 % of the total watershed area (*figure 2.5*). The general land uses for El Tejo area are the same than for La Parra, but El Tejo has a very small watershed and very steep margins, so direct human impact by farming, forest management or grazing is small.

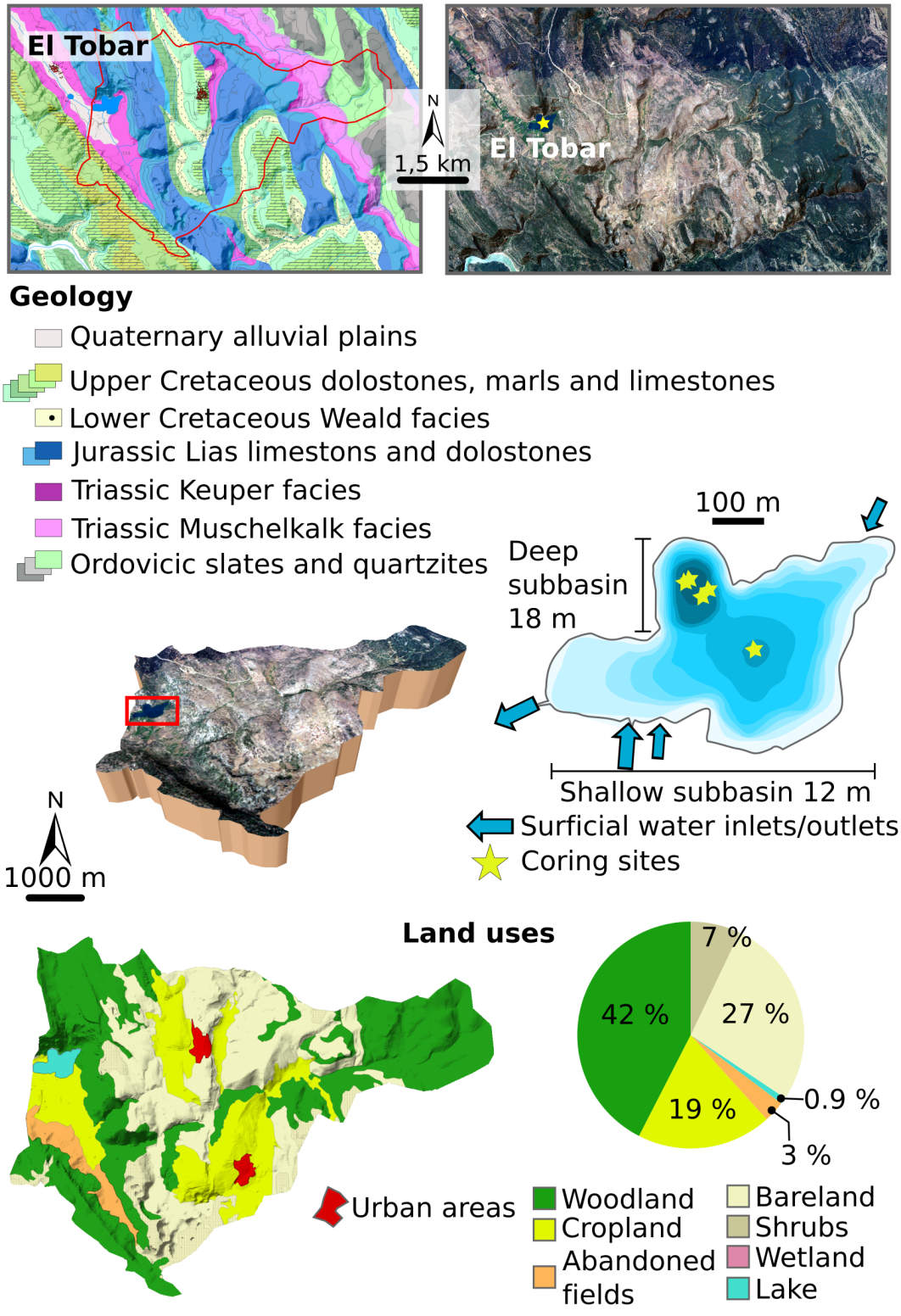


Figure 2.6. Top: *Geological map and orthoimage of lake El Tobar. Red line limits the watershed drainage area.* ***Center:*** *3D-otrhoimtage diagram of El Tobar watershed and the bathymetric map in which yellow stars indicate the long-cores sites.* ***Bottom:*** *Today land-uses map from aerial otrhoimages of El Tobar watershed and surface percentage from total.*

2.2.3 El Tobar

2.2.3.1 Geology

El Tobar Lake (40.544502, -2.049254; 1200 m a.s.l.) is located in the Serranía Alta, at the headwaters of the Tagus River (*figure 2.6 and 2.7*). The low altitude areas (~1100 m.a.s.l.) of the watershed are carved in easily erodible materials (Upper Triassic Keuper facies, composed by mudstones, evaporites and gypsum rocks). This Keuper facies act as an impermeable layer sealing the base of the Jurassic and Cretaceous regional aquifer. The Cretaceous and Jurassic limestones and dolostones formations dominate the catchment highlands (~1400 m.a.s.l.). A number of sinkholes occur in the watershed, likely developed by dissolution of the evaporitic Keuper facies and the overlying Jurassic and Cretaceous limestones and dolostones formations, which have been also affected by gypsum-driven dedolomitization karstification processes (Bischoff et al., 1994).

Figure 2.7: *Views of Lake El Tobar. In the bottom is shown the natural watergorund sources feeding the lake.*

2.2.3.2 Hydrology and limnology

The watershed, although relatively small, is one of the largest in the region (10.8 km^2 surface area) and is drained by several ephemeral creeks. El Tobar Lake is the largest karstic lake in the region, with a surface area of 0.17 km^2, and a maximum depth of 20 m. It is divided into two sub-basins: (i) a smaller funnel-shaped, deeper (0.03 km^2, 20 m depth) meromictic basin with an anoxic hypersaline hypolimnion (NaCl, brine, TDS = 19,116 ppm), and (ii) a

larger shallower holomictic basin (12 m depth, 0.14 km^2) with fresher waters (TDS = 408 ppm) (López-Blanco et al., 2011b; Vicente et al., 1993; Miracle et al., 1992; Vicente and Miracle, 1988). The lake is hydrologically open, with subaquatic spring inlets in the eastern shore (TDS = 428 ppm; pH = 7.7) and ephemeral inlets (pH = 8.2) from a small brook (Valle Solanilla creek) in the southern shore. In 1967 a connection with the nearby La Tosca reservoir (3 km southwest, fed by the Cuervo River) was established by an underground canal and, since then, El Tobar acts as a regulatory water reservoir (Esteban Cava, 1994). This canal provides the freshest waters (TDS = 268 ppm) dominated by $CO^2{}_3^-$ (3.6 meq/L), Ca^{2+} (1.4 meq/L) and Mg^{2+} (0.9 meq/L). The only surface outlet is the Masegar River, a tributary of the Guadiela River. A quantitative water balance for the lake is not available, but groundwater and the artificial canal are the main inputs. Subaquatic springs and ephemeral inlet waters have similar compositions to epilimnetic waters (IPE surveys, 2012). However, the occurrence of a stable hypersaline hypolimnion suggests an active groundwater input from saline springs draining evaporitic Keuper facies (Vicente et al., 1993).

Lake El Tobar is crenogenic meromictic with a permanent, very sharp, halocline that separates the upper water layers from the monimolimnion, constituted by sodium chloride brine (Miracle et al., 1992). The hypolimnion waters are dominated by Cl^- (305 meq/L) and Na^+ (261 meq/L) with pH = 7.6, while in the epilimnion these concentrations decrease until 1.7 and 1.9 meq/L respectively, with higher $CO_2{}^{3-}$ (3.7 meq/L) and pH = 8.3.

The lake surveys show a metalimnetic oxygen maximum during thermal stratification and oxygen exhaustion in the deep hypolimnion. A second relative oxygen maximum, located just at the top of the halocline occurs during spring and summer, due to the density gradient and an accumulation of phytoplankton at this depth (Miracle et al., 1992).

Isotopic measurements during several surveys in 2012 in the holomictic sub-basin water varies from -9.04 to -9.64 δ18O and from -59.21 to 62.06 δD per mil at surface and 10 m water depth, respectively. The meromictic sub-basin isotopic composition ranges from -9.25 to -9.72 $\delta^{18}O$ and from -57.74 to -59.81 δD per mil at surface and 15 m water depth, respectively. Isotopic measurements of the surface water (brook: -9.75 $\delta^{18}O$, -61.65 δD; channel: -9.94 $\delta^{18}O$, -63.65 δD) are relatively heavier compared to groundwater (-10.51 $\delta^{18}O$, -61.54 δD). Lake water values are close to surface water values, although slightly heavier values in the lake water suggest some evaporation processes. Relatively lighter values with depth in both sub-basins could indicate some mixing with groundwater in depth. Relatively light values in the isotopic composition of groundwater could imply a nearby recharge area, probably the highlands occupied by limestones, and also indicate a high transitivity, leading

to short residence times of recharge water.

2.2.3.3 Land uses

Most lowlands and flatlands in the valleys surrounding Lake El Tobar are occupied by cereal and *Salix* crops. The lake's watershed is of the largest in the area and therefore with a diversified land use: woodlands comprise 41 % of watershed surface, bareland about 27 %, croplands, 19 %, shrubs, 7% and abandoned fields 3 % (*figure 2.6*). The lake's area constitutes the 0.9 % of total watershed surface.

3

Material and methods

Multidisciplinary and multiproxy analyses of the sediment core sections were performed to address the objectives shown in the *Introduction* section. They included sedimentological, physical, mineralogical, geochemical and biological techniques. This approach, joined with an accurate age-model based on radiometric dating techniques allows reconstructing the evolution of the three lacustrine systems during the last 2000 years and the anthropic and climate synergies.

The paleoenvironmental interpretation of each proxy is explained in the research papers of this PhD thesis memoir. In this chapter, the techniques employed in the surveys, samplings and analyses are described.

Starting the field campaing in Lake La Parra.
Comenzando la camapaña de campo en la Laguna de La Parra.

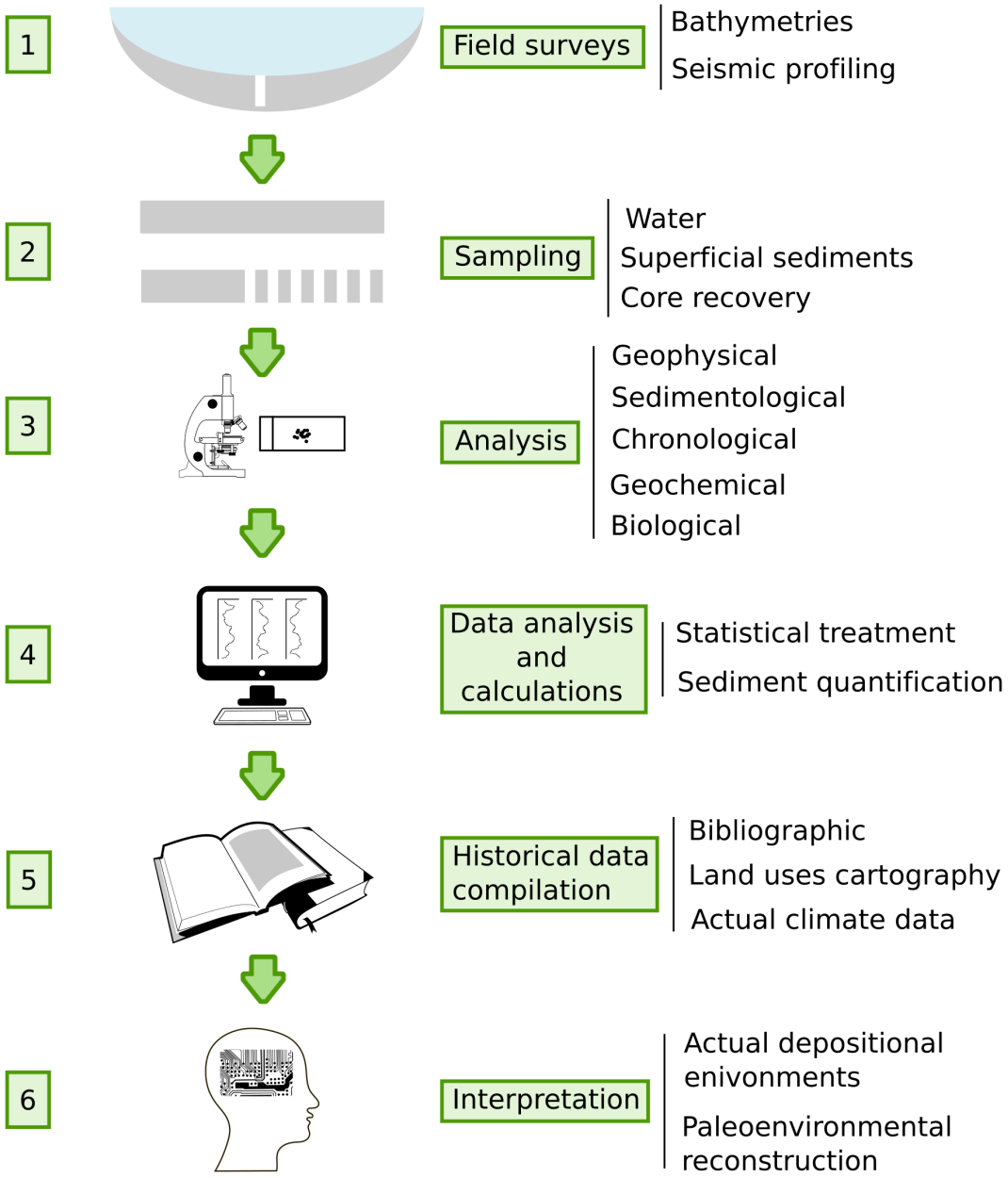


Figure 3.1. Methodological flow-diagram abstract that conducted to this research (modified from Douglas, 2007). It consisted in six main steps: **1)** Field surveys, including bathymetries and seismic profiling to select the appropriate coring site and following methodologies. **2)** Sampling was performed, involving water and superficial sediments sampling and short- and long-cores recovery, with subsequent laboratory subsamplings, preparations and appropriate storage. **3)** Main analysis were conducted in the samples using different instruments and methodologies, which included geophysical, sedimentological, chronological, geochemical and biological studies. **4)** After that, obtained data was organized, cleaned and prepared using statistical treatment when necessary for later interpretation or application of quantification techniques. **5)** Concurrently, past and recent historical information were compiled by using previous bibliographic studies, aerial orthoimages and also actual climate data (last 50 years) was compiled form nearby weather stations. **6)** Finally, data was contrasted with the historical information and interpreted.

3.1 Water sampling

During the 2010 and 2015 several surveys to measure water properties along depth profiles were conducted in the three lakes. In 2014 and 2015, during four seasonal campaigns temperature, pH, conductivity, salinity and dissolved oxygen (D.O.) were measured with a multiparametric probe YSI Professional Plus at 5 m interval from surface to the maximum depth in El Tejo and La Parra lakes. Also a 1 L water samples were obtained with a Niskins type sampling-bottle (*figure 3.2*) for analysis of principal cations (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}) and anions (SO_4^{2-}, Cl^{-}, NO^{2-}, NO^{3-}, NH^{4+}) in the IPE-CSIC water laboratory by using chromatography techniques. pH and Total Dissolved Solutes were also measured. Additionally, water samples were also taken from the nearby natural springs, water-bodies (El Tejo and La Parra) or active water inlets (lake El Tobar). Also δD, $\delta^{18}O$ and C^{13}_{DIC} stable isotope analysis were carried out in the stable isotope analysis laboratory service of the Salamanca University and in the water laboratory of the Instituto Andaluz de Ciencias de la Tierra (IACT-CSIC).

Figure 3.2.: *Preparing the equipment to pick water samples in the center of Lake La Parra.*

3.2 Sampling of superficial sediments

On April 2011, up to 21 short cores up to 30 cm long) were recovered from Lake La Parra using a Uwitec short corer. They were distributed in three NW-SE transects. From each short core the topmost first centimeter, representative of the most recent sedimentation processes, was sub-sampled for a sedimentological study. Macro and microscopic analyses using smear slides were performed using the methology outlined by the Limnological Research Center (LRC, http://lrc.geo.umn.edu/).

3.3 Geophysical survey

3.3.1 Bathymetries

Bathymetric and seismic surveys were conducted in all lakes. Transects with coordinates and depth data were acquired to obtain the bathymetric maps of El Tejo, La Parra and El Tobar lakes, using a Sonar Mite echosounder connected to a DGPS Max. The survey included 15 transects with a total length of 1.6 km in El Tejo; 15 transects with a total length of 1.5 km in La Parra; and 42 transects with a total length of 9 km in El Tobar. Later, a TIN interpolation model was calculated with the hydrographic software HYPACK, providing the final bathymetric maps.

3.3.2 Seismic profiling

A geophysical survey was also carried in the three lakes using a high-resolution seismic system with an EdgeTech Chirp 3100 SB-424 multi-frequency sub-bottom profiler and a frequency range of 2-10 kHz for 20 ms (*figure 3.3*). In El Tejo and La Parra a total of 1.6 km in 20 profiles and 1.4 km in 16 profiles were obtained respectively. In both sites, penetration was limited to the upper few meters. In El Tobar a total of 5.8 km distributed in 24 seismic profiles were obtained. Penetration was very limited in the shallow sub-basin (0.5 m) but reached up to 8 m in the deep sub-basin. The raw-data (band-pass filter, flat gain) were processed, visualized and interpreted with the EdgeTech Discover SB3200 XS software.

3.4 Core recovery

The long sediment cores were retrieved during several coring fieldwork expeditions. In Lake El Tobar, in April 2004 in the frame of the research project Limnocliber (REN2003-09130-CO2-02) and in collaboration with the LRC (University of Minnesota, US). Four Kullenberg cores (TOB04-1A-1 K, 5.4 m; TOB04-1B-1 K, 7.7 m; TOB04-1C-1 K, 7.4 m and TOB04-1D-1 K, 7.5 m) were recovered in the deepest part of the deep lake sub-basin (20 m); and one in the shallow sub-basin (TOB04-2B-1 K, 7.1 m), In 2007, a short gravity core (TOB07-1A-1G, 52 cm) and its replica were retrieved with the Uwitec gravity corer for

^{210}Pb and ^{137}Cs dating assays in the deep subbasin.

In Lake La Parra, in May 2010, two parallel Uwitec piston cores (PA10-1A-U, 7 m and PA10-1B-U, 5.2 m) were recovered in the deepest part of the lake (14 m) with the IPE-CSIC UWITEC platform. Also a short gravity core (PA10-2A-1G, 33 cm) and its replica were retrieved with the UWITEC gravity corer for ^{210}Pb and ^{137}Cs dating essays at the same coring point. Later, in summer 2011, a network of 21 short gravity cores was retrieved with the UWITEC gravity corer.

In Lake El Tejo, in June 2011, two parallel Uwitec piston cores (TEJ11-1A-U, 3.8 m and TEJ11-2A-U, 5.6 m) were recovered in the deepest part of the lake (25 m) with the IPE-CSIC UWITEC platform and coring equipment. Also four short gravity cores were retrieved and one of these (TEJ11-2C-1G, 72 cm) was sampled in the field for ^{210}Pb and ^{137}Cs dating essays at coring site 2.

To recover undisturbed long sediment cores from lakes is a complex task that requires specialized devices, great logistics and workforce. The Paleo-IPE research group has the capabilities to realize this work successfully and also the laboratory and storage facilities. The main methods to retrieve sediment core are described (*figure 3.4*).

Figure 3.3: *Seismic profiling during the geophysical survey in Lake El Tejo.*

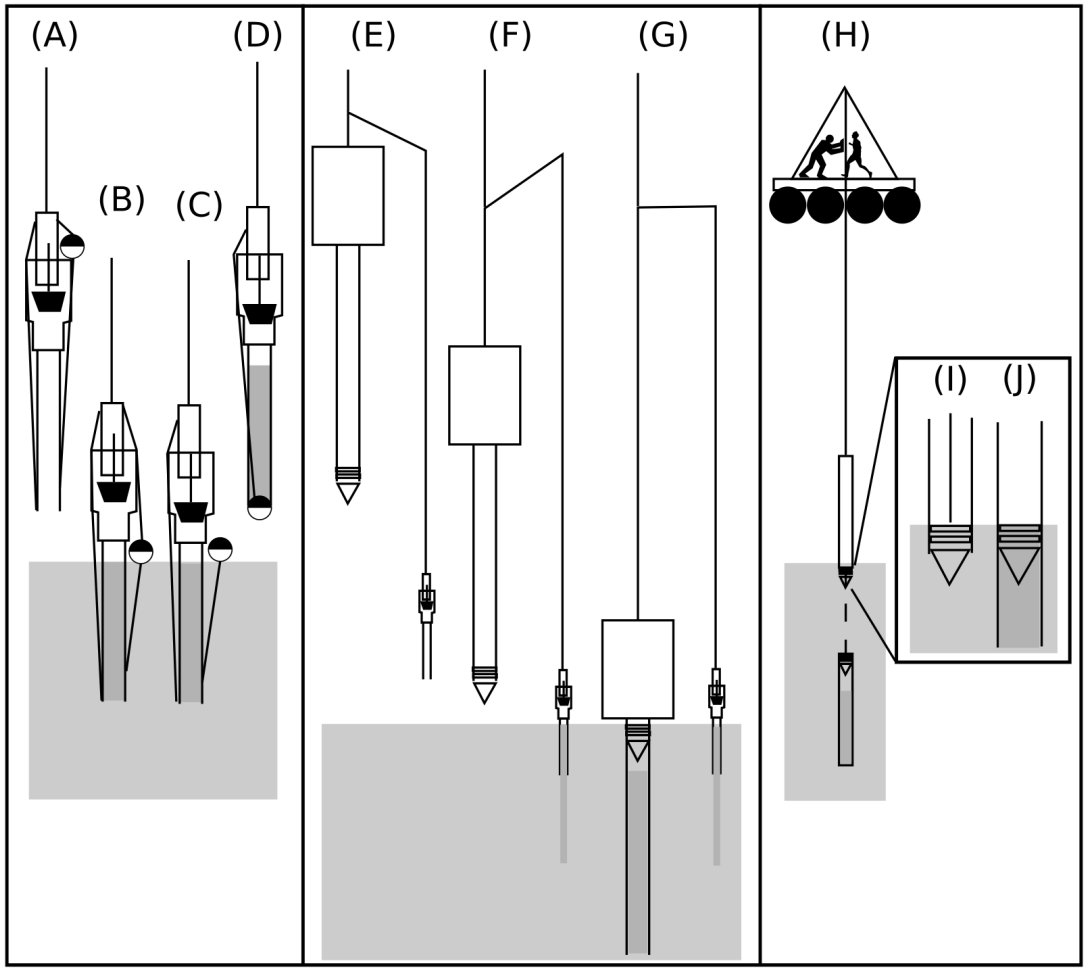


Figure 3.4. *Sketch of the three sediment corers used in this research (modified from Douglas, 2007). **(A-D)** The gravity short-corer is lowered down through the lake water slowly into the lake sediment. Once seated in the sediment, a weight is used to hammer the corer into the sediment. This releases a plug that seals the bottom of the corer when it is pulled-up and joined with the plunger at the top of the system, both avoid the loss of sediment in the gravity corer when recovering it. **(E-G)** Kullenberg corer: it is dropped into the sediment from a short distance (typically 0 to 3m), propelled by the momentum of 450 kg lead weights on the core head. The corer drop is triggered when an auxiliary gravity corer, suspended on a second cable to the side of the Kullenberg corer, enters the sediment and ceases downward travel. That allows capturing the upper sediments that are disturbed by the long corer. **(H-J)** Uwitec platform and piston corer: It uses suction in the same manner as a gravity corer to capture sediment within a section of core tube. Deployed from a stable floating platform, a rigid set of rigid rods supporting a rigid steel sampling tube (the corer) is lowered close to the sediment surface. The core tube is then forced to enter in the sediment by means of pushing the rods while the piston remains locked in place with a control cable, acting as a plunger. Once the core tube has been pushed to its further extent into the sediment, the assembly is retrieved to the surface. Piston cores may be deployed and retrieved sequentially in order to create one continuous record for the entire sediment stratigraphy. Cores are recovered in steel barrels lined with plastic tubes (standard polycarbonate).*

3.4.1 Long Kullenberg cores

The long sediment cores from lake El Tobar were recovered with the LRC Kullenberg platform (*figure 3.5*). This device consists of a single-drive, cable-deployed piston corer that is released from a floating-platform into the lake's floor sediment after being lowered on a wire from the side of the platform. The piston corer approaches the lake floor (about 3 m) preceded by an auxiliary gravity corer, that when poked into the sediment, triggers the long corer release sending it on a fast fall to the bottom. The weight at the corer head (450 kg) facilitates the penetration of the core barrel into the sediment, while the action of the piston creates a pressure differential at the top of the sediment column, allowing the soft sediment to enter the PVC core liner without disruption (*figure 3.4*). The Kullenberg piston corer rarely preserves the water-sediment interphase, but the system includes an accompanying gravity core (usually the auxiliary gravity corer) that captures the upper sediments that are disturbed or not recovered in the long corer (*figure 3.4*).

Figure 3.5: *Kullenberg platform coring in Lake El Tobar (2004).*

This system is appropriate to core soft and fine sediments because the recovered long core is continuous and only a single-drive is needed to obtain an up to 10 m long sequence.

3.4.2 Long Uwitec cores

The long sediment cores from lakes La Parra and El Tejo were recovered with the Uwitec piston corer floating-raft from the IPE-CSIC (*figure 3.6*). This device consists of a multi-drive, cable-deployed piston and rope-operated corer similar to the Kullenberg, deployed from the floating-raft into the lake's floor sediment with a winch-hoist system suspended from a tripod. Once the piston corer is at the right coring depth, the piston is released with the cable allowing the sediment to enter the polycarbonate plastic liner without disruption (*figure 3.4*). The core barrel (*figure 3.6*) is pushed into the sediment with a two weights hammer (up to 40 kg) also suspended in the tripod with a winch-hoist. When the drive is completed, the core is recovered with the winch-hoist system. The repetition of these steps with the successive addition of 2 m long rods for each additional drive allows retrieving a long sequence, determined by the number of rods and the hardness of the sediments.

Figure 3.6: *IPE-CSIC Uwitec floating platform.*

This system allows the recovery of the water-sediment surface, although parallel short gravity cores are also retrieved.

3.4.3 Short gravity Uwitec cores

Due to the great importance of the preservation of the water-sediment interphase, short gravity cores were recovered in the three lakes. The Uwitec short gravity corer consist on a single-drive corer that, once lowered 1-2 m above the lacustrine sediment floor with a cable, is released under their own weight to recover undisturbed sediment cores usually < 1 m length, depending to the weight in the corer head and the hardness of the sediment (*figure 3.4 and 3.7*). During the recovery ascending way, a valve in the top PVC liner prevent the lost of sediment due to upwards suction (*figure 3.4*). To increment the sediment length recovery, also reiterative percussion with auxiliary ropes and heavy weights can be used.

Figure 3.7: Top: *Uwitec short corer.* ***Bottom:*** *Recovered short and long sediment cores.*

3.5 Core description

Sedimentological analyses include a detailed visual description of the sediment, which also allows establishing a sampling strategy for the different analysis. Macroscopic and microscopic studies have been performed in all the cores recovered in the three lakes (*figure 3.8*). The sediment cores were split in two halves, imaged with a Charge Coupled Device (CCD) digital camera and described based on macroscopic (color, grain size, mineralogy, sedimentary structures, fossil content) and microscopic observations of smear slide samples. Some selected samples were observed with a Scattered Electron Microscope

(SEM) to help with the identification of some minerals.

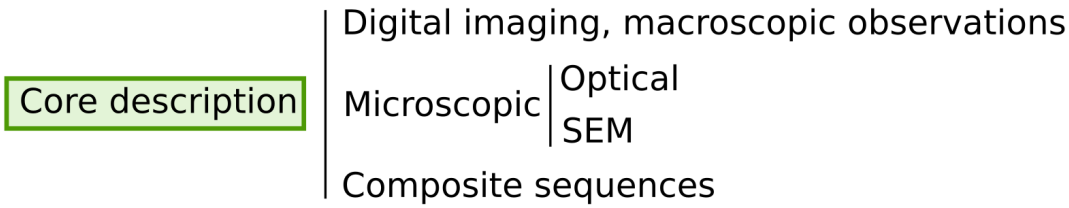


Figure 3.8. *Summary of the processes involving the sediment-cores description for posterior facies analysis and study of the depositional environments evolution, once the master composite sequence is defined.*

3.5.1 Digital imaging, macroscopic observations

The cores recovered in lakes La Parra and El Tejo were transported to the IPE-CSIC cold room facility and later to the Marine Geosciences Department of the University of Barcelona (UB, Spain) for core splitting, core imaging and initial non-destructive geochemical analysis. After being split in half longitudinally—the working half and the archive half - the sediment surface was carefully cleaned and optical images were taken of each individual core section with the high-resolution CCD camera attached to the Avaatech X-Ray Fluorescence (XRF) scanner from the UB XRF-Core Scanner Laboratory.

The cores recovered from lake El Tobar were transported to the LRC storage facilities and physical parameters were measured with the Geotek core scanner. Afterwards, the cores were split longitudinally in the working and archive halves. High-resolution (10 pixel/mm) optical images were taken of each individual core section with the DMT Core Scanner camera. Due to the fine laminations observed in this sequence, also additional X-Ray (XR) images, from the XR sensor attached to the Itrax X-Ray Fluorescence core scanner located in the Large Lakes Observatory (LLO, MN-US), were obtained to better study their structure. In a posterior stage, the identification of light, gray and dark laminae occurring in the laminated facies by using the image quantitative parameter L* (*lightness*, from the CIELAB color space) was calculated with the ImageJ 1.48v graphic software (http://imagej.nih.gov/ij/).

3.5.2 Microscopic observations (optical and SEM)

To complete the macroscopic observation, the methodology described by Schnurrenberger et al (2003) and the TMI tools (https://tmi.laccore.umn.edu/) were used for the optic microscopic observations of smear slide sediment samples. Smear slides consist of a thin layer of unconsolidated sediment on a glass slide and they provided qualitative information about sediment components and texture (mineralogy, form, size, biological components).

Smear slides were taken for the facies identified in the composite sequences.

Selected samples (laminated facies) were analyzed using Scanning Electron Microscopy (SEM). Samples were dried and then gold-coated to avoid peak overlapping. SEM observations were made in conventional high vacuum SEM using a JEOL JSM-6400 microscope from the Microscopic Services of the University of Zaragoza (UZ, Spain) coupled with an energy dispersive X-ray (EDAX), INCA 300 X-Sight, for elemental identification.

3.5.3 Composite sequences

Optical images from all three lakes core-sites were loaded into the Corewall software (http://www.corewall.org/) for correlation purposes. Sections from duplicate cores for each coring-site were aligned using visible and characteristic sedimentological patterns as laminations, sedimentary facies, boundaries or structures. Further tie points between the cores sites were matched using characteristic colors, physical properties and initial geochemical X-Ray Fluorescence (XRF) data. A composite and continuous master sediment core sequence was obtained for the three lakes selecting the best-preserved parallel core-sections in the different intervals and by splicing together various sections from each site to eliminate any gaps in the record. The composite sedimentary sequence was utilized in all subsequent analysis.

3.6 Sediment core analyses

The analysis performed in the recovered sediment cores range from geophysical to semiquantitative and quantitative geochemical techniques, including mineralogical, grain-size analysis and diatom counting (*figure 3.9*).

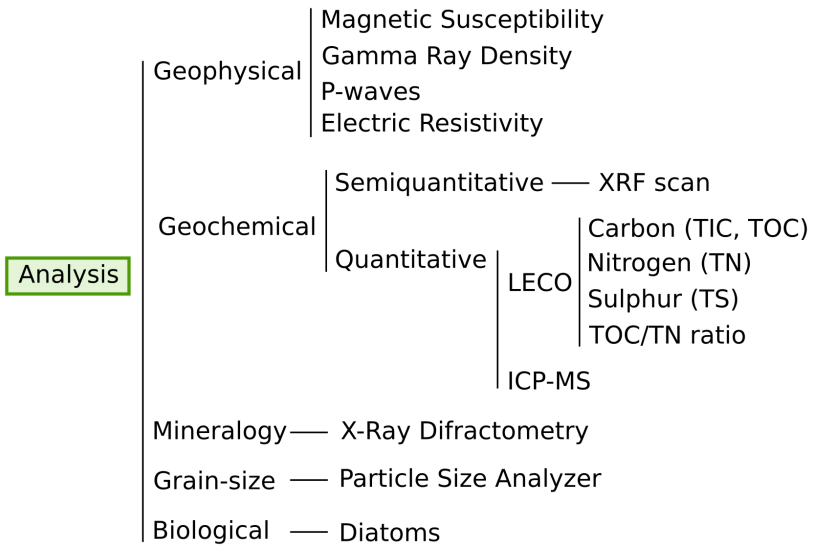


Figure 3.9. *Summary-diagram of employed methodology for geophysical, geochemical, sedimentological and biological analyses. XRF: X-Ray Fluorescence. TIC: Total Inorganic Carbon. TOC: Total Organic Carbon. TN: Total Nitrogen. TS: Total Sulphur. ICP-MS: Inductively Coupled Plasma-Mass Spectrometry.*

3.6.1 Geophysical properties analysis

Magnetic susceptibility (MS), which is related with the content of iron-bearing minerals, and Gammy Ray density, linked to the wet bulk density (ρ) of sediments, are valuable proxies for rapid characterization of the sediments. Geotek scanners use a ^{137}Cs radioactive source for the density measurements, while a Bartington loop measures the MS. They are also equipped with piezoelectric transducers to measure the amplitude and velocity of P waves in the sediment, and a double-coil to record the electric resistivity.

In order to provide the most complete characterization of the recovered sediments, the El Tobar cores were scanned for sediment gamma density and MS at 1 cm resolution with the LRC LacCore (MN-US) Geotek Multisensor Core Logger (MCL). The piston cores from lake El Tejo were scanned for sediment gamma density and MS at 1 cm of resolution with the Geotek MCL operated by the Maritime Technology Unit of the Mediterranean Center for Marine and Environmental Research (CMIMA-CSIC, Spain). Sediment cores from lake La Parra were split and not scanned for physical properties.

3.6.2 X-Ray Fluorescence (XRF) core scanner

X-Ray Fluorescence (XRF) core scanning data are widely applied to paleoclimate reconstructions on timescales ranging from seasonal to millions of years (Tjallingii et al., 2006). Every section of the composite sedimentary sequence from each lake was run through an XRF core scanner at 5 mm resolution. The XRF core scanner is a computer-controlled core-scanning tool that analyzes the chemical composition of sediments directly at the surface of a split sediment core. Therefore, XRF core scanner measurements are non-destructive, consumable costs are relatively low, and sample preparation is minimized compared to conventional chemical analysis on discrete XRF samples. Moreover, the high sampling resolution of the XRF core scanner (down to 0.5 mm) provides nearly continuous information about the chemical composition of the sediment and meets the growing demand on high-resolution sedimentary records.

The Scanning XRF uses X-rays to excite and ionize the electrons of atoms within the sediments and forcing them into higher energy states. When the electrons move back into lower energy state, energy is released in the form of fluorescence. According to Moseley's law, the outgoing fluorescence radiation is linked to the atomic number of the element, resulting in larger response depths for heavier elements that emit relatively high fluorescence energies. Consequently, each element within the XRF detection range has fluorescence radiation at well-characterized energies that can be count. An additional problem is that owing to the nature of the of split surfaces, particularly effects

resulting from sample inhomogeneity and surface roughness, the water content, the grain size and the matrix effect, the radiating energies for the same atoms may differ or interfere. Therefore, results are semiquantitative, yet provide reliable records of the relative variability in elemental composition down-core (Richter et al., 2006). So this method provides a semiquantitative estimation for the main geochemical composition of the sampled sediments. Heterogeneity and surface roughness effects could become more pronounced for coarser-grained sample material (Tjallingii, 2006). As consequence, to analyze the split sediment cores with XRF scanners is very important to reduce at maximum the possible physical inhomogeneities in a split core by cleaning carefully its surface. Additionally, the sediment surface has to be covered with a 4 µm thin Ultralene foil to prevent contamination of the measurement unit and desiccation of the sediment during the XRF scanner analyzes.

El Tobar sediment core-sections were analyzed with the Itrax XRF scanner (Richter et al., 2006) from the University of Minnesota, Duluth (US-MN) with a Mo tube under the following working conditions: 30 kV, 20 mA and 30 s of exposition time per measurement point. The La Parra and El Tejo composite core sections were analyzed with the Avaatech XRF core scanner (Tjallingii, 2006) from the UB (Spain), using a current of 20 mA, with two passes of 10 kV and 30 kV X-Ray voltage at 15 s and 25 s count time respectively.

The data obtained are expressed as element intensities (counts per second). Element concentrations are not directly available from the XRF measurements, but the obtained values can be used as estimates of relative concentrations (Richter et al., 2006).

3.6.3 Carbon, Nitrogen, Sulphur and TOC/TN ratio

The carbon content in lacustrine sediments may be a component of both, the inorganic and the organic fraction. The Total Inorganic Carbon (TIC) represents the inorganic fraction of the Total Carbon (TC), while the Total Organic Carbon (TOC) reflects the quantity or organic matter in the sediment. Total Nitrogen (TN) and Total Sulfur (TS) represent the total amount of nitrogen and sulfur respectively in the sediment in different phases and minerals (organic matter, nitrates, gypsum, sulphides). Moreover, additional information about the source of organic matter (aquatic or terrestrial) can be obtained analyzing the TOC/TN (or C/N) ratio variability: aquatic phytoplankton usually presents TOC/TN values between 4 and 10, while terrestrial vascular plants present a ratio ≥ 20 (Meyers, 1997). Variations in these parameters provide appreciate information for interpretation of biological cycles and the depositional evolution of the lake (Meyers and Lallier-Vergés, 1999; Meyers, 1997). In the three composite sediment cores, TC, TIC, TOC and TS were analyzed with a 2 cm sampling interval, while TN was analyzed each 4 cm. La

Parra and El Tobar composite cores were analyzed for TC, TIC and TOC with a LECO SC144DR from the IPE-CSIC, while La Parra TN values were measured with a FLASH EA 1112 LECO TRUSPEC-CN at the Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC, Spain). El Tobar TN was analyzed with a VARIO MAX CN elemental analyzer available at the IPE-CSIC. TC, TIC, TOC and TN from El Tejo were measured in the CEBAS-CSIC.

3.6.4 Elemental geochemical analysis

To enable a complete geochemical description for each sedimentary facies and to check the reliability of the XRF core scanner analysis, the elemental geochemical composition of sediment samples was also determined by quantitative elemental assays of major and trace elements by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), using a Perkin/Elmer Nexion 300X ICP-MS at the University of Pittsburgh (US-PA), following the methodology from Pompeani et al. (2013). Fifty three samples were measured in El Tobar, 52 in La Parra and 50 in El Tejo along the composite sequences and covering all sedimentary facies.

3.6.5 Mineralogy

X-Ray Difractometry (XRD) was used for semiquantitative mineralogical characterization of each facies from the three lakes. Mineralogy was determined on selected samples covering all facies variability by a Siemens D-500 X-ray diffractometer (Cu kα, 40 kV, 30 mA, graphite monocromator) at the Servicios Científico-Técnicos of the Instituto de Ciencias de la Tierra Jaume Almera (ICTJA-CSIC, Spain). Identification and relative abundance of the predominant mineralogy of the crystalline fraction were determined following Chung (1974a,b).

3.6.6 Grain-size analysis

To better characterize the sedimentary composition of El Tobar record, three samples from each sedimentary facies were analyzed for grain-size distribution using a Beckmann Coulter LS 13 320 Particle Size Analyzer from the Departamento de Suelo y Aguas de la Estación Experimental Aula Dei (EEAD-CSIC, Spain) and facies were then classified using the textural Shepard diagram (Shepard, 1954) in sand grain-size (2000 to 50 µm), silt grain-size (50 to 2 µm) and clay grain-size (< 2 µm). The organic matter was eliminated prior to analyses by H_2O_2 attack (10 %). The sediment was then disaggregated by using $Na_2H_2P_2O_7$ during 24 h.

3.6.7 Biological indicators: Diatoms

Diatoms were studied in detail in the composite record of lake La Parra,

where they were relatively abundant. Margarita Caballero, from the Universidad Nacional Autónoma de México (UNAM, México), prepared the diatom samples and performed the counting and taxonomic identifications. Standard extraction and counting methods (Stoermer et al., 1996) were applied to 20 samples for diatom analyses. The samples were selected considering sedimentary facies variability, and therefore, the depth and time resolution are variable. Diatom concentration per unit weight of dry sediment was calculated following Battarbee (1986) and is expressed as valves per gram of dry sediment (v/gds × 10^6). Relative abundances of the diatom taxa were calculated in two ways: (1) based on the total diatom sum, which were used for the calculation of the planktonic and non-planktonic percentages, and (2) based on a partial diatom sum which included all species except for *Cyclotella cyclopuncta*, the most contributing species. This method for expressing diatom relative abundance was chosen given the high dominance of *Cyclotella cyclopuncta* in the record, as excluding it from the diatom sum allows for the variations along the sequence of the non-dominant species to be more evident. Taxonomic identifications and autoecological requirements for the principal diatom taxa were made using literature (Håkansson, 2002; Håkansson and Carter, 1990; Julià et al., 1998; Kiss et al., 2007; Krammer and Lange-Bertalot, 1986–1991; Morellón et al., 2011). The dominant species in the La Parra record was identified as *Cyclotella cyclopuncta*; however, this species is considered to be very close or possible conspecific with similar small centric diatoms such as *Cyclotella delicatula* or *Cyclotella distinguenda* var. *unipunctata* (see Kiss et al., 2007). The statistical treatment of the diatom dataset for cluster analysis was performed using the R software package (R Development Core Team, 2013) together with the package 'vegan' (Oksanen et al., 2013). Distances between clusters were recomputed by the Bray–Curtis method, using a data matrix corrected by the square root of the species percentages.

3.6.8 Dating

The composite cores of the three studied lakes were dated using two main methods: ^{137}Cs and ^{210}Pb probe essays for the topmost recent part of the records (*figure 3.10*); and ^{14}C for longer timescale. This approach has allowed the construction of robust age-models for the three lake sequences.

To establish the chronology of the lacustrine composite sequence for lake La Parra, 13 Absortion Mass Spetrometry (AMS) ^{14}C dates were obtained at the Poznan Radiocarbon Laboratory (Poland) and the DirectAMS Laboratory (US-WA) from wood fragments in long core PA10-1A-U. ^{137}Cs and ^{210}Pb activities in short core PA-10-2A-1G were obtained by gamma ray spectrometry at the St Croix Watershed Research Station (US-MN). The ^{210}Pb age model was determined following Appleby (2001). The upper part of core PA10-1A-U was correlated with the short core PA-10-2A-1G using TOC values. Radiocarbon

dates were calibrated using the curve IntCal09 (Reimer et al., 2009) and selecting the median of the 95.4% distribution (2σ probability interval). Age–depth model was obtained with Clam 2.0 code (Blaauw, 2010), adjusting the curve with a locally weighted spline.

The age model for Lake El Tejo is based on 12 radiocarbon dates from wood macro-rest samples, analyzed at Direct-AMS (US-WA) and BETA (US-FL) laboratories. Two samples were previously split and also sent to Poznan laboratory (Poland) to double-check the results. The uppermost sediments of the sequence were recovered in the short core TEJ11-2C-1G and correlated with the uppermost part of the composite long core using TOC values. ^{210}Pb activity profiles were obtained in the short core by gamma ray spectrometry at the St. Croix Watershed Research Station (US-MN), following (Appleby, 2001). Radiocarbon dates were calibrated using the curve IntCal 13 (Reimer et al., 2013) and selecting the median of the 95.4% distribution (2σ probability interval). The final El Tejo sequence age model was performed with Clam 2.2 code (Blaauw, 2010) and is based on the 12 radiocarbon dates from the long core and on ^{210}Pb essays from the short core. Only two of the wood samples were discarded because they were stratigraphycally inconsistent (too old), probably due to sediment reworking processes. The final age-depth curve, after different fits with several regression models, was adjusted with a degree 3 polynomial regression from the top of the core until the depth of 467 cm. From 467 to 600 cm, a lineal regression model was applied. Therefore, the final age-model is based in the combination of both, the polynomial and lineal regression models.

The construction of the age-model for El Tobar sequence has been a long and iterative process that involved different types of samples to date the sequence (TOB04-1B-1K) with ^{14}C techniques. Firstly, three wood macrorests were dated soon after the cores were retrieved (two *Salix* sp. at 551 and 789 cm depth, and one sample species not identified at 765 cm). As the results were contradictory, and no more macrorests were found in the sequence, macro-charcoal particles were picked, and although their presence in the sediments also was scarce, three samples (472, 756 and 768 cm depth) were dated. Finally, in a third attempt to improve the age-model and due to the scarcity of wood or charcoal fragments, bulk sediment (one sample at 789 cm depth) and pollen concentrates (three samples at 206, 279, and 507 cm depth) were also dated. Three different laboratories have been involved in dating the 10 samples from core TOB04-1B-1 K: the Poznan Radiocarbon Laboratory (Poland), the DirectAMS Labora- tory (US-WA) and the Quaternary Dating Research Unit Laboratory from the Council for Scientific and Industrial Research (South Africa). Radiocarbon dates were calibrated using the curve IntCal 13 (Reimer et al., 2013) and selecting the median of the 95.4%

distribution (2σ probability interval). The uppermost sediments of the sequence were recovered in the short core TOB07-1A-1G and correlated with the uppermost part of the TOB04-1B-1 K long core using TOC values. ^{137}Cs and ^{210}Pb profiles were obtained in the short core by gamma ray spectrometry at the St. Croix Watershed Research Station (US-MN). The ^{210}Pb dates were determined following Appleby (2001). A final age-depth model based on four ^{14}C dates and the ^{137}Cs peak was performed with Clam 2.2 code (Blaauw, 2010). The final curve, after different fits with other regression models, was adjusted with a degree 3 polynomial regression, which provided the best-fitting curve for the dates.

***Figure 3.10**: Field sampling of slices from the short cores recovered in La Parra for ^{210}Pb-^{137}Cs dating.*

3.7 Data analysis and calculations

3.7.1 Statistical treatment

The Principal Component Analysis (PCA) is a common technique widely used to describe and interpret X-Ray Fluorescence (XRF) continuous scans of geochemical data (Carrevedo et al., 2015; Trunova et al., 2015; Develle et al., 2011; Giralt et al., 2011; Giralt et al., 2008). XRF geochemical scans from sediments get semi-quantitative measurements of the relative content of the chemical elements (Kylander et al., 2011; Richter et al., 2006), but the source of

these elements is multiple, from different minerals and varied sediment provenance. Therefore, instead of interpreting elemental ratios independently from the rest of elements that compose the sample, many authors use PCA tools to investigate their interrelations and find combined indexes integrating several elements. PCA techniques are a powerful tool to study how the elements are grouped and related with each other in order to provide a more realistic and accurate interpretation of their behavior and the processes behind geochemical changes in sediment composition. PCA also reduce the number of observed variables to a smaller number of factors, providing insight into the structure of the variance of the parameters and to identify which set of variables form coherent subsets that are relatively independent of each another. Variables that are correlated with one another and which are largely independent of other subsets of variables are combined into factors. Finally factors are plotted in a PCA correlation biplot, which provides information on interrelationships between each of the variables, which may help to further elucidate the sedimentary processes responsible for the observed stratigraphic and geochemical changes recorded in the sediments.

Therefore, to highlight the main underlying environmental processes in each of the three records, the relationships among the geochemical and sedimentological signals have been investigated with PCA by using R software 3.2.0 (R Development Core Team, 2014) and the package FactoMineR 1.29 (Lê et al., 2008). The dataset includes XRF scanned (El Tejo and El Tobar) or ICP analyzed-elements (major elements, trace elements and REE; La Parra) and bulk geochemistry (TOC, TIC and TN). In the case of XRF data, to maximize the quality of the results, only elements with more than 1500 cps (counts per second) have been used. To compare both datasets, the XRF data were re-sampled from the original resolution of 0.5 mm to 2 cm (LECO resolution). LECO resolution was re-sampled as well to ICP resolution (≈10 cm) when necessary. All variables were also normalized with respect to their mean and standard deviation.

3.7.2 Sediment quantification

The quantitative relationships between denudation in the three drainage areas respect to the sediment accumulation in the three lakes have been approached following the methods described in Einsele and Hinderer (1998). From known sedimentation rates, the average denudation rate and mass denuded for a determined time interval can be calculated. Denudation rate is defined by these authors as the average amount of lowering of the land surface in a certain region over a given time span, which comprises mechanical and chemical denudation. Here it is calculated as the total denudation rate (DRt) and no distinction has been between mechanical or chemical denudation.

Mechanical denudation prevails over chemical denudation in regions of high relief and is less dependent on climate or rock type than on relief (Einsele and Hinderer, 1998). In mountainous lakes with active fluvial inlets, biogenic sediment production is limited and can often be neglected in relation to the rapid input of terrigenous material (Einsele and Hinderer, 1998). As sedimentological analyses have shown in these lakes, the major part of the sediments is originated by mechanical erosion in the watershed (Corella et al., 2014; Moreno et al., 2008). Thus, terrigenous carbonatic and siliciclastic are the dominant mineral fraction in the sediment.

It is needed to assume that in closed systems, the mass denuded (Md) is equal to the mass accumulated in the lake (Ml) for a certain unit of time. In open systems, Md is greater than Ml, because part of the dissolved load entering the lake is lost through outflow, but the mechanically eroded mass is considered to be completely stored in open lakes (Einsele and Hinderer, 1998). In large watersheds as El Tobar, sediments may also accumulate in some parts of the watershed area due to a higher variety of geomorphological landforms (i.e. channels, slopes, palustrine areas, low areas disconnected from the main hydrological network, etc.). Thus, only relatively high-energy floods are capable to wash these trapped sediments and transport them until the lake. Therefore the real mass denuded could be greater than the mass accumulated in the lake (Ml).

A detailed lake bathymetry is also key for the calculations, as we need to know the lake area (Al) for each sediment interval analyzed in the sediment cores. Lake area (Al) was calculated from the bathymetric maps using GIS software. In the smaller lakes (Tejo, Taravilla, La Parra) the lake surface area with slopes < 11º was considered as the depositional area, to avoid over estimations due to some sediment focusing in the deepest areas. In El Tobar, the seismic survey demonstrates that main depositional events occur with similar thickness in both the deep and shallow basin, and consequently, the total lake area was also considered the depositional area.

To obtain the minimum mass denuded (Md) in the catchment of each lake, the mass accumulated in the lake (Ml) may be calculated by using the sedimentation rate (SR), the lake area (Al) and the density of the sediments (ρ):

$$(1)\ Md \geq Ml = SR\ Al\ \rho = [T\ yr^{-1}]$$

Once get the mass accumulated in the lake (Ml), it is possible to calculate the mass denuded from the catchment (Mdc) normalizing by the drainage area (Ad):

$$(2)\ Mdc = Ml/Ad = [T\ \ km^{-2}\ yr^{-1}]$$

The changes in the velocity of the denudation along time, can be assessed from the total denudation rate (DRt) using the sedimentation rate (SR), the lake area (Al) and the drainage area (Ad):

$$(3)\ DRt = SR\ Al/Ad = [cm\ yr^{-1}]$$

So these calculations based on simple assumptions provide information about the mass denuded in the whole lake watershed (Mdc), the mass that reach the lakes after the transport processes in the watershed (Ml) and the rates of the denudation processes (DRt) during the long-term time span of the records or selected intervals along. When using this approach, only order of magnitude approximations of erosion rates are possible, as these retain a very large degree of uncertainty (Einsele and Hinderer, 1998).

The sedimentary rate (SR) used for calculations has been obtained from the age-models previously computed for each lake.

Another important parameter for the calculations is the sediment density. El Tejo and El Tobar lake sequences have been scanned with a Geotek MCL and gamma density values were available. However, the Lake La Parra cores were not logged prior to splitting. However, because El Tejo and La Parra facies are similar, it has been possible to compare them (see *supplementary table A3* from the *Annex 3, Results subection 4.6*), calculate the mean value of gamma density for each facies of El Tejo sequence and assign that same value to the equivalent facies in the La Parra record. This approximation gives an idea of the density values of the facies along the La Parra sequence, and allows using them to calculate the denudation values for this watershed.

3.8 Historical and recent land uses changes

3.8.1 Bibliographic compilation of land uses

In Spain, documentary evidence of land uses since medieval times is abundant, although in sparsely populated areas such as Serranía de Cuenca, information is scarcer. For the purposes of this research, some recent compilations as Esteban Cava (1994), Lozano-Sahuquillo (2002) and the review of Valbuena-Carabaña et al. (2010) have been used. They provide an integrated and dynamic account of the evolution of the geographical landscape, the socio-territorial, industrial and economic changes in this area for the last millennium.

3.8.2 Actual land uses cartography and land use changes

Actual land uses in lakes La Parra, El Tejo and El Tobar have been studied by using the last available aerial orthoimages from the Instituto Geográfico Nacional (IGN) 2009 aerial survey framed in the Plan Nacional de Ortofotografía Aérea (PNOA).

In the watershed of Lake El Tobar, the recent land use changes have been

carried out using series of historical aerial images (1956, 1984, 2009) and historical documentation. They provided information about the relative abundance of forested and cultivated areas and a reconstruction of major land-use changes since the mid-20th century.

3.8.3 Climate data

Recent climate data (last 50 years) have been obtained from the nearby meteorological stations: Cuenca meteorological station, 12 Km NW from lakes El Tejo and La Parra; Beteta and Cañizares meteorological stations, 4 km NW and 20 km SW respectively from lake El Tobar. Additionally, the climatic information provided by the Climatic Atlas from the Iberian Peninsula (Ninyerola et al., 2005) has been used for the construction of the local climographs.

4

Results

In this section are presented and compiled the unedited published four research papers which compose this PhD thesis. Here the contributions of each collaborator are also shown and a brief abstract resumes their main content.

Coring platform ready to recover cores in Lake La Parra.
Plataforma de sondeos en la Laguna de La Parra lista para la acción.

4.1 Introduction to published articles

The results of this research have been published in four articles: one published in Spanish in a national journal indexed by Scopus (*Cuadernos de Investigación Geográfica*) and three published in English international journals indexed by the Journal Citation Report (*The Holocene, Science of the Total Environment and CATENA*). These papers reflect an incremental detailed study of the evolution of the Serranía de Cuenca lacustrine systems during the last 2000 years: starting with sedimentological aspect; moving into a wider regional context with the climatic implications and the main human land-use changes, to finalize with a quantitative approach linking watershed sediment yield and lake depositional estimates with experimental catchment results. Such a research only can be addressed with a multidisciplinary approach, including sedimentological, geochemical and biological proxies, and involving researchers experts in different disciplines, who have collaborated in the research and in the final papers (Table 4.1).

In subsection 4.2, a brief summary for each article with the main findings is included. From subsections 4.3 to 4.6, the published versions of the papers are included.

Table 4.1: *Published articles collaborators and their main contributions on the exposed articles. XRF: X-Ray Fluorescence. XRD: X-Ray Diffraction. XR: X-Ray.*

Coauthors	Article 1	Article 2	Article 3	Article 4
Abbott, M.			ICP-MS analysis collaboration	
Brown, E.			Collaboration interpreting Itrax XRF scanner data and XR images	
Caballero, M.		Preparation, analysis and diatom interpretation		
Giralt., S.	XRD analysis and interpretation. Manuscript revision.	Avaatech XRF scanner and XRD analysis and interpretation. Statistical approach. Manuscript revision.	Avaatech XRF scanner and XRD analysis and interpretation. Statistical approach. Manuscript revision.	Manuscript revision.
González-Sampériz, P.				Vegetation context, manuscript revision.
Hillman, A.			ICP-MS analysis and interpretation collaboration.	

			Manuscript revision.	
Morellón, M.			Seismic survey collaboration and seismic profiles interpretation. Manuscript revision.	
Moreno, A.	Collaboration in sampling, analysis and sedimentological and geochemical advice. Manuscript revision.	Collaboration in sampling, analysis and sedimentological and XRF scanner data advice. Manuscript revision.	Collaboration in sampling, analysis and sedimentological and XRF scanner data advice. Manuscript revision.	Collaboration in sampling, analysis and sedimentological and XRF scanner data advice. Manuscript revision.
Nadal-Romero, E.				Collaboration linking watershed and monitoring catchments. Manuscript revision.
Valero-Garcés, B.	Results interpretation and manuscript revision.	Results interpretation and manuscript revision.	Results interpretation and manuscript revision.	Results interpretation and manuscript revision.

4.2 Articles summaries

Research article 1

Barreiro-Lostres, F., Moreno, A., Giralt, S., Valero-Garcés, B.L., 2013. Evolución sedimentaria del lago kárstico de La Parra (Cuenca) durante los últimos 1600 años: paleohidrología, clima e impacto humano. Cuadernos de Investigación Geográfica 39, 179–193.

This paper serves as a methodological basis for the other three articles as illustrates the use of most of the techniques applied to the lake records in this research to one of the lakes. In this paper (subsection 4.3), the paleohydrological evolution of the Lake La Parra along the last 1600 cal. years BP is reconstructed through the study of the 6.93 m long sedimentary record from the central-deepest area of the lake (17.5 m in 2010). The reconstruction is based in a sedimentary facies model characterized by a high variability of carbonate facies (11 types in total), combining the macro and microscopical observations, the elemental geochemical proxies (TN, TOC/TN, TIC, TOC) and main mineral composition (detrital and endogenic minerals). The analysis of

modern sediments representative of the distinct sedimentation environments from the lake allowed the definition of four modern depositional environments: a littoral platform (0-2 m depth), a steep talus (2-10 m depth), a transitional-distal zone (10-16 m depth) and the deep-distal zone (16-17 m depth). The preliminary age-model was based in seven radiocarbon samples from vegetal remains lineally interpolated.

The sedimentary sequence of Lake La Parra is mainly controlled by fluctuations in the detritic carbonate sediment fraction input, which in first term is controlled by oscillations in the hydrological balance. Five main hydrological stages can be distinguished in the evolution of La Parra Lake during the last 1600 years. Deposition started during a (i) humid phase around 300 CE and the establishment of the lacustrine system. Then (ii) water-levels rose during the Dark Ages period (DA, AD 500-900), followed by (iii) generally lower levels during the Medieval Climatic Anomaly (MCA, AD 1000-1300) also characterized by increased coarse detritic input. The (iv) highest lake-levels were reached during the Little Ice Age (LIA, AD 1300-1850) with developing of more frequent anoxic conditions in the lake's bottom and preservation of fine-laminated intervals. The late stage (v) is characterized by frequent hydrological fluctuations during the XXth century, with a slight lake level rise during the first XXth-half and a relative decrease until recent times.

La Parra record showed a synergistic effect of socio-economic and climatic changes during the Medieval and the Contemporary Epochs leading to periods of increased sedimentary inputs to the lake. The paleohydrological and depositional evolution of La Parra Lake is coherent with the previous reconstructions realized in other of the lakes from the sinkhole complex of Cañada del Hoyo.

Research article 2

Barreiro-Lostres, F., Moreno, A., Giralt, S., Caballero, M., Valero-Garces, B., 2014. Climate, palaeohydrology and land use change in the Central Iberian Range over the last 1.6 kyr: The La Parra Lake record. The Holocene 24, 1177 – 1192. doi:10.1177/0959683614540960.

This article covers one of the main objectives of this research: To obtain a high-resolution reconstruction of the hydrological and environmental variability of the Las Torcas sinkhole lake Complex through the multi-proxy study of the ca. 7 m Lake La Parra sedimentary record. This paper integrates the facies model described in Article 2 (subsection 4.4) with geochemical and mineralogical proxies and a diatom study.

Although most available lacustrine records from the Iberian Peninsula lack enough temporal resolution during the last 2000 years to establish

decadal-scale comparisons, the Lake La Parra hydrological climatic-related changes are in agreement with the climate reconstructions from these regions: relatively more humid condition during the end of the Roman Period (AD 350), moderate but fluctuating water-levels during the AD 400-1200 period with particularly lower lake-levels during AD 750-850 and the highest levels during the AD 1200-1600 period. Lake levels remained moderate after AD 1600. Interestingly, the La Parra record agrees with a complex pattern of wetter and drier intervals during the 'LIA', suggesting that lake-level fluctuations frequency was higher during the 'LIA' compared with the 'MCA'.

An important contribution of this study is to provide support for the existence of latitudinal gradients within the Iberian Peninsula, with increased humidity during Iberian–Roman times and an early onset of the 'MCA' restricted to southern Spain; while the humid phases of the 'LIA' started and ended earlier in the central Iberian Range compared with the Pyrenean Domain and southern Spain. The La Parra record also agrees with the hypothesis of an antiphasic behavior between Western and Eastern Mediterranean during the last millennium, suggesting an active role for North Atlantic Oscillation (NAO) dynamics over the past two millennia in the Western Mediterranean climate patterns.

Research article 3

Barreiro-Lostres, F., Brown, E., Moreno, A., Morellón, M., Abbott, M., Hillman, A., Giralt, S., Valero-Garcés, B., 2015. Sediment delivery and lake dynamics in a Mediterranean mountain watershed: Human-climate interactions during the last millennium (El Tobar Lake record, Iberian Range, Spain). Science of The Total Environment 533, 506–519. doi:10.1016/j.scitotenv.2015.06.123.

The next step in this investigation was published in Article 3 (subsection 4.5) and includes the reconstruction of sediment delivery fluctuations in Lake El Tobar (headwaters of the Tagus River),to explore the relationships between sediment delivery dynamics and natural (climate) or anthropic (land use changes) forcings.

The comparison of the main sedimentary delivery events and phases based on sedimentological, physical and geochemical properties and the historical documentary data indicate that the four main events of increased sediment delivery occurred during the LIA and in recent times: around 16th, late 18th, mid 19th and early 20th centuries. As it was shown in La Parra Lake, these events of intense sediment delivery to the lake were due to positive synergies of increasing human impact (forest clearing, farming and grazing during periods of increasing population) and period of higher rainfall.

In this article it is also shown how despite the lake watershed has been

highly affected by anthropic activities during the last millennium, the lake system depositional and geochemical processes showed resilience to land uses changes in the lake's watershed. This study demonstrates that degradation processes in Iberian Range watersheds are strongly controlled by anthropic activities (land use changes, soil erosion) but modulated by climate-related hydrological changes (water availability, flood and runoff frequency).

Research article 4

Barreiro-Lostres, F., Moreno, A., González-Sampériz, P., Giralt, S., Nadal-Romero, E., Valero-Garces, B., accepted for publication. Erosion in Mediterranean mountain landscapes during the last millennium: a quantitative approach based on lake sediment sequences (Iberian Range, Spain). CATENA.

Article 4 (subsection 4.6) represents the last main objective of this research: the integration of all available records from the Western Branch of the Iberian Range for the last millennium – the three studied lakes and also Lake Taravilla (previously published by Moreno et al., 2008 and Valero-Garcés et al., 2008) – to investigate the relationship of lake depositional evolution with historical land uses changes and climate fluctuations and quantify the sediment balance between watershed and lake basin to provide quantitative long term series of past erosion dynamics. This new integrated strategy to quantify erosion at centennial scales is based on the methods described by Einsele and Hinderer (1998). The results from the lake records were then contrasted with data from monitored experimental catchments in Mediterranean mountain catchments from the Central Pyrenees (García-Ruíz et al., 2010).

This study provides long-term series of sediment dynamics in Mediterranean mountain basin beyond the instrumental short-period of existing experimental plots and watersheds studies. During the last millennium, lake sequences show comparable values of denuded and accumulated sediments than those obtained from the experimental catchments during the last decades. Main variability between catchments is associated mainly with the watershed size: small watersheds show relatively low and more constant values along time and large watersheds export higher amounts of sediments, although they also have a complex behavior as they also function as sediment delivery regulators.

Results based on long-term lake sequences provide a longer perspective of erosion processes in Mediterranean watersheds, showing that the size of the watershed, the land cover and the erodibility of the geological formations and soils are key factors to control the sediment fluxes. This study validates the main factors identified in monitoring surveys.

This long-term approach is essential to understand the evolution of sediment denudation and accumulation processes along time in highly human

disturbed areas and key to improve predictions of the impacts of recent socio-economic and climate changes and to design sustainable management policies.

4.3 Article 1

Evolución sedimentaria del lago kárstico de La Parra (Cuenca) durante los últimos 1600 años: paleohidrología, clima e impacto humano.

Sedimentary evolution of La Parra karstic lake (Cuenca) over the last 1600 years: paleohydrology, climate, and human impact

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Resumen. La laguna de La Parra (39º 50.948', 1º 52', 1014 m) es un lago pequeño (1 Ha), relativamente profundo (Zmax = 17.5 m) de agua dulce (TDS = 356 mg/L), monomíctico y con morfología circular (116 m diámetro), formado en una dolina que interceptó el acuífero regional del Jurásico y Cretácico Medio. Forma parte del complejo kárstico de las Torcas de Cañada del Hoyo constituido por siete lagos y situado en la Cordillera Ibérica (Cuenca, Este de España). La secuencia sedimentaria del lago se ha estudiado mediante técnicas sedimentológicas, microscópicas, geoquímicas y físicas aplicadas a sondeos de gravedad cortos y a un sondeo largo (6,93m) que registra la evolución del lago desde su inicio, La secuencia está caracterizada por una gran variabilidad de facies clásticas carbonatadas, controladas principalmente por fluctuaciones en la entrada de aportes detríticos al lago y variaciones en el balance hídrico. La cronología está basada en 7 dataciones de ^{14}C AMS. Los cambios en los ambientes de depósito de La Parra reflejan una amplia variabilidad hidrológica durante los últimos 1600 años. Con anterioridad a la época romana, la dolina de La Parra era una torca seca, y la laguna sólo se desarrolló a partir del siglo IV de nuestra era. La reconstrucción paleohidrológica y paleoambiental muestra una fase árida durante la Anomalía Climática Medieval (ACM) y otra más húmeda durante la Pequeña Edad del Hielo (PEH). La principal afección antrópica en el lago y su entorno se produjo durante la Edad Media (500 – 1400 DC) y los siglos XVIII- mitad del siglo XX relacionada con cambios en el uso del suelo (trashumancia, deforestación, agricultura) y se refleja en cambios en la tasa de sedimentación y la composición de los sedimentos.

Abstract. Lake La Parra (39º 50.948', 1º 52', 1014 m) is a small (1 Ha), relatively deep (Zmax = 17.5 m), freshwater (TDS = 356 mg/L) monomictic lake with a circular morphology (116 m diameter), developed in a doline that intercepted the local Jurassic-Cretaceous aquifer. It is part of a karstic lake complex of seven lakes located in the Iberian Range (Cuenca, East of Spain). Sediment cores obtained in the central part of the lake were analysed using sedimentological, microscopic, geochemical and physical techniques. The ca. 7 m long sequence is mainly composed by clastic carbonated sediments, characterized by a high variability of sedimentary facies, indicative of large fluctuations in the sediment delivery to the lake. Chronology is based on 7 AMS radiocarbon dates. The depositional evolution of La Parra sequence reflects a high hydrological variability during the last 1600 years. Prior to the Roman Epoch, La Parra doline was dry and only became a lake after 4th century AD. Shallower conditions and higher sediment input occurred during the Medieval Climate Anomaly (MCA) and more humid phases during the Little Ice Age (LIA). The main human impact in the lake and the watershed environment is related to changes in the land uses (transhumance, deforestation, crops) during the Middle Ages (500 – 1400 DC) and during 18th – mid 20th centuries.

Palabras clave: Holoceno tardío, facies sedimentarias, geoquímica, Península Ibérica, lago kárstico, ambientes de sedimentación lacustre, paleohidrología, facies sedimentarias, geoquímica.
Key-words: Late Holocene, sedimentary facies, geochemistry, Iberian Peninsula, karstic lake, lacustrine depositional environments, palaeohydrology, sedimentary facies, geochemistry.

1. Introducción

Recientemente se han llevado a cabo numerosas reconstrucciones climáticas en el área mediterránea basadas en estudios multidisciplinares (isótopos, polen, geoquímica, sedimentología) de sistemas lacustres, que han demostrado ser archivos excepcionales de la evolución ambiental y climática a escala regional (ver referencias en Valero-Garcés y Moreno, 2011; Moreno et al., 2012; Roberts et al., 2012). En la Península Ibérica, los lagos están localizados en una gran variedad de condiciones geográficas, climáticas y ecológicas. Existen lagos de montaña formados por la actividad glaciar (Enol, Sanabria) (Moreno et al., 2009; López-Merino et al., 2011); lagos kársticos cuyo origen es debido a la acción exokárstica (Taravilla, Somolinos) (Moreno et al., 2008; Currás et al., 2012) o a la disolución de evaporitas o carbonatos (Banyoles, Moncortés, Zoñar, Estanya) (Höbig et al., 2012; Corella et al., 2012, Martín-Puertas et al., 2009; Morellón et al., 2011); también se encuentran lagos salinos efímeros en las cuencas de los ríos Ebro, Duero y Tajo, originados por la combinación de procesos erosivos y kársticos (por ejemplo, salinas de Bujaraloz) (González-Sampériz et al., 2008). En todas las secuencias lacustres se han descrito cambios climáticos significativos en el Holoceno tardío, particularmente durante el Periodo Húmedo Ibero-Romano, la Anomalía Climática Medieval y la Pequeña Edad de Hielo (Valero-Garcés y Moreno, 2011; Moreno et al., 2012).

En este trabajo se ha llevado a cabo un estudio sedimentológico y geoquímico de alta resolución en sondeos obtenidos en la laguna kárstica de La Parra, situada en la Cordillera Ibérica (NE de España, provincia de Cuenca). Facies y composición química han estado influenciadas tanto por el clima como por el impacto humano en el área (ganadería, agricultura, fuegos), muy intenso al menos desde la época medieval. El robusto modelo cronológico proporcionado por técnicas de datación de radiocarbono AMS, ha permitido describir los cambios en las condiciones del lago, su cuenca de recepción e investigar la compleja interrelación entre el clima y las actividades humanas desde el final del Periodo Romano.

2. Zona de estudio

La laguna de La Parra (39º 50’ N, 1º 52’ E, 1014 m.s.n.m.) es una dolina que pertenece al sistema de lagos kársticos de Cañada del Hoyo (*Fig. 1*), formada por procesos de disolución y diaclasado (Alonso, 1986) en calizas y dolomías cenomanienses-turonienses, afectando también a materiales jurásicos. La falla de Valdemoro y un anticlinal regional de eje principal NW-SE han sido claves en el desarrollo de este sistema kárstico (Eraso et al. 1979, Carmona y Bitzer, 2001).

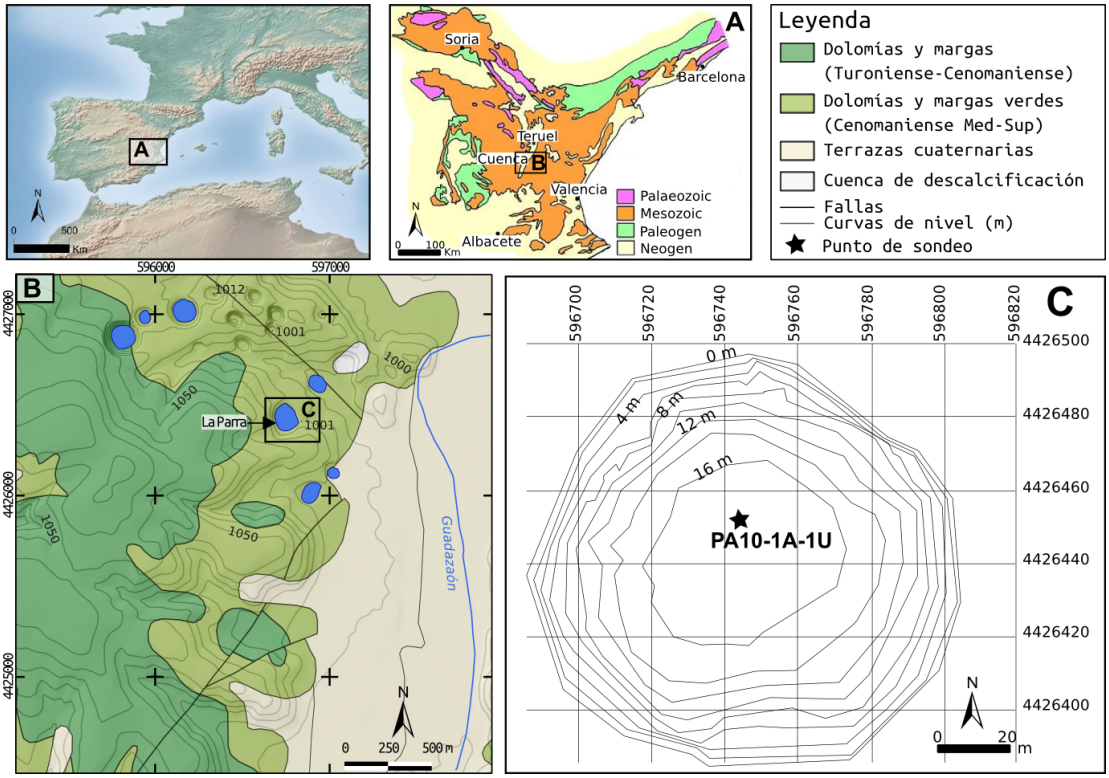

***Fig. 1: A** – Localización de la zona de estudio y esquema geológico de la Cordillera Ibérica. **B** – Mapa geológico detallado del entorno de la laguna de La Parra (ver leyenda en la esquina superior derecha, basado en Ramírez del Pozo et al., 1973 y mapa topográfico nacional, IGN, 2002). **C** – Batimetría de la laguna y punto de toma del sondeo estudiado (estrella).*

Climáticamente, se encuentra en un contexto Mediterráneo, modulado por influencias continentales con un elevado contraste diario y estacional de las temperaturas (Tº media desde 4 ºC en enero hasta 23 ºC en julio). La precipitación media anual se sitúa en 542 mm, siendo julio el mes más seco y octubre el más húmedo.

La vegetación local está dominada por Pinus nigra, Quercus faginea, Quercus ilex rotundifolia, Juniperus thurifera, Buxus sempervirens y Quercus coccifera. Las depresiones y zonas bajas están destinadas al cultivo de cereal.

La laguna de La Parra tiene morfología circular (113 m de diámetro, 1 Ha de superficie), y una profundidad máxima de 17,5 m. No tiene entradas o salidas de agua superficiales permanentes, pero está conectada hidraúlicamente (Carmona and Bitzer, 2001) con las aguas subterráneas del acuífero local carbonatado de la Formación de Dolomías de Cortes de Pallás (Gil et al. 2004). Un escarpe en dolomías del Cretácico Superior (Fm Dolomías de la Ciudad Encantada) rodea la laguna desde su parte oeste hasta el sureste.

El comportamiento hidrológico de la laguna está controlado por: i) una cuenca de recepción pequeña (~ 10 Ha); ii) la relación entre el acuífero local y

el regional, iii) un régimen de precipitaciones fuertemente estacional; iv) una alta evaporación y v) fluctuaciones del nivel freático del acuífero regional por extracciones agrícolas (pozos). Análisis de las aguas llevados a cabo en 2010 indican una composición dominada por bicarbonatos (4,78 meq/L) y magnesio (3,96 meq/L), coherente con la litología circundante. La conductividad eléctrica oscila desde los 305 µS/cm en superficie hasta los 356 µS/cm a 16 m de profundidad. La alcalinidad se sitúa en torno a los 6.0 meq/L, siendo el pH de 8. La composición isotópica de las aguas es similar en superficie y en el fondo por lo que corrobora la naturaleza holomíctica de la laguna. Por otra parte, los valores relativamente más positivos que los del acuífero y las aguas superficiales (Carmona and Bitzer, 2001) sugieren una evolución con respecto al acuífero por procesos de evaporación.

3. Metodología

En mayo de 2010 se recuperó un sondeo de 693 cm de longitud (PA10-1A-1U) en la parte más profunda de la laguna de La Parra (17,5 m) con la plataforma de sondeos flotante UWITEC ® del IPE-CSIC. Posteriormente, en verano de 2011 se tomaron 21 sondeos cortos distribuidos en una malla de muestreo que cubre todo el lago.

Los sondeos se cortaron en dos mitades, se fotografiaron con la cámara CCD acoplada al escáner de fluorescencia de la Universidad de Barcelona y se definieron las facies sedimentarias en base a la inspección visual macroscópica, incluyendo color, tamaño de grano, estructuras sedimentarias, contenido fósil y también la observación de frotis de sedimento al microscopio óptico. Para el estudio microscópico de las facies sedimentarias se siguió la metodología descrita por Schnurrenberger et al. (2003) y se completó con microscopía electrónica de barrido (alto vacío) usando un JEOL JSM-6400 de la Universidad de Zaragoza acoplado a un sensor EDAX INCA 300 X-Sight para la identificación elemental.

El sondeo largo (PA10-1A-1U) se muestreó cada 2 cm para analizar el carbono orgánico total (TOC) y el carbón inorgánico (TIC); cada 6 cm para nitrógeno total (TN); y cada 10 cm para análisis mineralógicos. El TOC y el TIC se midieron en el LECO SC144 DR del Instituto Pirenaico de Ecología (CSIC), mientras que el TN se midió en el LECO TRUSPEC CN del Centro de Edafología y Biología Aplicada del Segura (CSIC).

La mineralogía se analizó con un difractómetro de rayos X Siemens D-500 (Cu kα, 40 kV, 30 mA con monocromador de grafito) y la identificación mineral y abundancia relativa se determinó a partir de los picos de intensidad siguiendo el procedimiento descrito por Chung (1974a, b).

La cronología para la secuencia lacustre se basa en la interpolación lineal de sietedataciones de macrorrestos vegetales terrestres por ^{14}C AMS del

sondeo PA10-1A-1U, analizadas en el Poznan Radiocarbon Laboratory (Polonia) y calibradas usando el software CALIB REV 6.0.0 (Stuiver and Reimer, 1993) y la curva de calibración INTCAL09 (Reimer et al., 2009), eligiendo el punto medio del intervalo de probabilidad 2σ. El registro sedimentario abarca desde los 1639±77 cal. yr. BP (coincidiendo con la etapa final del Periodo Húmedo Ibero-Romano) hasta el presente (*fig. 2*).

4. Resultados

4.1 El medio sedimentario reciente

El estudio de las facies sedimentarias de los primeros centímetros de los 21 sondeos cortos ha permitido diferenciar cuatro ambientes de depósito modernos en la cuenca de la laguna: (i) una plataforma litoral con vegetación que estabiliza el sustrato, afectada por procesos de caída de rocas del escarpe carbonatado; (ii) una zona de talud escarpado (2-10 m de profundidad), que constituye un límite biológico a la vegetación por falta de luz y donde se pueden generar pequeños movimientos de masa por desestabilización; los sedimentos en la zona de talud están formados por limos y arenas con abundantes clastos carbonatados y restos vegetales; (iii) una zona transicional distal (10-16 m de profundidad) amplia (> 80 m anchura) caracterizada por una morfología plana y la presencia de limos masivos; y (iv) una pequeña zona distal alargada (16-17 m de profundidad) compuesta por limos finos masivos oscuros con abundante materia orgánica que comprende la parte central más profunda del lago.

4.2 La secuencia sedimentaria

La identificación e interpretación de las diferentes facies del registro sedimentario combina las observaciones sedimentológicas y microscópicas con los datos geoquímicos y mineralógicos. El sondeo largo PA10-1A-U está compuesto principalmente por limos detríticos carbonatados masivos y bandeados con diferentes proporciones de materia orgánica y de restos orgánicos y con intercalaciones de arenas y gravas. Se han diferenciado 11 facies (Barreiro-Lostres, 2012). La mayoría de las facies son detríticas y proceden de la erosión de materiales carbonatados de la cuenca de recepción, arrastrados por corrientes efímeras y escorrentía superficial, retrabajados por procesos litorales y depositados en la zona central del lago.

Las facies más abundantes son limos finos grises depositados por procesos de transporte de baja energía en la parte central de la laguna, lejos de la influencia de la escorrentía superficial y de los procesos litorales de retrabajamiento (oleaje, etc). La alternancia de capas claras y oscuras de estos limos implicaría cambios en las condiciones redox, más reductoras durante la sedimentación de los limos oscuros. Los niveles de limos gruesos presentan

texturas granodecrecientes con una base irregular erosiva que indican procesos "turbidíticos" capaces de transportar los sedimentos desde la zona litoral hacia el centro del lago.

Las facies de arenas gruesas son típicas de la zona transicional y litoral, depositadas por procesos de escorrentía superficial y retrabajamiento litoral de menor (arenas finas) a mayor (arenas gruesas) energía. La presencia puntual de facies de gravas en la secuencia se interpreta como resultado de procesos de transporte tractivos de alta energía iniciados en la cuenca de recepción de la laguna y canalizados por un pequeño barranco situado al SO, con posible retrabajamiento del sedimento de las zonas más someras del lago. El depósito de facies gruesas (gravas y arenas) en las zonas más centrales del lago sugiere una intensificación de la escorrentía en la cuenca y complementariamente, niveles del lago más bajos y predominio de condiciones litorales en toda la laguna.

Las facies de limos finos laminados contienen láminas blanquecinas de calcita autigénica compuestas por cristales calcíticos de 3-5µm formados en el epilimnion durante el clímax de desarrollo algal en verano y láminas grises oscuras, compuestas por materia orgánica y silicatos depositados en otoño e invierno; ambas láminas tienen aprox. 1 mm de espesor. Estas facies son similares a las laminitas carbonatas encontradas en otros lagos kársticos de la Península Ibérica (Zoñar, Martín – Puertas et al., 2008; Arreo, Corella et al., 2010; Montcortès, Corella et al., 2010; La Cruz, Romero-Viana et al., 2008). Este tipo de laminación está asociada a ambientes de depósito de muy baja energía, escasa influencia aluvial y se ve favorecida por procesos de estratificación de las aguas, generalmente en etapas con nivel alto del lago (Brauer et al., 2004). La formación de estos cristales de calcita se considera bioinducida al coincidir con una mayor actividad biológica y condiciones limnológicas adecuadas para la preservación de carbonatos endógenos.

Basándonos en las facies sedimentarias, la secuencia de La Parra se ha dividido en cinco unidades sedimentológicas (Unidades I a V, *fig. 2*).

La base de la secuencia está formada por margas verdes cenomanienses con evidencias de alteración kárstica (texturas de disolución y brechificación). La matriz está formada por clastos carbonatados angulares homométricos de 50-70µm y granos de cuarzo de 80-100µm.

La Unidad V (680 – 580cm) marca el inicio de la sedimentación lacustre y está constituida por una secuencia granocreciente de limos marrones finos en la base (subunidad V B) y limos oscuros gruesos a techo (subunidad V A). A mitad del tramo una intercalación de limos finamente laminados marca la separación entre dos subunidades. La subunidad inferior V B (680-625cm) está dominada por minerales detríticos (dolomita, silicatos) y presenta los valores más bajos de TIC y TOC de toda la secuencia. Los valores de TOC/TN muestran

los valores más bajos en la base de esta sub-unidad y aumentan rápidamente hacia techo; la subunidad superior V A (625 - 580cm), está caracterizada por mayor presencia de carbonatos endógenos (calcita y, secundariamente aragonito y calcita magnesiana) y valores relativamente altos de TIC, TOC y TN.

La Unidad IV (580 - 400cm) está formada por arenas medias y gruesas en la base, seguidas de limos medios. El contenido mineral está dominado por minerales de origen detrítico. Los valores de TN, TOC, TIC y TOC/TN son bajos.

La Unidad III (400 - 260cm) consiste en una alternancia de limos medios y gruesos con gravas en la base. Los minerales de origen detrítico siguen siendo dominantes.

La Unidad II (260 – 30cm) es la que presenta una mayor variedad de facies, desde arenas gruesas hasta limos, siendo característica la intercalación de limos finos laminados en capas de 5 cm de potencia. Presenta el contenido más alto de minerales carbonatados endógenos (calcita + aragonito + calcita magnesiana) de la serie. Se puede dividir en dos subunidades, la inferior II B (260 - 125cm) está constituida por la alternancia de limos gruesos y facies finamente laminadas con los valores más altos de TN (~0,6%) y de TOC (~6%) y los valores más bajos de TOC/TN (~9) de toda la serie. La subunidad II A (125 – 30cm) está formada por una alternancia de limos grises claros de tamaño de grano medio y oscuros más gruesos con alguna intercalación de arenas gruesas y gravas. Presenta valores de TN relativamente bajos (~0,1%), un descenso del TOC y los mayores valores de TOC/TN de toda la secuencia.

La Unidad I (30 – 0cm) está constituida por limos oscuros gruesos, mineralógicamente caracterizada por un contenido menor en minerales detríticos (Dolomita + Cuarzo + Feldespatos) que la subunidad II A y geoquímicamente por una tendencia ascendente del TOC y descendente de TOC/TN.

A lo largo de toda la secuencia, los valores de TIC muestran escasa variabilidad (en torno al 6%), con los valores más bajos en la subunidad V B, y los valores relativamente más elevados en la parte basal de la unidad IV y la subunidad II B. En cuanto a la mineralogía, la fracción carbonatada es el componente principal en los sedimentos. La mayoría de estos carbonatos (dolomita, calcita) son de origen detrítico y proceden de formaciones carbonatadas del entorno de la laguna de La Parra. Los minerales exógenos (principalmente dolomita, cuarzo, minerales de la arcilla y feldespatos) son relativamente constantes en la secuencia y alcanzan los mayores valores en las facies limosas. Los minerales autigénicos (mayoritariamente calcita, secundariamente aragonito y calcita magnesiana) aparecen en cinco intervalos de facies de limos y arenas (base y techo Unidad IV, base y techo Subunidad II B, y Unidad I).

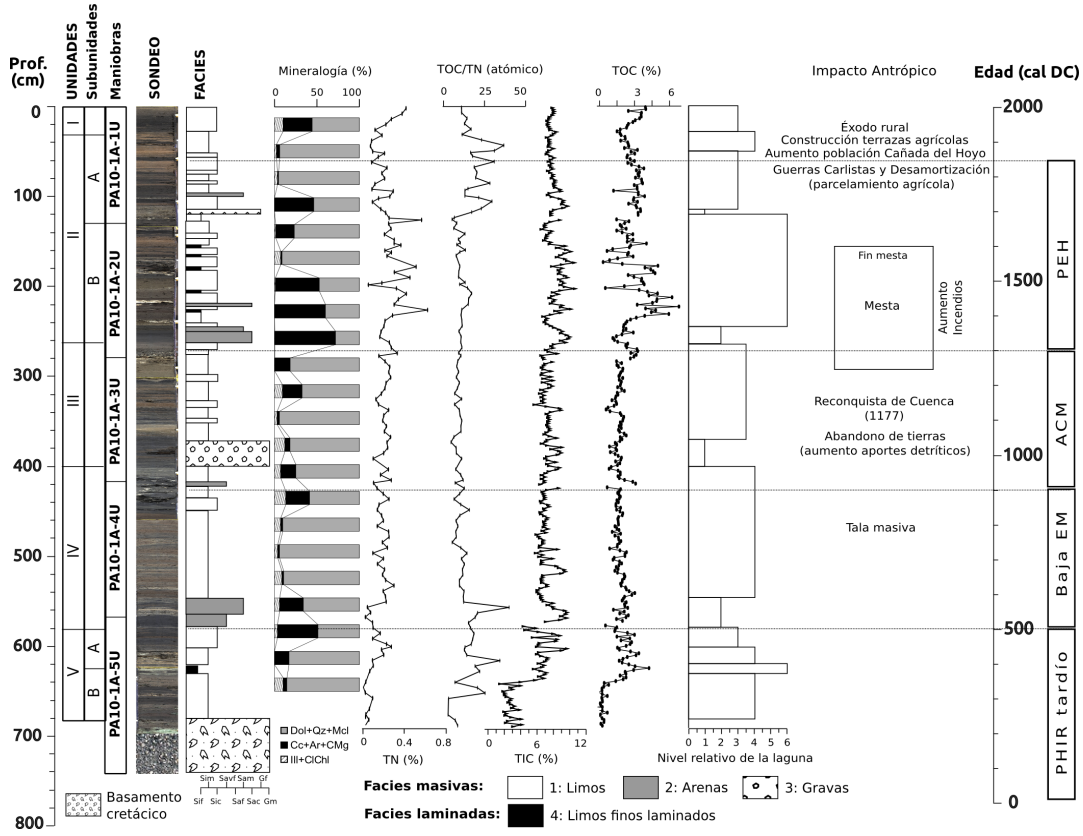

***Fig. 2**: Secuencia sedimentaria del sondeo PA10-1A-1U, que incluye unidades y subunidades, fotografía del sondeo, perfil sedimentológico; perfiles mineralógico (Qz: cuarzo, Micl: microclina, Ar: aragonito, Cc: calcita, CMg: calcita magnesiana, Ill: illita, ClChl: clinoclorita), TN, TOC/TN, TIC y TOC; nivel relativo de la laguna; principales eventos de impacto antrópico en la laguna; y escala temporal derivada del modelo de edad actual. PHIR: Periodo Húmedo Ibero-Romano. ACM: Anomalía Climática Medieval. PEH: Pequeña Edad del Hielo.*

El contenido en materia orgánica (% TOC) y sus características (TOC/TN) muestran cambios significativos a lo largo de la secuencia. El perfil de TOC sigue una tendencia similar al de TIC, con una media en torno al 3%, pero alcanza los valores más altos (6-7%) coincidiendo con la sedimentación de láminas finas de calcita endógena durante la subunidad II B y en épocas recientes (4,5%, Unidad I). El TN sigue una tendencia diferenciada a la del TOC, oscilando entre el 0,1 y el 0,7, lo que sugiere distintas fuentes de materia orgánica. Los valores más elevados (mayor proporción de materia orgánica de origen lacustre) coinciden con la sedimentación de facies finas laminadas en la subunidad II B, cuando las condiciones para la conservación de la materia orgánica eran óptimas debido al dominio de condiciones anóxicas en el fondo del lago, coincidiendo con menor entrada de material exógeno al lago (menor dilución sedimentaria de la MO).

La relación TOC/TN es variable (3 a 40), aunque relativamente baja a lo

largo de toda la secuencia, lo que sugiere un predominio del origen lacustre de la materia orgánica (Meyers y Lallier-Vergès, 1999). Solo en dos intervalos - de 650 a 550 cm (380-630 DC) y de 120 a 30 cm (1700-1920 DC) – los valores son > 15 sugiriendo una mayor influencia de materia orgánica vegetal terrestre del entorno de la laguna. En épocas recientes el TOC/TN vuelve a presentar valores relativamente bajos.

5. Discusión

A partir de las facies y de los análisis geoquímicos y mineralógicos (fig. 2) se pueden establecer cinco etapas principales en la historia sedimentaria de la laguna de La Parra, durante los últimos 1600 años. Cada etapa, excepto la más antigua y la más reciente, se inicia con el depósito de facies gruesas y continúa con facies de limos (fig. 2).

i) El primer episodio (300-500 DC) comienza con la inundación de la cuenca de La Parra, tras un aumento rápido del nivel piezométrico de la zona y la sedimentación de material detrítico fino, poco carbonatado y prácticamente sin materia orgánica. Las características peculiares de estos sedimentos (bajo TIC y TOC) sugieren que el material originario podría ser producto de los procesos kársticos de descalcificación que afectaron a la dolina seca de La Parra durante el periodo árido anterior. El aumento del TIC y el TOC en los sedimentos (350 DC) marca el desarrollo de condiciones propiamente lacustres en la dolina, con el depósito de limos grises oscuros y laminados que indican el rápido desarrollo de ambientes de sedimentación relativamente profundos durante la etapa final (380-420 DC). Esta etapa final sugiere niveles del lago relativamente elevados que corresponderían con el final del Periodo Húmedo Ibero – Romano. Los valores relativamente altos de TOC/TN indican aportes significativos de materia orgánica terrestre y sugieren una fase de erosión de suelos de la cuenca de recepción que pudiera estar relacionada con un mayor impacto antrópico durante el final de la época romana y el comienzo de la dominación visigoda, como talas masivas identificadas en el cercano registro de la laguna de La Cruz (Julià et al., 1998).

ii) La segunda etapa (500-980 DC), correspondiente a la Baja Edad Media, se inicia con un drástico cambio limnológico con la sedimentación de arenas gruesas en el centro del lago, que sugieren un aumento del transporte de sedimentos al lago desde la cuenca de drenaje así como, probablemente, un descenso en el nivel del lago. Tras esta fase relativamente corta, vuelve a dominar la sedimentación de limos en un ambiente relativamente más profundo, aunque los aportes terrígenos exógenos seguirían siendo elevados (altos % de dolomita y silicatos) pero con menores aportes de materia orgánica exógena (TOC/TN < 12) y, por consiguiente una reducción en la erosión de los suelos en la cuenca.

iii) La tercera etapa (980-1350 DC) comienza con el depósito del mayor paquete de gravas de toda la secuencia indicando ambientes someros incluso en el centro del lago. Durante todo este periodo aumenta la presencia de facies de limos gruesos respecto a la etapa anterior, indicando un ambiente ligeramente menos profundo. El aumento de minerales carbonatados endógenos hacia el techo y el ligero aumento del TOC podría indicar condiciones más adecuadas para la precipitación de calcita en el epilimnion, pero sin desarrollo de facies laminadas. Esta etapa engloba la Anomalía Climática Medieval (ACM).

iv) El cuarto estadio (1350-1950 DC) comienza con el depósito de facies de arenas y está caracterizado por el depósito de limos finamente laminados durante toda la secuencia, intercalados entre limos gruesos (subunidad II B, 1400-1700 DC), un aumento de TOC y TN y la presencia de minerales endógenos. En esta etapa, el ambiente de depósito correspondería a un lago profundo con frecuentes condiciones anóxicas en el fondo y una mayor actividad biológica. Este estadio corresponde a la Pequeña Edad del Hielo (PEH).

De un modo similar, tanto en la cercana laguna de La Cruz como en el Lagunillo del Tejo se reconstruye un clima más húmedo para la PEH. Así, en La Cruz (Julià et al., 1998; Romero-Viana, 2010) también se ha descrito la sedimentación de facies laminadas, procesos meromícticos y alto nivel de agua, mientras en el Lagunillo del Tejo (López-Blanco et al., 2011) se reconstruyen niveles del lago más altos durante esta etapa. El desarrollo de las condiciones meromícticas en estos lagos podría estar relacionado con factores climáticos (mayor precipitación, temperaturas más frías y niveles más altos de los lagos), antrópicos, como la expansión de la mesta (trashumancia) en la zona, facilitando los aportes detríticos de finos por roturación y quema de tierras para pastos, y el aumento de la bioproductividad en los lagos (Julià et al., 1998).

Hacia el final de este periodo (unidad II A, entre 1700-1850 DC) domina la sedimentación de gravas, arenas y limos gruesos y se registran los valores más elevados de TOC/TN, indicativos de intensa erosión de los suelos en la cuenca. Esta fase de mayor erosión correspondería con la de mayor impacto humano en la cuenca e incluiría incendios durante las Guerras Carlistas y cambios de usos del suelo tras la Desamortización al propiciar el parcelamiento agrícola, el aumento en la población de Cañada del Hoyo y la construcción de terrazas agrícolas en la zona de lagos (López-Blanco et al., 2011). Aunque la sedimentación de limos más finos sugiere una recuperación de los niveles hidrológicos durante el siglo XIX, los elevados valores de la relación TOC/TN testifican el elevado impacto humano en la cuenca hasta mediados del siglo XX. En el Lagunillo del Tejo se observa también un aumento en la tasa de

sedimentación durante el siglo XIX y comienzo del XX, coincidiendo en este caso con niveles del lago más bajos (Romero-Viana et al., 2009; López-Blanco et al., 2011).

v) Durante la quinta etapa (1950-2010 DC) se produce un descenso rápido en la entrada de material detrítico y orgánico acompañado de un aumento de la bioproductividad de la laguna (aumento de TOC y TN), posiblemente debido al éxodo rural y abandono de las áreas de cultivo. La ausencia de facies laminadas indica que durante este periodo han predominado condiciones óxicas en el fondo de la laguna.

Los principales estadios hidrológicos y climáticos identificados en La Parra son coherentes con las reconstrucciones disponibles en la Península Ibérica, tanto locales como regionales. En general, los últimos milenios están caracterizados por : i) un periodo húmedo contemporáneo a la época romana de importancia regional, aunque con una gran variabilidad, descrito desde el sur (Martín-Puertas et al., 2008) hasta el NE de España (lago de Estanya, Morellón et al., 2008; lago de Moncortés, Corella et al., 2010) y también en la zona central (Somolinos, Currás et al., 2012; Laguna de la Cruz, Julià et al., 1998). En La Parra, este aumento de humedad ocurrió al final de dicho periodo (300-500 DC), contrariamente al sur de la Península donde este periodo húmedo fue más prolongado (500 AC- 500 DC, Martín-Puertas et al., 2008) ii) un periodo más árido correspondiente a la ACM (500-1400 DC), coincidente con niveles del lago más bajos y un aumento de aportes detríticos. Similares características se observan en Moncortés (Corella et al., 2010) y Estanya (Morellón et al., 2008) y en numerosos registros continentales y marinos de toda la Península (Moreno et al., 2012) y iii) fases húmedas durante la PEH (1450 - 1650 DC) caracterizadas por niveles hidrológicos altos y el desarrollo de facies laminadas con carbonatos endógenos. Estas fases húmedas dentro de la PEH han sido descritas en otros registros continentales ibéricos, aunque dentro de una amplia variabilidad hidrológica y climática (Morellón et al., 2008, 2012).

6. Conclusiones

La secuencia sedimentaria de la laguna de La Parra representa el registro más largo (6,93m, últimos 1600 años) y mejor datado (nueve muestras de ^{14}C) obtenido en el complejo lacustre de las Torcas de Cañada del Hoyo.

La secuencia sedimentaria de La Parra es característica por su alta variabilidad de facies (11 en total), constituida principalmente por sedimentos carbonatados con diferente contenido en materia orgánica, y está controlada por fluctuaciones en los aportes detríticos y el balance hidrológico durante los últimos 1600 años. La reconstrucción sedimentaria e hidrológica basada en análisis sedimentológicos, geoquímicos y mineralógicos ha permitido la identificación de cinco unidades sedimentarias y cinco episodios

paleohidrológicos coherentes con otros registros paleoclimáticos de la Península Ibérica, mostrando fases áridas (anterior al periodo romano y durante la ACM) y más húmedas (final del periodo romano y la Pequeña Edad del Hielo). La historia hidrológica de la laguna empieza con (i) un aumento del nivel piezométrico y el inicio de la sedimentación lacustre hacia el año 300 DC; posteriormente (ii) tras una breve etapa somera, aumentan progresivamente los niveles durante la Baja Edad Media (500-900 DC); seguido (iii) por niveles del lago relativamente bajos durante la ACM (1000-1300) con un elevado aporte de material detrítico y erosión de suelos; después (iv) prosigue con un periodo de niveles lacustres altos y desarrollo de condiciones anóxicas frecuentes coincidiendo con la PEH (1300-1850 DC); y por último (v) fluctuaciones hidrológicas durante el siglo XX, comenzando con un ligero aumento de los niveles a principios de siglo y tendencia hacia un descenso relativo en tiempos recientes (1950-actualidad). Aunque el complejo de lagunas de Cañada del Hoyo está actualmente protegido, el acuífero kárstico regional está siendo explotado para usos agrícolas.

Los mayores aportes detríticos en la laguna de La Parra durante la Edad Media y la Edad Contemporánea producidos por los cambios socioeconómicos (principalmente la trashumancia y roturación de bosques) y climáticos son coherentes con las reconstrucciones realizadas en otros lagos del complejo de las Torcas.

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4.4 Article 2

Climate, paleohydrology and land use change in the Central Iberian Range over the last 1.6 ka: The La Parra Lake record

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Abstract. A multiproxy study of a 7 m long sedimentary sequence from Lake La Parra (39º 50.948', 1º 52', 1014 m a.s.l) supported by 11 ^{14}C AMS and $^{210}Pb/^{137}Cs$ dates provides a robust, high-resolution hydrological and environmental variability record for the last 1600 years of the Las Torcas sinkhole Complex in the Central Iberian Range. The succession of depositional environments in Lake La Parra sinkhole is controlled by both changes in the regional water table and by the balance between sedimentary input through ephemeral creeks and in-lake production of carbonates and organic matter. Although synergetic links with climate are likely, phases of increased sediment delivery to the lake at ca 500–700 AD, ca 1000 AD, 1450-1500 AD, 1550-650 AD and since 1700 till recent times are driven primarily by human impact in the watershed. Prior to ca 300 AD the sinkhole was dry, then became a lake at the end of the Roman Period (350 AD) when the doline was flooded, and it has not dried out during the last 1600 years. Moderate lake levels with deposition of coarser clastic facies dominated up to the 12th century (400-1200 AD), and relatively higher levels with deposition of laminated facies during the 13th-15th centuries (1200-1600 AD). The pattern of paleohydrological evolution at a centennial scale is roughly coherent with most Iberian lacustrine records, however, the 'La Parra' sequence indicates that increased humidity during Iberian-Roman times was restricted to southern Spain, and the humid phases of the LIA starting and ending earlier in the central Iberian Range compared to the Pyrenean Domain and southern Spain. This new sequence highlights the heterogeneity through space and time of the main dry and wet climatic periods at shorter scales, emphasizing the impact of latitudinal climate gradients on the Iberian Peninsula climate variability.

Keywords: Late Holocene, sedimentary facies geochemistry, diatoms, Iberian Peninsula, karstic lake, palaeohydrology, human impact.

1. Introduction

Late Holocene palaeoclimate reconstructions are critical improving our understanding of current climate variability and predictions of environmental responses to future climate changes (Bradley et al., 2003; Mayewski et al., 2004; Mann et al., 2009; Jones et al., 2009). Most North Hemisphere palaeoclimate records spanning the last two millennia include evidence of two main climate periods, although the timing is not yet well constrained (Mann et al., 2009): a warmer Medieval Climate Anomaly (MCA, 950-1250 AD; see Lamb, 1965; Hughes and Diaz, 1994) followed by a cooler Little Ice Age (LIA, 1400-1700 AD; see Bradley and Jones, 1993). However, previous reviews of these intervals have shown clear centennial-scale temperature and precipitation anomalies, and have also emphasized their spatio-temporal heterogeneity (Bradley et al., 2003; Mann et al., 2009; Diaz et al., 2011; Ahmed et al., 2013), and even an anti-phase behavior (e.g. between the western and eastern Mediterranean, Roberts et al., 2012).

A number of climate reconstructions over the last two millennia for the Mediterranean region have been recently published (see Valero-Garcés and Moreno, 2011; Moreno et al., 2012; Lionello, 2012; Roberts et al., 2012, Magny et al., 2013) which describe rapid environmental and climatic changes coinciding chronologically with the MCA and the LIA with underlying regional trends. These trends highlight timing discrepancies in palaeohydrological shifts, with associated variability in inferences concerning the definition of age ranges for wet and dry phases. In the Iberian Peninsula, numerous Late Holocene lake sequences have been analysed in a variety of geographic, climatic and ecologic settings (Julià et al., 1998; Luque & Julià, 2002; Pla & Catalan, 2005; Moreno et al., 2008, 2009; Martín-Puertas et al., 2009; López-Merino et al., 2011; Morellón et al., 2011; Corella et al., 2012; Currás et al., 2012; Höbig et al., 2012) using a variety of geological (facies, geochemistry) and biological (pollen, ostracods, diatoms, quironomids) proxies (Moreno et al., 2008, 2009; Martín-Puertas et al., 2009; Morellón et al., 2011; Corella et al., 2012; Currás et al., 2012; Höbig et al., 2012). Diatom studies have demonstrated large environmental changes in Iberian lakes during the last 2000 years in water depth, salinity and trophic status: Laguna de Medina (Reed et al., 2001), Sanabria (Luque and Julià, 2002), Enol (López-Merino et al., 2011), La Cruz (Julià et al., 1998; Kiss et al., 2007), Arreo (Corella et al., 2011), Montcortès (Scussolini et al., 2011), Estanya (Riera et al., 2004), Estany Redon (Plá and Catalán, 2005), Zoñar (Martín-Puertas et al., 2008) and Lagoa Grande (Reed, 1998; Leira, 2005). The available records show that Iberian lake dynamics responded primarily to changes in hydrology, with relatively humid conditions coinciding with the Iberian-Roman Period (IRHP, 650 BC-350 AD; Martín-Puertas et al., 2008), early Middle Ages (Dark Ages, DA, 500-900 AD; Moreno et

al., 2012) and the LIA (1300-1850 AD; Morellón et al., 2011). Higher aridity usually occurs during the MCA (900-1300 AD; Moreno et al., 2012) (see reviews in Valero-Garcés and Moreno, 2011). The Iberian records show different intensities of the hydrological signatures and some asynchronies of the main changes that could be related to variable lake sensitivity and low-resolution age models, but also they suggest a regional variability in the Iberian Peninsula related to Atlantic versus Mediterranean climate impacts. Human impact in Iberian landscapes is also significant during the last two millennia (Pèlachs et al., 2009; Gil-Romera et al., 2010; Corella et al., 2013) and the climate signature in some lake records may be obscured by anthropogenic effects in the lake dynamics (Martínez-Cortizas et al., 1999; Moreno et al., 2008; López-Blanco et al., 2011; Currás et al., 2012; Roberts et al., 2011; Simonneau et al., 2013). To disentangle the complex interplay of climate and human impact during the last 2000 years and the significant regional variability in the Iberian Peninsula, more high-resolution, multiproxy and well-dated records are needed. To contribute to that effort, here we present a paleo-environmental and paleohydrological reconstruction from a detailed sedimentological, geochemical and diatom study with a robust chronological model in sediment cores obtained from the karstic Lake La Parra (Iberian Range, NE Spain).

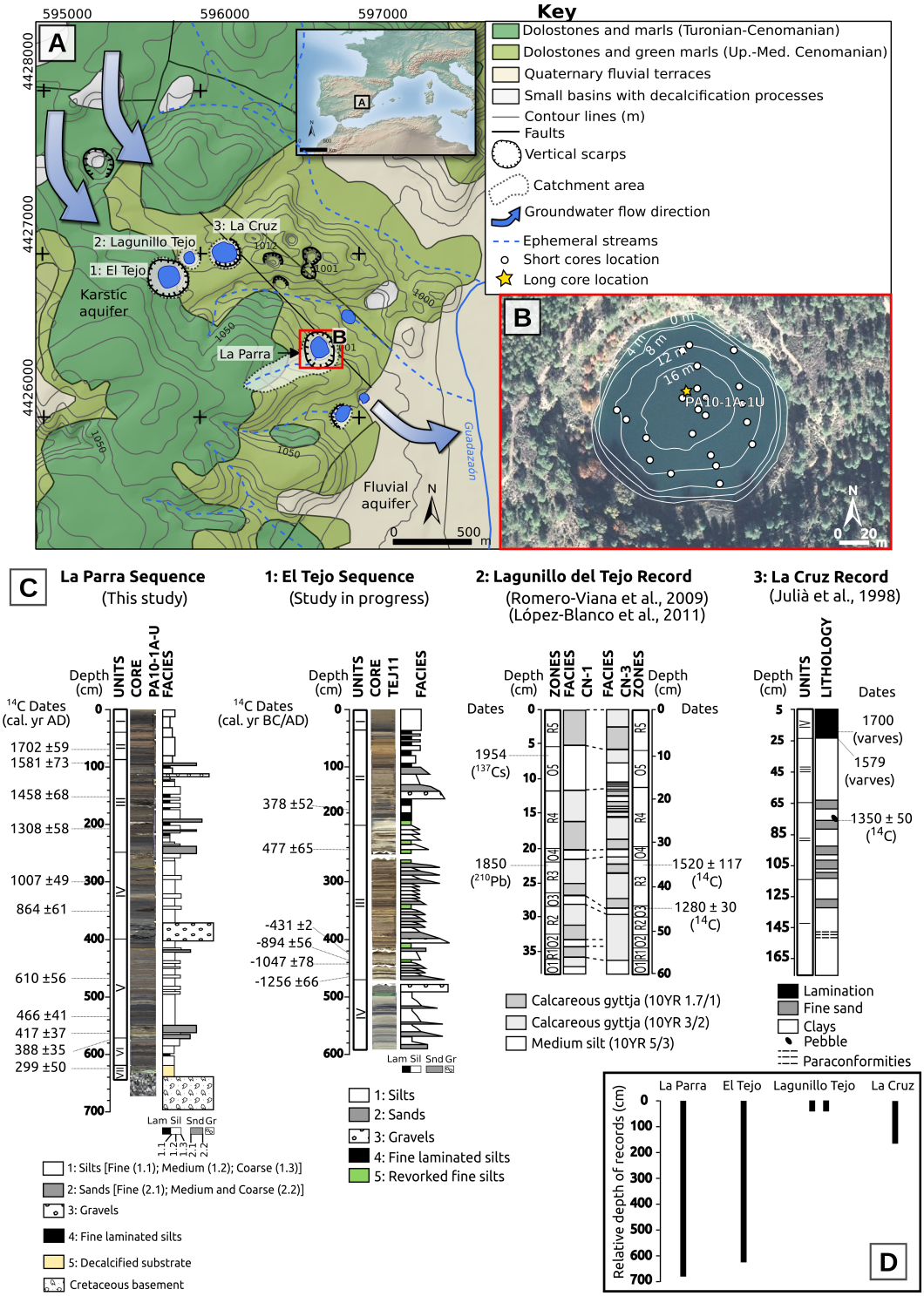

Figure 1. *A) Location of study site and detailed geological map of the lake complex from Cañada del Hoyo (based on IGME, (1973) and IGN (2002).* ***B)*** *Lake La Parra bathymetry with short cores (white dots) and long core PA10-1A-U (yellow star) location.* ***C)*** *Cores recovered up to date on the lake complex in depth with the main dates and sediment stratigraphy (1: El Tejo; 2: El Lagunillo del Tejo; 3: La Cruz).* ***D)*** *Relative depth of each record.*

2. Regional setting and study site

La Parra (39º 50' N, 1º 52' E, 1014 m a.s.l.) is one of the seven flooded sinkholes located in the complex karstic-lake system of Cañada del Hoyo, Central Iberian Range (*Figure 1*). This complex is developed by dissolution and fracture processes since the Pliocene (Gutiérrez Elorza and Valverde, 1994) on Jurassic and Middle to Upper Cretaceous limestone and dolostone formations (Alonso, 1986). Regional tectonic structures as the Valdemoro fault and the occurrence of a NW-SE anticlinal fold have both also played a significant role in the development of this karstic system (Eraso et al., 1979; Carmona and Bitzer, 2001).

The study site has a Mediterranean climate modulated by continental influences with large daily and seasonal temperature contrast, harsh cold winters and hot summers (from 4 ºC mean monthly temperature in January to 23 ºC in July). Annual mean rainfall is 542 mm, with July the driest month and October the wettest. Local vegetation is dominated by *Pinus nigra, Quercus faginea, Q. ilex rotundifolia, Juniperus thurifera, Buxus sempervirens* and *Q. coccifera*. Depressions and lowlands are occupied by cereal crops.

Lake La Parra has a circular morphology (113 m diameter, 1 ha surface) and steep margins (17.5 m maximum depth; *Figure 1*) with 10 m high vertical scarps composed of Upper Cretaceous dolomites surrounding the lake from W to SE. Influenced by a dolomite-rich watershed, the lake waters are dominated by HCO_3^- (4.78 meq/L) anions and Mg^{2+} (3.96 meq/L) cations, with pH of 8.

The lake is holomictic (Miracle et al., 1992) as shown by chemical (Electrical Conductivity from 305 µS/cm to 356 µS/cm at 16 m depth) and isotopic measurements (from -4.01 to -4.20 per mil $\delta^{18}O$, and from -38.11 to -37.46 per mil δD at surface and 16 m water depth respectively). The lake has an ephemeral inlet and no permanent surface outlet (Carmona and Bitzer, 2001). Although no hydrological balance is available, the recent lake level fluctuations are controlled by: i) the small watershed (~ 10 ha) with reduced run-off input; ii) the low transmissivity of local and regional aquifers; iii) a high-seasonal rainfall regime with high evaporation and iv) recent use of regional aquifers by agriculture wells. The enriched $\delta^{18}O$ values in lake water (ca -4 per mil) compared to aquifer and surface waters $\delta^{18}O$ values (-8.5 to -7 per mil, Carmona and Bitzer, 2001) demonstrate a strong impact of evaporation processes in lake hydrology.

The lakes of Las Torcas karstic system are hydraulically connected to the regional carbonate aquifer and the lake levels reflect the regional groundwater levels. The main aquifer recharge area (60 % total water influx) is located in a 25 km^2 karstic area, located some 15 km north of the Las Torcas Complex. The groundwater flux is estimated as 300 l/s (Carmona and Bitzer, 2001) and follows N-S trend fractures and karstic conduits towards the south and only

floods the sinkholes located topographically at <~1000 m a.s.l. From the sinkholes, groundwater drains towards the Guadazaón River fluvial aquifer.

3. Material and methods

In May 2010 two parallel piston cores (PA10-1A-U and PA10-1B-U) were recovered in the deepest part of the lake with the IPE-CSIC UWITEC platform and coring equipment. Later, in summer 2011, a network of 21 short gravity cores was retrieved with the UWITEC gravity corer. The piston cores were split longitudinally and photographed with the CCD camera attached to the AVAATECH X-Ray Fluorescence (XRF) scanner from the XRF-Core Scanner Laboratory of the University of Barcelona (UB, Spain). 52 samples were taken from the core PA10-1A-U for quantitative elemental geochemistry of major and trace elements by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), using a Perkin/Elmer Nexion 300X ICP-MS at the University of Pittsburgh (US-PA), following Pompeani et al. (2013). The same core was sub-sampled every 2 cm for Total Organic (TOC) and Total Inorganic (TIC) Carbon; and every 6 cm for Total Nitrogen (TN). TIC and TOC were measured with a LECO SC144DR available at the IPE-CSIC and TN with a FLASH EA 1112 LECO TRUSPEC-CN at the Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC, Spain). Principal Component Analysis (PCA) was carried out to investigate the relationship between the chemical elements present on the sediments. Statistical treatment of the data was performed using R software (R Development Core Team, 2013). The dataset includes major elements, trace elements, and REE (determined by ICP), and also bulk geochemistry (TOC, TIC and TN). All variables were normalized with respect to their mean and standard deviation. Mineralogy was analysed every 10 cm by a Siemens D-500 X-ray diffractometer (Cu kα, 40 kV, 30 mA, graphite monocromator) at the Serveis Científico-Tècnics of the ICTJA-CSIC (Spain). Identification and relative abundance of the predominant mineralogy of the crystalline fraction were determined following Chung (1974a, b).

Sedimentary facies were described following Schnurrenberger et al. (2003). Selected samples from each facies were analysed with a JEOL JSM-6400 electron microscope coupled with an EDAX INCA 300 X-Sight for elemental identification at the University of Zaragoza (Spain).

Standard extraction and counting methods (Stoermer et al. 1996) were applied to twenty samples for diatom analyses. The samples were selected considering sedimentary facies variability and therefore, the resolution varies from 20 to about 150 yr. Diatom concentration per unit weight of dry sediment was calculated following Battarbee (1986) and is expressed as valves per gram of dry sediment (v/gds $x10^6$). Relative abundances of the diatom taxa were calculated in two ways: i) based on the total diatom sum, which were used for

the calculation of the planktonic and non-planktonic percentages and, ii) based on a partial diatom sum which included all species except for *Cyclotella cyclopuncta;* species percentages presented in figure 5 were calculated in this way. This method for expressing diatom relative abundance was chosen given the high dominance of *Cyclotella cyclopuncta* in the record, as excluding it from the diatom sum allows for the variations along the sequence of the non dominant species to be more evident; this explains the above 100% abundances of *C. cyclopuncta* in the diatom diagram. Taxonomic identifications and autoecological requirements for the principal diatom taxa were made using literature (Krammer and Lange-Bertalot, 1986-1991; Håkansson and Carter, 1990; Julià et al. 1998; Håkansson, 2002; Kiss et al., 2007; Morellón et al. 2011). The dominant species in this record was identified as *Cyclotella cyclopuncta,* however this species is considered to be very close or possible conspecific with similar small centric diatoms such as *C. delicatula* or *C. distinguenda* var. *unipunctata* (see Kiss et al. 2007). The statistical treatment of the diatom dataset for Cluster Analysis was performed using the R software package (R Development Core Team 2013) together with the package ''vegan'' (Oksanen et al. 2013). Distances between clusters were recomputed by the Bray-Curtis method, using a data matrix corrected by the square root of the species percentages.

To establish the chronology of the lacustrine sequence 13 AMS ^{14}C dates were obtained at the Poznan Radiocarbon Laboratory (Poland) and the DirectAMS Laboratory (US-WA) from wood fragments in long core PA10-1A-U; and ^{137}Cs and ^{210}Pb dates in short core PA-10-2A-1G, were obtained by gamma ray spectrometry at the St. Croix Watershed Research Station (US-MN). The ^{210}Pb dates were determined following Appleby (2001). The upper part of core PA10-1A-U was correlated with the short core PA-10-2A-1G using TOC values (*Figure 2*). Radiocarbon dates were calibrated using the curve INTCAL 09 (Reimer et al. 2009) and selecting the median of the 95.4% distribution (2σ probability interval). Age-depth model was performed with Clam code (Blaauw, 2010), adjusting the curve with a locally weighted spline.

4. Results

4.1 Chronological model

Table 1. *Radiocarbon dates used for the construction of the age model for the Lake La Parra sequence. Dates were calibrated using CLAM software (Blaauw, 2010) and the INTCAL09 curve (Reimer et al., 2009); and the 2σ probability interval was selected. Dates with * were discarded (reversals or stratigraphically inconsistent).*

Core depth (cm)	Laboratoy code	^{14}C AMS age (BP)	2σ calibrated age (cal. yr. AD)	Material
66	Poz-37954	230 ± 30	1660 ± 24	Wood fragment
93	Poz-37955	390 ± 35	1482 ± 42	Wood fragment
145	Poz-37956	265 ± 30	1644 ± 26	Wood fragment
209	D-AMS 1217-210	693 ± 25	1296 ± 28	Wood fragment
300	Poz-37957	1190 ± 30	834 ± 64	Wood fragment
352	Poz-37958	1155 ± 30	854 ± 53	Wood fragment
416	D-AMS 1217-211	1614 ± 34	462 ± 80*	Wood fragment
464	D-AMS 1217-212	1328 ± 28	684 ± 34	Wood fragment
508	Poz-37959	2060 ± 30	-83 ± 84*	Wood fragment
537	D-AMS 1217-213	1609 ± 30	490 ± 93	Wood fragment
563	Poz-37960	1640 ± 30	403 ± 65	Wood fragment
578	Poz-37962	1700 ± 30	362 ± 49	Wood fragment
628	Poz-37963	1740 ± 30	311 ± 75	Wood fragment

La Parra sedimentary sequence described in this paper is based in 11 AMS ^{14}C dates from wood samples (13 total, with two discarded reversals) (*Table 1*). The chronological model spans from the 3rd century AD till 2010 (*Figure 2*) and exhibit no apparent hard water effect. The sediment accumulation rate is rather constant throughout the record (about 4.3 mm/yr), although the deposition of some thick clastic beds (e.g. a gravel bed at 400-380 cm depth) likely represent a rapid event. ^{210}Pb/^{137}Cs inferred accumulation rates are as well rather constant during mid 1800–mid 1900 (0.03-0.1 g/cm^2/yr^{-1}), however increased since 1970s up to 0.2 g/cm^2/yr^{-1}. ^{210}Pb dating is considerably less accurate below 25 cm, therefore the time resolution decreases prior to 1900. The ^{137}Cs profile shows a gradual pattern rather than having a sharp peak, as consequence of some post-depositional diffusion of ^{137}Cs. However, the broad ^{137}Cs peak provides additional support for the ^{210}Pb dating and the ^{14}C-based chronology.

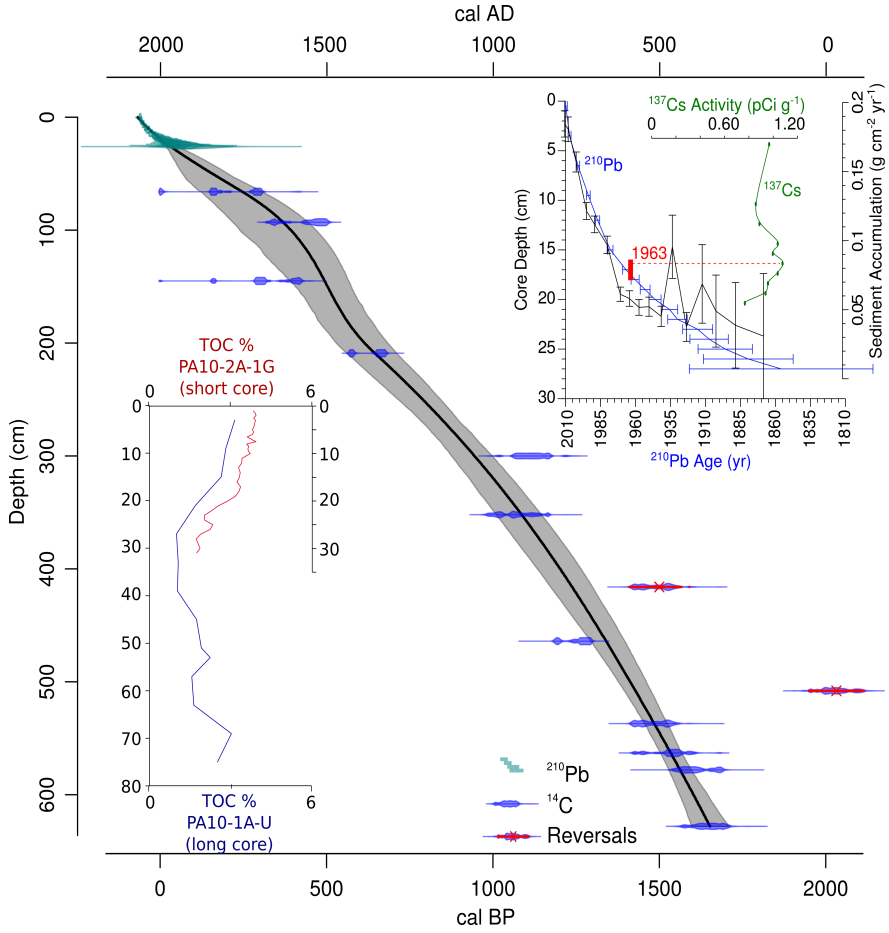

Figure 2. *Chronological model of the studied sequence based on weighted spline regression (Blaauw, 2010) of 13 AMS ^{14}C dates from the long core (blue lines) and ^{210}Pb dates (green lines) from the short core. Two reversal dates are also represented (red crossed dates). The black continuous line represents the age-depth function framed by error lines (grey shaded area). At top-right is showed the agreement between ^{137}Cs and ^{210}Pb dating, and the sediment accumulation rate for the first 30 cm of the core. At bottom-left is represented the good correlation between the short core PA10-21-1G (red) and the main long core PA10-1A-U (blue) using TOC (%) values.*

4.2 Sedimentary Facies and Units

Sedimentological description of surface sediments obtained from 21 short cores allows three main lacustrine environments to be defined across the basin (Barreiro-Lostres, 2012): i) an external-littoral platform up to 2 m water depth, with aquatic vegetation stabilizing the substrate, deposition of coarse sand and silt sediments (facies 2.2 and 1.3 respectively; see Table 2) and with the presence of active gravity processes as rock falls, where rocks are detached from the northern vertical margin of the doline; ii) an internal-littoral to profundal-distal zone with a steep and narrow talus (2-10 m depth) with brown and grey coarse to fine silts (facies 1.3 and 1.1); and iii) a profundal-distal zone (10-16m depth, 80 m wide) with deposition of banded grey silts grading to black, more organic silts in the deeper central areas (facies 1.1, 16-17 m depth).

The La Parra long core (PA10-1A-U) reached the Cenomanian greenish marl substrate and so the whole lacustrine sequence deposited in the doline was recovered (*Figure 1*). The marl substrate (facies 5, see *Table 2*) shows evidences of carbonate dissolution, brecciation and alteration and clay enrichment, common in carbonate substrate after a prolonged period of karstification (Gutiérrez et al., 2008). The La Parra sedimentary sequence is mostly composed of clastic carbonate facies ranging from gravels (*see Table 2*, facies 3); fine and medium-coarse sands (facies 2.1 and 2.3 respectively); fine, medium and coarse silts (facies 1.1, 1.2 and 1.3 respectively); to finely laminated silts (facies 4). They are organized in fining-upward sequences from 10 to 60 cm thick. This great facies variability is notorious for a relatively small karstic lake (*Table 2*). Clastic carbonates are common in Iberian karst lakes and they reflect deposition in littoral (coarse facies) to distal (fine facies) settings influenced by variable lacustrine reworking and alluvial processes (see review by Valero-Garcés et al., 2014). Deposition in La Parra Lake is controlled by the carbonate nature of the watershed (source area), the varied intensity of the sediment delivery processes (run-off and creek activity) and the changing limnological conditions (water depth, organic productivity, bottom redox conditions). Although lake level fluctuations are difficult to quantify from clastic facies sequences, grain size and texture provide some constrains for depositional depths. So, the short-core survey shows that massive to banded silts are common lacustrine facies in sublittoral to more profundal settings. Finely laminated facies (facies 4) in these karst lakes only appear when anoxic environments dominate the lake bottom, often associated with higher lake levels and/or limnological conditions conducive to more frequent water stratification (Julià et al., 1998; Romero-Viana et al., 2009a; López-Blanco et al., 2011; Valero-Garcés et al., 2014). The occurrence of gravels (facies 3) and coarse sands (facies 2.3) in the central areas of La Parra Lake indicates periods of increased erosion and runoff during likely lower lake levels.

Carbonate minerals (dolomite and calcite) are the main sediment component, and rather constant along the sequence (80-90 % mean). They are mostly of detrital origin, eroded from the Cretaceous carbonatic rocks in the watershed and transported by the small creek entering the lake at the SW margin. Endogenic minerals (calcite as main component and secondarily aragonite and high-magnesium calcite) appear in five discrete intervals, either in fine laminated facies due to the in-lake calcite precipitation or in coarser sandy and gravel facies, likely due to reworking of older lacustrine sediments. Laminated facies (facies 4, see *Table 2*) contain both white laminae made up of 3-5 µm calcite crystals and dark laminae composed of amorphous organic matter and silicates, similar to those found in other karstic lakes of the Iberian Peninsula (La Cruz, Romero-Viana et al., 2008; Zoñar, Martín-Puertas et al., 2008; Montcortès, Corella et al., 2010; Arreo, Corella et al., 2011), and interpreted as seasonal deposition of calcite precipitated in the epilimnion in summer during the climax of algal development (white laminae) and clastic material deposited during autumn-winter (dark laminae). This lamination is associated with low energy sedimentation environments, favoured by water stratification during high lake levels and prone to anoxic redox conditions in the bottom (Brauer et al., 2004).

Table 2. La Parra sedimentary facies: description, composition and depositional processes and environments. TIC, TOC, and TOC/TN are averaged values for each facies.

Lithology	Facies	Description	Depositional Processes	Depositional Environments
Clastic facies				
Silts	**1.1** ***Fine dark silts***	Dark grey and black, massive carbonate and quartz fine silts, with abundant diatoms and amorphous Organic Matter (OM) in 10-25 cm thick beds with gradational (dark grey). and sharp (black beds) boundaries. TIC: 8% TOC: 3% TOC/TN: 15	Low energy tractive currents and out of suspension	Profundal-distal, deeper areas, alternating oxygenated and anoxic conditions
	1.2 ***Medium brown silts***	Dark and light brown, banded, carbonate and quartz silts, with macrophyte remains in 5-20 cm thick layers with diffuse boundaries. TIC: 7% TOC: 2% TOC/TN: 14	Low energy tractive currents. Frequent redox changes	Profundal-distal to proximal, relatively deep, dominant oxygenated conditions.
	1.3 ***Coarse grey silts***	Light grey and dark massive carbonate and quartz silts with abundant mm-sized, OM fragments and presence of ostracods and some disperse carbonatic cm-long pebbles. They appear in fining-upwards beds, 2-10 cm thick, with irregular basal boundaries. TIC: 8% TOC: 3% TOC/TN: 12	Flood events	Profundal-distal to proximal oxygenated, moderate depth
Sands	**2.1** ***Fine green sands***	Greenish, massive sands dominated by angular carbonate and quartz grains with a greenish silty matrix. They occur in few 3-4 cm thick beds. TIC: 7% TOC: 1% TOC/TN: 11	High energy alluvial tractive currents	Littoral to proximal, shallow, with strong alluvial influence
	2.2 ***Medium and coarse brown sands***	Brown, massive sands dominated by angular carbonate and quartz grains with a fine-medium silty matrix in 2-10 cm thick beds with irregular boundaries. Coarse sands occur in a single 10 cm thick bed with irregular boundaries.. TIC: 9% TOC:		

		2% TOC/TN: 30		
Gravels	**3 *Fine and Medium brown gravels***	Brown, massive gravel composed of carbonate, angular clasts (2-25 mm) in a silty matrix. They occur in a single 30 cm thick bed with irregular boundaries. Fine gravels occur in a single 2 cm thick bed, 0.5-2 mm clasts, and present some invertebrate exoskeleton fragments. TIC: 8% TOC: 1% TOC/TN: 9	High energy alluvial tractive currents	Littoral, shallow, with strong alluvial influence
Laminated, endogenic carbonate facies				
Silts	**4 *Fine laminated silts***	Sets of 5 cm thick intervals composed of 1 mm thick white calcitic and dark OM-rich laminae with net and regular boundaries. Organic layer shows a high amount of diatoms and amorphous organic matter and calcite layer is mostly composed of ~25 µm long homometric subidiomorphous calcite grains. TIC: 9% TOC: 3% TOC/TN: 10	Out of suspension organic deposition, endogenic calcite bioproduction	Profundal-distal, permanently or seasonally anoxic
Substrate				
Breccia	**5 *Decalcified substrate***	Whitish, massive mixture of angular, irregularly-shaped carbonate fragments (2-30 mm), embedded in a green coarse-silty matrix. TIC: 2% TOC: <1% TOC/TN: <8%	Karstic processes: washing decalcification, dissolution and brecciation of carbonate substrate.	Dry doline

From the bottom to the top, seven sedimentological units (VII to I, Figure 3) have been characterized. The units are defined by the occurrence of distinctive facies and the boundaries are set at abrupt changes at the base of fining upward sequences. The basal Unit VII (640-620 cm) is bounded by the Cretaceous basement at the bottom and the onset of banded grey silts at the top. It is comprised of a mixture of decalcified silty matrix (see Table 2, facies 5; >90% clay minerals and quartz) and large carbonate clasts (1-5 cm of diameter) with irregular and angular morphologies. Unit VI (620-570 cm) is composed of medium to coarse banded silts (see Table 2, facies 1.2 and 2.2)

and finely laminated silts (facies 4) with presence of endogenic carbonates (calcite and secondly aragonite and high-magnesium calcite). This unit represents the onset of lacustrine sedimentation and the upper boundary is set in the first occurrence of sandy facies. Unit V (570-400 cm) started with a 60 cm thick fining upward sequence comprised of fine and coarse (see Table 2, facies 2.1 and 2.2 respectively) and medium silt (facies 1.2); following with deposition of five fining upward sequences (darker coarse-medium silts, facies 1.2 and 1.3). Unit IV (400-250 cm) is separated from Unit V by the presence of a unique 20 cm thick coarse gravel layer at 400 cm (facies 3). Unit IV is composed of three fining upward sequences of alternating medium to coarse silts (facies 1.2 and 1.3 respectively) in layers with irregular, erosive bases. The base of Unit III (250–95 cm) is set at a coarse sandy interval (facies 2.2); the occurrence of fine laminated sediments with endogenic carbonates (calcite + aragonite + high-magnesium calcite; facies 4) singles out this unit. Internally it is composed of seven fining upward sequences including coarse silts (facies 1.3, 15 cm mean thick intervals) and fine-laminated silts (facies 4, in ca. 5 cm thick sets), with punctual intercalation of coarse sands (facies 2.2, 5 cm thick). Unit II (95-40 cm) is composed of coarse banded silts (facies 1.3) with high TOC/TN values deposited after a thin coarse sandy interval (facies 2.2) at the base. Unit I (40-0 cm) is characterized by deposition of fine-medium dark grey silts (facies 1.1 to 1.2) topped by coarse dark silts (facies 1.3), with low TOC/TN values. Most units (V, IV, III and II) show a general fining upward trend, and within each unit, sediments are also organized in fining upward sub-sequences (sand-silt or coarse-fine silts). The only coarsening upwards sequence occurs in Unit VI.

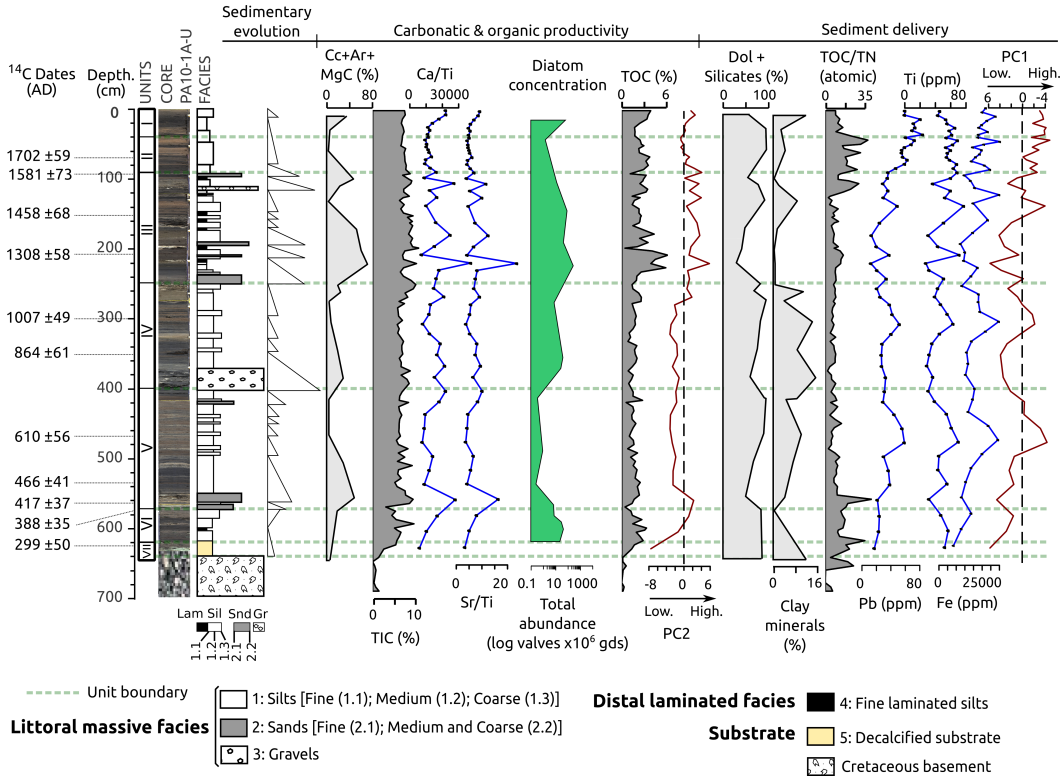

Figure 3. Sedimentary sequence of the PA10-1A-U core in depth (cm), with subdivision in units, core image, sediment stratigraphy and sedimentary evolution organized mostly in fining-upward sequences. Profiles for detrital (Do: Dolomite and Silicates), clays and endogenic (Cc: Calcite, Ar: Aragonite and MgC: Magnesian Calcite) minerals are expressed in percentages. Geochemical stratigraphy shows main quantitative ICP ratios (Ca/Ti, Sr/Ti) and Pb, Ti and Fe values (blue dotted lines), expressed in ppm. First (PC1) and second (PC2) principal components of the Principal Component Analysis (PCA) are plotted in red. Negative values of the first PCA eigenvector (PC1) represent increased detrital input, while positive values of the second eigenvector (PC2) are interpreted as higher biological productivity. TIC (%), TOC (%) and TOC/TN (atomic) values along the sequence are represented in dark gray. Dates are cal. yr AD.

4.3 Geochemistry

Total Inorganic Carbon (TIC) values along the sequence show a slight variability around mean values of 6%, with the lowest values at the base of the core and the highest values associated with fine laminated facies (Figure 3). TOC content follows a similar trend to TIC (~3% mean) with the highest values in finely laminated facies (6-7%) and towards the top Unit I (4.5%). TOC/TN atomic ratios show large variability (3-40). The highest values (40) are located at the base of the sequence (Unit VII) and towards the the top of unit III and in unit II. Geochemical composition is driven by the detrital nature of the sediments. Ca/Ti and Sr/Ti ratios present relatively low values along the Units VI and V, except at the bottom of Unit V (560 cm), and a slightly increasing

trend in Unit IV. Ca/Ti and Sr/Ti ratios show peak values in Unit III during the deposition of finely laminated silts and in recent times (Unit I). Ti, Pb and Fe values follow a similar trend on the whole sequence, with distinctive peaks at 470 cm (Unit V), 310 cm (Unit IV) and an increasing trend from 250 cm (start of Unit III) towards the top of Unit I (*Figure 3*).

The principal component analysis (PCA, *Figure 4*) of the geochemical dataset including ICP and LECO results shows that the first two components explain 48% of the total variance of the dataset (26% the first eigenvector and 22% the second). The remaining PCA components explain variance percentages <12% and they have not been taken into account. Negative values of the first principal component (PC1) are related to elements associated with clastic input (Fe, Ti, Pb, Si, Al) and with high TOC/TN values suggesting that terrestrial organic matter (plant macrofossils and soil organic matter, see Meyers and Lallier-Vergés, 1999) enters the lake with the terrigenous material. PC1 and detrital mineral (dolomite + quartz + clay minerals) profiles show similar patterns. The second principal component (PC2) is related to chemical elements associated with in-lake biological and endogenic carbonate productivity, such as Ca, Sr, TOC and TIC (Figure 4). The plot of PC1 with respect to the sample core depth highlights three short intervals of higher clastic input (negative values) to the lake in units V, IV and III (ca. 550, 1000 and 1500 AD) and a longer interval in Units II and I (1600–1950 AD). After 1950 AD, PC1 values slightly decreased. On the other hand, the plot of PC2 values with respect to their core depth indicates that higher in-lake carbonatic and organic productivity (positive values) occurred in three main intervals coinciding with relatively lower clastic input to the lake and with the sedimentation of fine laminated facies with endogenic carbonates - transition from Unit VI to Unit V (380-450 AD), top of Unit IV and Unit III (1150-1600 AD) - and in Unit I (after 1950 AD).

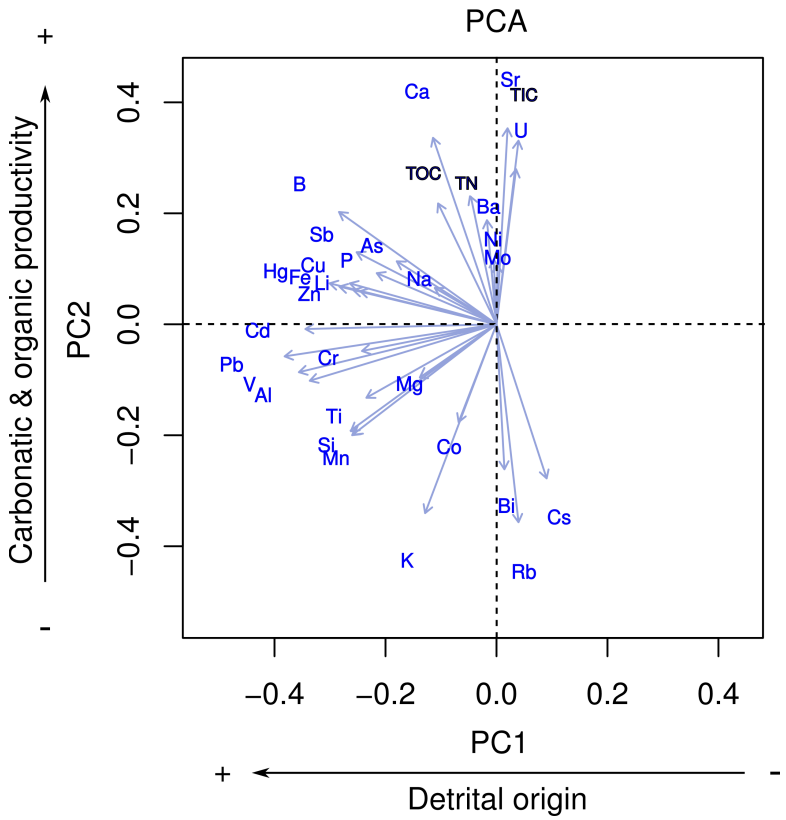

Figure 4. *Principal Component Analysis (PCA) of the PA10-1A-1U core geochemical composition (TOC, TIC, TOC/TN -black- and major and trace elements from ICP –blue-). Dataset contains 35 variables and 52 cases. The first eigenvector (PC1) highlights the detrital inputs, whereas the second eigenvector (PC2) has been interpreted as changes in carbonatic and organic productivity.*

4.4 Diatoms

Diatom preservation is good along the record except for the samples from sandy intervals –e.g. 440 cm, 660 AD; 199 cm, 1339 AD-. In total, 43 diatoms species were identified, dominated by planktonic species (82-96 %), amongst which *Cyclotella cyclopuncta* is the most abundant taxa followed by *C. distinguenda*, a species indicative of higher alkalinity (Krammer & Lange Bertalot 1991). Diatom zonation based on cluster analyses identifies four major zones with boundaries which coincide with the limits between lithostratigraphic units. Given the lower resolution of the diatom record its zones tend to be broader compared with lithostratigraphic units: diatoms zone 1 includes units I and II; zones 2 and 3 correspond to unit III and IV respectively, and zone 4 includes units V and VI (*Figure 5*). The bottom of diatom zone 4 (unit VI) has relatively high diatom abundance with high proportions of *C. distinguenda* and the presence of *D. stelligera*. At the top of zone 4 (Unit V)

diatom concentration and *C. cyclopuncta* abundance have their lowest values while *C. distinguenda* and non-planktonic diatoms *(N. diluviana*) are the most abundant. In zone 3 (Unit IV) there is a recovery in diatom concentration, again dominated by *C. cyclopuncta* and *C. distinguenda.* The highest diatom concentration is in zone 2 (Unit III), which also shows maximum values of *C. cyclopuncta*, and minimum of *C. distinguenda.* This zone also has high abundance of non-planktonic taxa such as *A. minutissimum, E. microcephala* and *E. cesatii.* In zone 1 (Units II and I) *C. distinguenda* increases in abundance again, with persistent high values of *C. cyclopuncta*; the most recent sample is characterized by an increase in *D. stelligera* and in total diatom abundance.

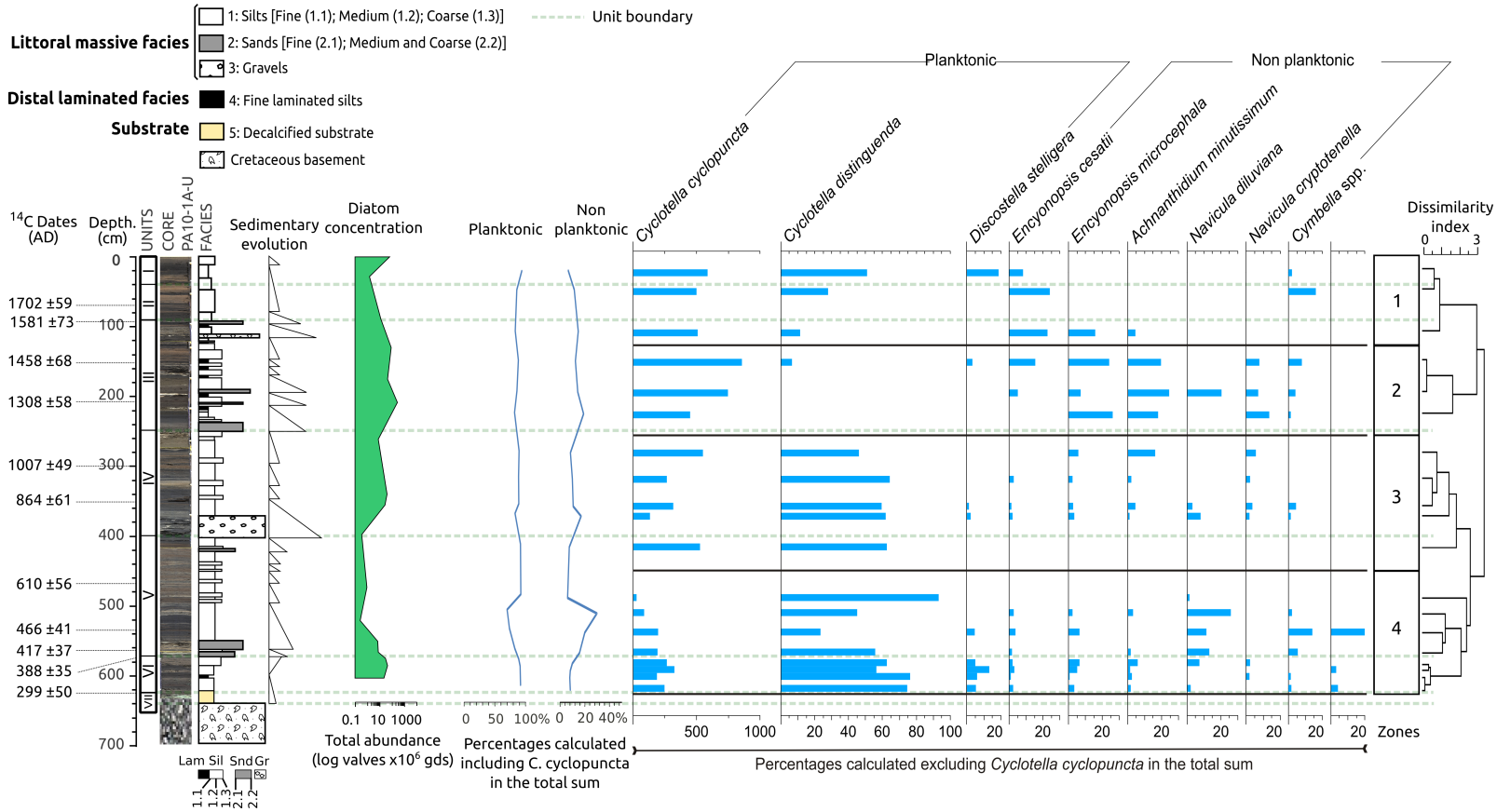

Figure 5. *Main diatom species distribution in La Parra sequence. The most abundant species are planktonic C. cyclopuncta and C. distinguenda; Non-planktonic group includes benthonic and tychoplanktonic species. Values are expressed in percentages, excluding Cyclotella. Diatom concentrations are expressed in valves per gram of sediment.*

The bottom of diatom zone 4 (unit VI) has relatively high diatom abundance with high proportions of *C. distinguenda* and the presence of *Discostella stelligera*. At the top of zone 4 (Unit V) diatom concentration and *C. cyclopuncta* abundance have their lowest values while *C. distinguenda* and non-planktonic diatoms *(Navicula diluviana*) are the most abundant. In zone 3 (Unit IV) there is a recovery in diatom concentration, again dominated by *C. cyclopuncta* and *C. distinguenda.* The highest diatom concentration is in zone 2 (Unit III), which also shows maximum values of *C. cyclopuncta*, and minimum of *C. distinguenda.* This zone also has high abundance of non-planktonic taxa such as *A. minutissimum, Encyonopsis microcephala* and *E. cesatii.* In zone 1 (Units II and I) *C. distinguenda* increases in abundance again, with persistent high values of *C. cyclopuncta*; the most recent sample is characterized by an increase in *D. stelligera* and in total diatom abundance.

5. Discussion

5.1 Depositional Evolution of La Parra

The decalcified sediments of the base of La Parra sequence (Unit VII, 640–620 cm) represent the top of the karstified Cretaceous substrate. Prior to 300 AD the sinkhole drained to the aquifer and the bottom was subaerially exposed. High and increasing TOC/TN ratio values in this interval reflect high terrestrial organic mater content, likely related to soil-forming processes at the bottom of the sinkhole (*Figure 6*).

Deposition of brown fine silts with higher TOC, TIC and increasing Ca/Ti and Sr/Ti values (Unit VI, 620–570 cm, 340-400 AD) represent the early flooding of the sinkhole with raising groundwater levels (*figures 3 and 6*). The low clay mineral content and higher PC1 values mark reduced sediment input to the sinkhole; the low PC2 scores indicate low endogenic carbonate productivity during this early lake flooding stage. High diatom concentration and predominance of planktonic taxa (*C. cyclopuncta* and *C. distinguenda*) suggests the doline flooded quickly and reached relatively high water levels soon. At the same time, the high abundance of *D. stelligera* suggests relatively high nutrient availability (Köster and Pienitz, 2006) and may be related with remobilization of nutrients accumulated in the flooded soils. The early deposition of finely-laminated silts with precipitation of endogenic carbonates at 600 cm (350 AD), which is favored by water stratification during high lake levels as documented in the nearby Lake La Cruz (Romero-Viana et al., 2008), also points to rapid lake level increase during the early phase of lake development.

The occurrence of coarse sands in the centre of the lake underlines the drastic limnological change at the onset of Unit V (570–400 cm, 400-750 AD). PC1, as a geochemical indicator for watershed erosion and sediment delivery, shows a centennial increasing–decreasing trend along this unit. It peaked ca.

600 AD (*Figure 6*) and decreased afterwards suggesting a reduction of soil erosion, coherent with lower human pressure after the Visigoth decline (last half of 7th century AD) and during the Moorish period (8th-11th century AD) (Burjachs, 1996; López-Blanco et al., 2011). Fe and Ti profiles track the fining upward sequences and demonstrate the significant alluvial influence in the lake sedimentation during Unit V when diatom abundance is the lowest in the sequence maybe due to a dilution effect caused by the high clastic sediment input. The maximum *N. diluviana* and chrysophyte cysts values correspond with a decrease in the dominant *C. cyclopuncta* (planktonic), suggesting a shallower lake stage up to 500 cm (ca 550 AD). The decrease in non-planktonic species is coherent with a lake levels recovery during deposition of finer facies towards the top of the unit. Unit V, when diatom abundance is the lowest in the sequence may be due to a dilution effect caused by the high clastic sediment input. The maximum *N. diluviana* and chrysophyte cysts values correspond with a decrease in the dominant *C. cyclopuncta* (planktonic), suggesting a shallower lake stage up to 500 cm (ca 550 AD). The decrease in non-planktonic species is coherent with a lake levels recovery during deposition of finer facies towards the top of the unit. Carbonate and biological productivity along unit V is generally low (low Ca/Ti, Sr/Ti ratios and TOC values, low diatom abundance).

Unit IV (400–250 cm, 750-1150 AD) starts with deposition of the only gravel bed (400-380 cm) in the sequence. Both, high alluvial input and lower lake levels are main factors favoring sedimentation of coarse sediments in the deepest areas of the sinkhole. Although detrital minerals (dolomite, quartz and feldspars and clays) content is still high, geochemical indicators (PC1) continued with the decreasing trend initiated in the previous unit during the first three fining upward sequences (400–320 cm, 750-950 AD). A second peak in sediment delivery and watershed erosion occurred at 320-280 cm (950-1050 AD) as shown geochemical indicators (PC1, *Figures 3 and 6*). The abundance of *C. distinguenda* indicates persistence of relatively alkaline water.The abundance of *C. distinguenda* indicates persistence of relatively alkaline water.

Unit III (250-95 cm, 1150-1630 AD) is characterized by the presence of finely laminated silts composed of endogenic carbonatic minerals. It presents the highest values of Ca/Ti, Sr/Ti ratios and TOC (~6%), the highest diatom abundance and the lowest values of TOC/TN (~9) of the record (*Figure 3*). All of these indicators point to a period with the highest carbonate and biological productivity of the sequence. Diatom communities are diverse, dominated by planktonic *C. cyclopuncta* and non-planktonic *Encyonopsis* and *Achnanthidium* species; *C. distinguenda* shows minimum values, suggesting less alkaline waters, probably related with higher lake levels. Diatom communities are diverse, dominated by planktonic *C. cyclopuncta* and non-planktonic

Encyonopsis and *Achnanthidium* species; *C. distinguenda* shows minimum values, suggesting less alkaline waters, probably related with higher lake levels. The relatively higher abundance of benthic species during these laminated intervals may reflect the expansion of littoral environments caused by the rise of lake levels, the transport and reworking of benthic littoral diatoms as suggested by the occurrence of sandy layers intercalated within the fine laminated facies, or the high variability of lake level at annual/decadal scales during this period. Some thin gravel and sand layers occurred at the top of unit III, paralleling an increase in TOC/TN, detrital minerals and a PC1 peak.

The absence of laminated facies and the return to deposition of alternating light and dark grey silts marks the onset of Unit II (95–40 cm, 1630–1850 AD). This unit presents the highest TOC/TN (~40) values of the sequence and relatively lower TOC and diatom abundance. PC2 sharply decreased, pointing to less biological and endogenous carbonate productivity. Lower but increasing PC1 scores mark a third period of intense watershed erosion, starting around 1600 AD and lasting until the top of the unit (ca. 1850 AD, *Figure 6*).

The top Unit I (40–0 cm, 1850-2010 AD) is characterized by deposition of dark grey silts with higher TOC, significantly lower TOC/TN ratios, and an increasing trend in endogenic carbonates content. Sediment delivery to the lake as indicated by the dominance of finer silts facies and the PC1 values continued to be generally higher during the last century. However, significant changes in carbonate and organic productivity occurred. TOC values show three main periods: < 1.5 % between 40-28 cm (1850 - 1908 AD); an increase up to 3.5 % until 15 cm, (1908 -1966 AD) and higher than > 3.5 % during the top 15 cm (last 44 years) (*Figures 2 and 3*). This general increase in TOC is paralleled by a decrease in TOC/TN and reflects an increase in endogenic bioproductivity, while the reappearance of *D. stelligera* suggests nutrient-enriched water and some level of eutrophication. Compared to the 19th century, detrital and allochtonous organic material input decreased rapidly (low dolomite and silicate % and low TOC/TN values) parallel to an increase in bioproductivity during the early and mid 20th century (1920s till 1970, 23-13 cm). The decrease in soil erosion (lower TOC/TN) and the increase in carbonatic and organic productivity in the lake could be a reflection of the population decrease during the 20th century caused by the rural exodus from villages to cities and the abandonment of crop fields with the consequent decrease of anthropogenic disturbance. However, after the 1970s (top 13 cm), sediment accumulation in the lake rapidly increased from 0.05 to 0.2 gcm^{-2} yr^{-1} (*Figure 2*), although TOC continued increasing and TOC/TN remained low. Coarser sedimentation during the last 30 years in La Parra could imply a slight lowering of water levels accompanied by higher anthropogenic disturbance in the area.

These trends point to a recent change in the lake dynamics that could be caused by increasing human pressure due to tourism.

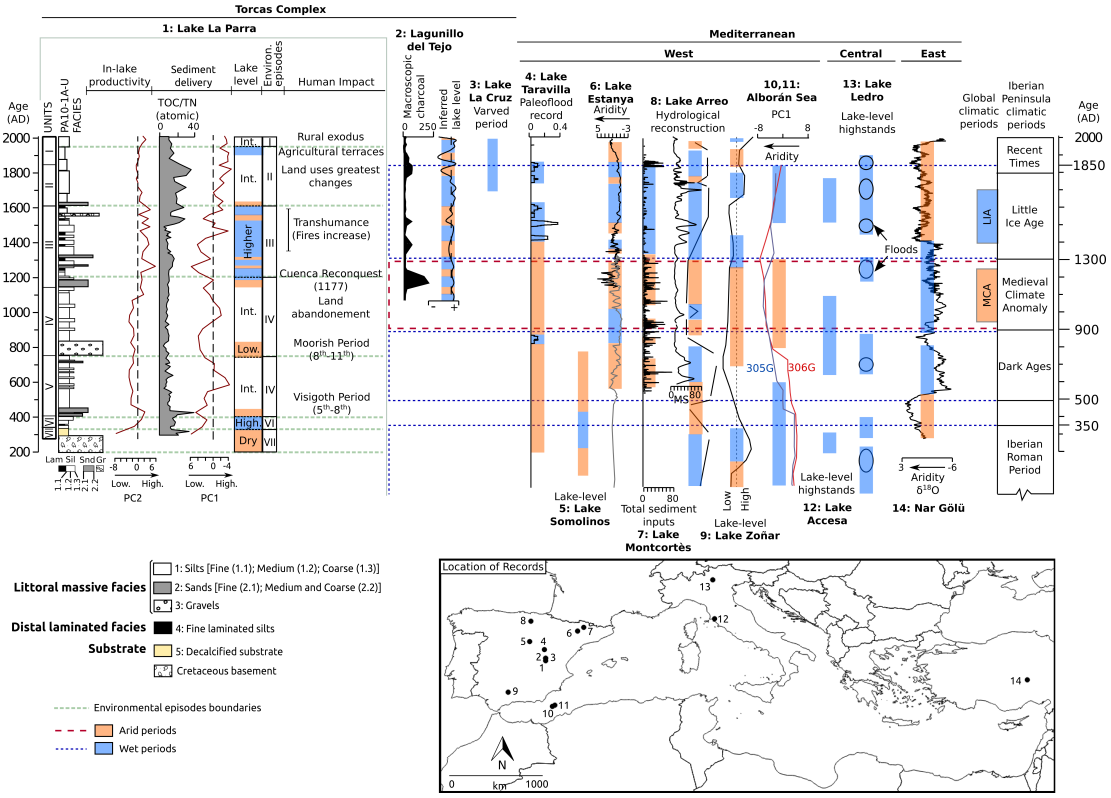

Figure 6. *Lake La Parra sedimentary PA10-1A-U sequence in calibrated years AD/BC (dates are based on AMS ^{14}C and ^{210}Pb dating), with subdivision in units and sedimentological profile. The global North hemisphere Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) are represented following the chronology of Mann et al. (2009). Chronology for main Iberian Peninsula climatic periods is based on Martín-Puertas et al. (2008), Moreno et al. (2012) and Morellón et al. (2011). Changes in sedimentary delivery to the lake are represented by TOC/TN (atomic) profile (in dark gray) and the negative values of PC1 (red line). Lake level fluctuations (dry, intermediate and high) and main paleoenvironmental and paleohydrological episodes explained on text are indicated. Principal human impact and historical events in the study area are shown. The record is compared with available records from the nearby Lagunillo del Tejo (López-Blanco et al., 2011) and Lake La Cruz (Julià et al., 1998) in the Torcas karstic lake Complex; West Mediterranean: Taravilla (Moreno et al., 2008), Somolinos (Currás et al., 2012), Zoñar (Martín-Puertas et al., 2008), Montcortés (Corella et al., 2012), Arreo (Corella et al., 2011, 2013), Estanya (Morellón et al., 2009, 2011) lakes and Alborán Sea records (Nieto-Moreno et al., 2011); and Central Mediterranean: Lake Ledro highstands (Magny et al., 2013) and floods frecuency (Wirth et al., 2013) and Lake Accesa high-stands (Magny et al., 2013) sequences; and East Mediterranean records (Nar Gölü, Jones et al., 2006). Locations on bottom-right map are: 1-La Parra, 2-Lagunillo del Tejo, 3-La Cruz, 4-Taravilla, 5-Somolinos, 6-Estanya, 7-Montcortès, 8-Arreo, 9-Zoñar, 10-Alborán core 305G, 11-Alborán core 306G, 12-Accesa, 13-Ledro, 14-Nar Gölü.*

5.2 Cañada del Hoyo hydrological and environmental changes for the last 1600 years

Lake records spanning the last millennium are available from three lakes of the Cañada del Hoyo karstic system (*Figure 1*): La Cruz (Burjachs, 1996; Julià et al., 1998; Rodrigo et al. 2001; Romero-Viana et al., 2008, 2009a, 2011); Lagunillo del Tejo (Romero-Viana et al., 2009b; López-Blanco et al., 2011) and La Parra (this study). Although chronological models do not have similar resolution (*Figure 1*), and the proxies used to reconstruct lake level and environmental changes differ from one another, the proximity of these lakes provide an opportunity to evaluate the regional significance of reconstructed hydrological/environmental changes in a context of similar climate forcing and human impact. Therefore, differences in climate forcing and human impact can be discounted in interpreting these environmental records. Furthermore, this study shows how some particular lake features may control the sensitivity of the system to record past changes. The ^{14}C age model for Lake La Parra is the most robust of the three sites: 11 ^{14}C AMS dates versus 1 for Lake La Cruz and 5 for El Lagunillo.

Palaeohydrological changes. The main episodes of hydrological change during the ca. 300 to 2010 AD period defined in lake La Parra (*Figure 3*) should be reflected in all Las Torcas complex (*Figure 6*). The most arid phase of the last 2 millennia, represented by Unit VII, occurred before ca. 300 AD, when the sinkhole was dry. The length of this period of subaerial exposure and vertical drainage in the sinkhole is unknown, but it was long enough to produce intense karstic decalcification processes and the alteration of the Cretaceous substrate. The flooding of the doline (Unit VI) at about 300 AD inaugurated a generally more humid period during the last 1.6 ka with highly fluctuating lake levels but without another drying out phase. Two main transitions occurred at 1200 and 1600 AD defining three main stages: i) intermediate but fluctuating lake levels occurred during the 400-1200 AD period (Units V and IV), with the lowest during 750-850 AD; ii) the highest lake levels occurred during 1200–1600 AD (Unit III), and iii) since 1600 (Units II and I) lake level remained lower than during the 1200-1600 AD period, although higher than before 1200 AD.

The rapid change in the hydrological behavior of La Parra sinkhole at about 300 AD (*Figure 6*, Unit VII) is a conspicuous feature. Rainfall and subsequent changes in aquifer-recharge and local groundwater flows play an important role in recent lake level changes (Carmona and Bitzer, 2001; unpublished data from Water Agency of Castilla-La Mancha Autonomous Community). At longer time scales, in this non-active tectonic area, other factors besides climate (changes in karst dynamics, local base level) could have been conducive to the flooding of the sinkhole. Although the complete lake sediment sequences has not been recovered in any of the other Cañada del

Hoyo lakes, the available data suggest they do not span more than a few millennia. The recovered La Cruz record spans the last ca. 1500 years and efforts to retrieve longer cores were encountered with a hard surface that might be interpreted as the Cretaceous substrate (Burjachs et al., 1996). The base of the sequence recovered in the nearby lake El Tejo in 2012 (*Figure 1C*, study in progress) is composed of coarse sands, suggesting littoral sedimentation and has been dated as 3200 ± 66 cal ^{14}C yr BP. Changes in the base level of the Guadazaón River could also have had an impact on groundwater and sinkhole lake levels. Higher fluvial incision prior to 300 AD could explain desiccation of the sinkholes but there is no geomorphologic evidence of such a river dynamic change during the 4th century AD (Gutiérrez Elorza and Valverde, 1994). As a whole, the available data support an increase in precipitation as the main reason for a rapid flooding of La Parra ca. 300 AD.

Sedimentological and geochemical indicators show a multi-decadal variability in lake level during 400–750 AD (Unit V). The deposition of the thickest gravel bed of the record (around 750 AD, *Figure 6*) marks a large depositional change in La Parra: coarse sedimentation reached the center of the lake during an episode of increased run-off and lower lake level. This episode coincide with three important droughts between 748-879 AD documented in Al-Andalus by contemporaneous Moorish historians (Domínguez-Castro et al., 2014). Once lake level recovered, during the next ca 400 years (AD 800–1200, Unit IV) only three major fining-upward sequences occurred. Later, the deposition of fine-laminated silts and the rapid increase in carbonate endogenic minerals content (the highest of the sequence) mark the transition towards a long period (1200–1600 AD, Unit III) characterized by higher lake levels in La Parra, with frequent anoxic conditions, and higher biological activity leading to more endogenic calcite formation. Up to seven finely laminated facies intervals with endogenic calcite (Ca/Ti and Sr/Ti peaks) occurred between 1200-1600 AD (*Figure 6*). They reflect decade-long periods of higher lake levels, and likely higher winter precipitation. In lake La Cruz and Lagunillo del Tejo (Julià et al., 1998; López-Blanco et al., 2011), more frequent anoxic conditions also occurred during the last centuries, but the onset is different and occurred generally later than in La Parra. In La Cruz, deposition of finely laminated facies indicative of meromictic conditions only started after 1700 AD but continued till recent times (Julià et al., 1998). In Lagunillo del Tejo, better laminated, more organic facies occurred during several intervals (1100-1150, 1250-1550, 1650-1800 and 1950-2000 AD). Fine laminated silts in El Tejo (*Figure 1C*) only occurred at the top of the sequence, after ca. 1600 AD. Development of meromictic conditions on these karstic lakes is related to the synergetic effects of climatic (higher winter precipitation, colder temperatures, weaker winds), hydrological (higher lake levels), and anthropic forcings (land-

cover changes, nutrient and sediment input).

5.3 Human impact and lake dynamics

The main periods of human impact in La Parra watershed as indicated by PC1 values (*Figure 3*) occurred at the end of the Visigoth Period and the early Moorish Period (ca 500–700 AD), at around ca 1000 AD, 1450-1500 AD, 1550-1650 AD and since 1700 AD till recent times. The increase in sediment delivery during the interval 950-1050 AD correlates with the Muslim and Christian wars when burning forest was a common military strategy (Burjachs et al., 1996). Deposition of the last thick sandy layer in the sequence at around 1200 AD (Unit III) could also reflect higher landscape transformation around the time of the Christian conquest of Cuenca (1177 AD).

The other two lake records from Las Torcas also show higher human activities in the watersheds during medieval times. Human impact in the watershed was mainly due to transhumance practices that peaked during the XVth-XVIth centuries (highest cattle heads around 1526 AD), deliberate fires and deforestation for grazing and farming (Burjachs, 1996; Julià et al., 1998; Romero-Viana et al., 2008; López-Blanco et al., 2011). In Lagunillo del Tejo three peaks of microscopic charcoal occurred during the 1200-1600 AD period indicative of higher human pressure in the landscape (López-Blanco et al., 2011; *Figure 6*). Pollen record from La Cruz confirms the more intense use of the land during the Medieval times (Burjachs et al., 1996).

The return to massive silt deposition with coarser silt intervals and the highest TOC/TN ratios of the sequence in La Parra point to intensified erosion in the lake's basin, higher input of allochtonous sediments and terrestrial organic matter, and relatively shallower water levels during the 1550–1650 AD. High scores of PC1 suggest another peak of large human impact between 1800-1850 AD (50-40 cm) that corresponds with higher population and also a period of Civil wars and significant land use changes related to new confiscation laws, changing from livestock to intensive agricultural practices (Lozano-Sahuquillo, 2002; López-Blanco et al., 2011). The maintained increase in watershed erosion and sediment delivery to the lake along 19th–20th centuries occurred during the period of increasing population in Cañada del Hoyo village and agriculture expansion in the lakes area (López-Blanco et al., 2011). A large macrocharcoal peak in Lagunillo del Tejo also occurred at this time (*Figure 6*; see López-Blanco et al., 2011).

Interestingly, each lake in the Cañada del Hoyo complex might record a different evolution during this period of the highest human pressure in the region. Some of the differences may be due to the age model uncertainties and the varied sensibility of the proxies used for each paleoenvironmental reconstruction. However, watershed topography, bathymetry and land uses

seem to play a definitive role in each lake basin. In Lagunillo del Tejo, lake levels dropped and erosion increased due to the construction of agricultural terraces within the lake basin (Romero-Viana et al., 2009b; López-Blanco et al., 2011). Lake La Cruz maintained a high water-level with varves sedimentation until present day (Julià et al., 1998). In La Parra, sediment delivery (PC1) remained high and bioproductivity as indicated by PC2 and diatom abundance remained low. Human impact was larger in Lagunillo del Tejo than in La Cruz and La Parra because of the topographic configuration of the watershed (more available flat areas for farming) and its shallower nature (< 7 m compared to 17 in La Parra and 25 in La Cruz).

5.4 Timing of paleohydrological changes in the Iberian Peninsula

The main paleohydrological changes identified in Las Torcas sequences have been documented in most Iberian records, but the timing shows noticeable differences.

The pre-300 AD arid period has also been detected in another Iberian Range karstic lake (Somolinos Lake, Currás et al., 2012). Interestingly, Lake La Parra was a dry sinkhole during much of the Iberian-Roman Humid Period (650 BC-350 AD, following Martín-Puertas et al., 2008) characterized as the most humid period in southern Spain during the last 4 ka. Although the relatively arid phase around 100 AD detected in Zoñar Lake could be correlated with La Parra arid phase, available records suggest that the Roman Period was wetter in the South than in central (Somolinos Lake, Torcas complex) and northern (Lake Arreo, Corella et al., 2013; Lake Moncortés, Corella et al., 2010; Lake Estanya, Morellón et al., 2008) Iberian Peninsula. As a whole, in the Iberian Peninsula more humid conditions prevailed during the early Iberian–Roman Humid Period (IRHP, 500-0 BC), and the climate became more arid towards the end of the Roman Period (100 BC–350 AD) (Gutiérrez-Elorza and Peña-Monné, 1998; Martín-Puertas et al., 2008; Currás et al., 2012; Pérez-Lambán, 2013), although with high variability in terms of timing and intensity (Corella et al., 2013).

Lower lake levels, evidences of increased aridity and a decrease of flood intensity and frequency have been documented all over the Iberian Peninsula somehow synchronous to the Medieval Climate Anomaly (MCA), from 900 AD to 1300 AD (following Moreno et al., 2012): in the South (Zoñar Lake, Martín-Puertas et al., 2008), in the Iberian Range (La Cruz Lake, Julià et al., 1998; Taravilla Lake, Moreno et al., 2008; Lagunillo del Tejo, López-Blanco et al., 2011), in the Central System (López-Sáez et al., in press, Somolinos Lake, Currás et al., 2012) and in the Pyrenees (Lake Redon, Pla and Catalán, 2005; Lake Montcortés, Corella et al., 2012; Lake Estanya, Morellón et al., 2011). The onset of this drier period is not synchronous all over the Iberian Peninsula, and, a

prior phase of low lake levels *ca* 750–850 AD has been documented in Central (La Parra; this study; Somolinos Lake, Currás et al., 2012; Taravilla Lake, Moreno et al., 2008) and Northern Spain (Lake Arreo, Corella et al., 2013). However, antiphasic hydrological conditions during the MCA are indicated in records from NW Iberian Peninsula, influenced by the Atlantic Ocean, relative to those from the South and Northeast, where a Mediterranean influence predominated (Lebreiro et al., 2006; Moreno et al., 2008). Despite local differences and some chronological inconsistencies, the Iberian sequences present a clear evidence that the MCA (900-1300 AD) was a dry period in the Mediterranean Iberian Peninsula, with decreased lake levels, more xerophytic and heliophytic vegetation, a low frequency of floods, major Saharan aeolian fluxes, and less fluvial input to marine basins (Moreno et al., 2012).

The first evidence for wetter conditions and higher lake levels after the MCA occurred almost at same time (~1200 AD) in La Parra and Zoñar, that is around 100 years before than in Northern Spain (Lake Arreo, Lake Montcortés, Lake Estanya, Lake Redon). Relatively more humid conditions lasted only for 400 years (1200-1600 AD) in central and southern Iberia, while in the North continued until 1900 AD. In La Parra, this wetter period is composed at least by seven hydrological oscillations, implying multi-decadal changes from 1200 to 1600 AD. Some of these fluctuations were severe enough to result in gravel deposition (ca. 1550 AD). An increase in winter rainfall has been interpreted by documentary sources (Rodrigo and Barriendos, 2008) for Andalusia (southern Spain) for the last decades of the 16th century and the first half of the 17th century, as well as an increase in the frequency of the floods in the Tagus river basin from 1590 to 1640 (Benito et al., 2003), and a general increase of floods in Taravilla Lake (Central Spain, Moreno et al., 2008). Dendroclimatic studies (Creus Novau, 2000; Saz-Sánchez, 2003) also found rainfall anomalies prevailed over thermal anomalies during the LIA in Spain. The tree ring index shows a rainfall maximum during the second half of the 16th century, general dry conditions in the 18th century, and a recovering of rainfall in the mid-19th century. Reconstructed rainfalls during the LIA from documentary data (Rodrigo and Barriendos, 2008) identified clear differences among Mediterranean locations showing a wide hydrological N-S variability in the Iberian Peninsula also pointed by other authors (Martínez-Cortizas et al., 1999; Domínguez-Castro et al., 2008; Fletcher and Zielhofer, 2013).

The change towards drier conditions in Lake La Parra at the end of the LIA (about 1600 AD) occurred about 200 years earlier than other northern Iberian lakes (about 1800 AD). These drier conditions are in good agreement with the documentary sources in Andalucía (Rodrigo and Barriendos, 2008) and the low frequency of paleofloods in the Tagus River (Benito et al., 2003) and Taravilla lake (Moreno et al., 2008) during the XVII-XIX centuries. Although

sedimentological and geochemical evidence suggest that lake levels in La Parra during the 20th century remained relatively constant, several lakes in Central (Lagunillo del Tejo), South (Lake Zoñar) and North Spain (Lake Estanya) have shown lower lake levels after the end of the LIA and during the early 20th century.

5.5 Mediterranean variability

La Parra main hydrological climatic-related changes are in agreement with the main West (Ahmed et al., 2013; Magny et al., 2013; Nieto-Moreno et al., 2011, 2013; Lebreiro et al., 2006) and Central Mediterranean (Magny et al., 2013) climate reconstructions, although most available lacustrine records from these regions lack of enough temporal resolution during the last 2000 years to establish reliable comparisons (Jones et al., 2009).

The wetter conditions in Lake La Parra at the end of the IRHP (350 AD) match with more humid conditions in the Alborán Sea (Nieto-Moreno et al., 2011) and an increase in flooding events described in North Italy sites (Lake Ledro, Wirth et al., 2013, Lake Accesa, Magny et al., 2013), as well as high lake levels (Magny et al., 2013). The drier (more humid) nature of the MCA (LIA) correlates well with an increase (decrease) in aridity interpreted by the Alborán records, linked with a decrease (increase) of flooding events in Lake Ledro. Although the MCA and LIA climatic phases from West and Central Mediterranean correlate well with Iberian records, despite minor local variability and some chronological differences, it is worth noticing that main hydrological changes occurred earlier in La Parra than elsewhere. La Parra suggests that the last part of the Dark Ages (500-900 AD) was already showing an aridity signature and that the MCA ended around 1200 AD, earlier than in northern Europe. The early onset of the more humid LIA around 1200 AD is in agreement with an increase in flooding events in the southern Alps (Lake Ledro, Wirth et al., 2013) during the 1200-1300 AD. These differences in timing detected in La Parra record and correlated to other regional sequences point to a singular hydrological response of the western Mediterranean areas during the last millennia to climate variability.

On the contrary, La Parra record shows an opposite hydrological pattern compared with East Mediterranean sites, as Nar Gölü (Jones et al., 2006) and the Dead Sea (Neuman et al., 2007), and supports the hypothesis (Roberts et al., 2012) of an East–West Mediterranean paleohydrological see-saw during the last 2 millennia (*Figure 6*). This anti-phase pattern between western and eastern Mediterranean records has been explained by atmospheric teleconnections between the North Sea and the Caspian Sea (Jones et al., 2006) and demonstrates that the LIA/MCA hydroclimatic pattern in the Mediterranean was determined by a combination of different climate modes

(including NAO forcing) along with major physical geographical controls.

The main hydrological and climatic changes identified in lake La Parra coincide with two Holocene rapid climate changes (RCCs) described by Mayewski et al. (2004) during the last millennium (800-1000 AD and 1400-1850 AD) and with global model simulations (Mann et al., 2009; Wanner et al., 2008), with a dry and warm Medieval Climate Anomaly (950-1250 AD, following Mann et al., 2009) and a wet and cold Little Ice Age (1400-1700 AD, following Mann et al., 2009). The Iberian Roman Humid Period (650 BC-350 AD; Martín-Puertas et al., 2008) identified in La Parra and other Mediterranean areas does not correspond to a global RCC. The period of relatively lower lake levels and increased sediment delivery to the lake in La Parra (400-1200 AD, and especially 750-850 AD) falls within the 800-1000 AD RCC interval at hemispheric scale due to southward migration of the Inter-Tropical Convergence Zone (Mayewski et al., 2004). Hydrological changes during the MCA and the LIA are consistent with a NAO–like dynamics at centennial scales (Trouet et al., 2009; Nieto-Moreno et al., 2011; Roberts et al., 2012) and changes in solar centennial-scale irradiance (Wanner et al., 2008; Lebreiro et al., 2006). A mechanism relating phases of decline in solar output and more frequent negative modes of the North Atlantic Oscillation (NAO) - thus reducing North-South pressure gradient over the North Atlantic and shifting the Westerlies to a southerly position - has been postulated to explain positive precipitation anomalies in the north-western Mediterranean area during the LIA (Xoplaki et al., 2004; Moreno et al., 2008; Nieto-Moreno et al., 2011). Nevertheless, the reconstructions do not show a univocal north-south trend in Iberian lakes, as proposed by Magny et al., (2013; 2012) for the Italian Peninsula, with clear latitudinal changes at latitudes about 40 N.

6. Conclusions

The sedimentary record of Lake La Parra demonstrates the high sensitivity to hydrological changes of small sinkholes and the rapid response to human induced land use changes in the watershed. The main periods of human impact in the watershed occurred at the end of the Visigoth Period and the early Moorish Period (ca 500–700 AD), at around ca 1000 AD, 1450-1500 AD, 1550-1650 AD and since 1700 AD till recent times.

The record provides a coherent paleohydrological reconstruction for the past 1600 years showing an arid period prior to ca 300 AD when the sinkhole was dry, followed by a humid stage at the end of the Roman Period (350AD) when the doline was flooded. The lake has not dried out during the last 1600 years, but experienced large lake level fluctuations: moderate but fluctuating lake levels occurred during the 400-1200 AD period with particularly lower lake levels during 750-850 AD. The highest lake levels occurred during the 1200–

1600 AD period. Lake levels decreased after 1600 AD but remained relatively high. Lake level fluctuations frequency was higher during the LIA compared to the MCA.

Although similar paleohydrological evolution occurred in most Iberian lacustrine records, La Parra supports latitudinal gradients within the Iberian Peninsula, with increased humidity during Iberian-Roman times restricted to southern Spain, and early onset of the MCA, and the humid phases of the LIA starting and ending earlier in the central Iberian Range compared to the Pyrenean Domain and southern Spain. Lake La Parra record agrees with a complex pattern of wetter and drier intervals during the LIA. The La Parra record also supports the hypothesis of antiphasic behavior between Western and Eastern Mediterranean, suggesting an active role for NAO dynamics over the past two millennia in the Western Mediterranean climate patterns. The documented heterogeneity through space and time of main global climatic phases stresses the need to integrate regional differences in global synthesis.

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4.5 Article 3

Sediment delivery and lake dynamics in a Mediterranean mountain watershed: Human-climate interactions during the last millennium (El Tobar Lake record, Iberian Range, Spain)

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Highlights

- Lake watershed highly affected by anthropic activities during the last millennium
- Proxies define 4 events of increased sediment delivery during LIA and recent times
- Events are due to positive synergies of increasing human impact and higher rainfall
- Lake system showed large resilience to land uses changes in the lake's watershed

Abstract. Land degradation and soil erosion are key environmental problems in Mediterranean mountains characterized by a long history of human occupation and a strong variability of hydrological regimes. To assess recent trends and evaluate climatic and anthropogenic impacts in these highly human modified watersheds we apply an historical approach combining lake sediment core multi-proxy analyses and reconstructions of past land uses to El Tobar Lake watershed, located in the Iberian Range (Central Spain). Four main periods of increased sediment delivery have been identified in the 8 m long sediment sequence by their depositional and geochemical signatures. They took place around 16th, late 18th, mid 19th and early 20th centuries as a result of large land uses changes such as forest clearing, farming and grazing during periods of increasing population. In this highly human-modified watershed, positive synergies between human impact and humid periods led to increased sediment delivery periods. During the last millennium, the lake depositional and geochemical cycles recovered quickly after each sediment delivery event, showing strong resilience of the lacustrine system to watershed disturbance. Recent changes are characterized by large hydrological affections since 1967 with the construction of a canal from a nearby reservoir and a decreased in anthropic pressure in the watershed as rural areas were abandoned. The increased fresh water influx to the lake has caused large biological changes, leading to stronger meromictic conditions and higher organic matter accumulation while terrigenous inputs have decreased. Degradation processes in Iberian Range watersheds are strongly controlled by anthropic activities (land use changes, soil erosion) but modulated by climate-related hydrological changes (water availability, flood and runoff frequency).

Keywords: Late Quaternary, Iberian Peninsula, karstic lake, geochemistry, sediment delivery, land use changes, palaeohydrology, resilience.

1. Introduction

Water and soil are two of the most important natural resources for historical and modern societies and the availability of both creates a unique link between people and their environment (Stern, 2006). This especially applies to the Mediterranean region characterized by a fragile hydrologic and environmental equilibrium with frequent droughts and severe flooding (Benito et al., 2008; Lionello et al., 2012). This is the case of the Iberian Peninsula, the largest territory of Southern Europe with a Mediterranean climate characterized by a hydrological deficit year around, particularly critical during the dry and hot summers.

Water availability and soil erosion have been recognized as the most significant environmental problems in the Iberian Peninsula (García-Ruíz et al., 2013, 2011; López-Moreno et al., 2007; Lorenzo-Lacruz et al., 2010), controlled by both, climate and human activities, as land clearance for crops or grazing, farming and mining developed (Carrión et al., 2010). Soil erosion is related with the absence of protective land cover whereas sediment export to lakes is determined by the onsite sediment production and the connectivity of sediment sources and the lake. The latter factor is also a function of land-use, as the sediment transport capacity is different for distinct types of land-use (Bakker et al., 2008).

Human impact in Iberian landscapes has been particularly intense during the last two millennia (Barreiro-Lostres et al., 2014; Corella et al., 2013; García-Ruíz et al., 2013, 2010; Pèlachs et al., 2009; Roberts et al., 2004). The Iberian Range, located between the Castille Plateau, the Ebro Basin and the Mediterranean coast, provides an excellent case–study for the complex interactions of human activities and climate change in Mediterranean mountain areas at a larger time scales than recent global changes. In this fragile ecosystem, societal and cultural changes have frequently resulted in the collapse of land management systems, higher fire frequency and intensity, and the activation of erosion processes (García-Ruíz et al., 2013). In particular, the evolution of the Iberian Range landscapes has been mainly a history of deforestation, linked with a unique and deep-rooted historical feature: the establishment during Medieval times of a highly complex system of sheep transhumance -the '*Mesta*'- that had intense social and economic implications and a high impact in mountain landscapes (Montserrat Martí, 1992; Pascua, 2012). Furthermore, social factors such as population growth or collapse linked to migrations, wars or large-scale diseases have a large impact on the intensity of soil conservation works in mountain areas, with large environmental implications in the landscape (Esteban Cava, 1994; García-Ruíz et al., 2013; Valbuena-Carabaña et al., 2010). Finally, the 20th century witnessed some of the largest changes in the Iberian Range, as most rivers were regulated

(Lorenzo-Lacruz et al., 2010), and after the 1950s, rural mountain areas were abandoned and population pressure greatly decreased, resulting in lower soil erosion due to vegetation recolonization (García-Ruíz et al., 2013).

In the Mediterranean region, lake sediments have been shown to be exceptional archives of past environmental and climatic evolution at the regional scale (see Lionello, 2012; Magny et al., 2013; Moreno et al., 2012; Roberts et al., 2012). In the Iberian Range, due to the dominant carbonate nature of the rock formations, most of the lakes are of karstic origin (Valero-Garcés and Moreno, 2011). Although both lake basins and watersheds are relatively small, intense depositional processes commonly leads to high sedimentation rates and thick deposits, providing long continuous sedimentary sequences with a high temporal resolution and an exceptional sensitivity to both regional hydrological balances and human induced land-use changes (Valero-Garcés et al., 2014). As observed by Dearing and Jones (2002), small lakes draining small-medium catchments (< 1000 Km^2) provide the largest number of sediment flux palaeorecords, from a variety of climatic zones. These studies also showed that during the Late Holocene, climate has been largely subordinate to human impact as main controller of long-term shifts in sediment loads, though the evidence for intense impacts from short-term climatic phases is also abundant. Small basins are most responsive to external impacts and will show the largest changes in sediment flux.

In this paper, we investigate the evolution of El Tobar Lake and its watershed during the last millennium using a multi-proxy analysis of the sediment sequence and historical and documentary data. The objectives of this study are: i) to reconstruct the main depositional phases in the lake, particularly sediment delivery fluctuations, and ii) to explore the relationships between these sediment delivery dynamics and natural (climate) or anthropic (land use changes) forcings. The results provide a general framework for the recent hydrological and land use changes in the region and long-term data to evaluate local and regional management policies.

2. The Iberian Range: climate, landscapes and human activities

2.1. The study area

El Tobar Lake (40°32'N, 3°56'W; 1200 m a.s.l.) is located in the *Serranía de Cuenca* (Western Branch of the Iberian Range), at the headwaters of the Tagus River (figure 1A). Jurassic and Cretaceous carbonatic formations dominate in the region, and karstic processes are main geomorphic agents (figure 1B). They led to the formation of lake basins behind travertine dams e.g., Lake Taravilla (40º39'N, 1º58'W, 1100 m a.s.l., Moreno et al., 2008) and in flooded sinkholes, as occurs in the seven karstic lakes of Cañada del Hoyo (39ºN, 1º52'W, 1000 m a.s.l., Barreiro et al., 2014) and also in El Tobar Lake (Vicente et al., 1993).

The watershed, although relatively small, is one of the largest in the region (1080 ha surface area) and is drained by several ephemeral creeks. The low altitude areas (~1100 m.a.s.l.) of the watershed are carved in easily erodible materials (Upper Triassic Keuper facies, composed by mudstones and gypsum rocks). Keuper facies act as an impermeable layer sealing the base of the Jurassic and Cretaceous regional aquifer. The limestones and dolostones formations dominate the catchment highlands (~1400 m.a.s.l.). A number of sinkholes occur in the watershed, likely developed by dissolution of the evaporitic Keuper facies and the overlying Jurassic and Cretaceous limestones and dolostones formations, that have been also affected by gypsum-driven dedolomitization karstification processes (Bischoff et al., 1994).

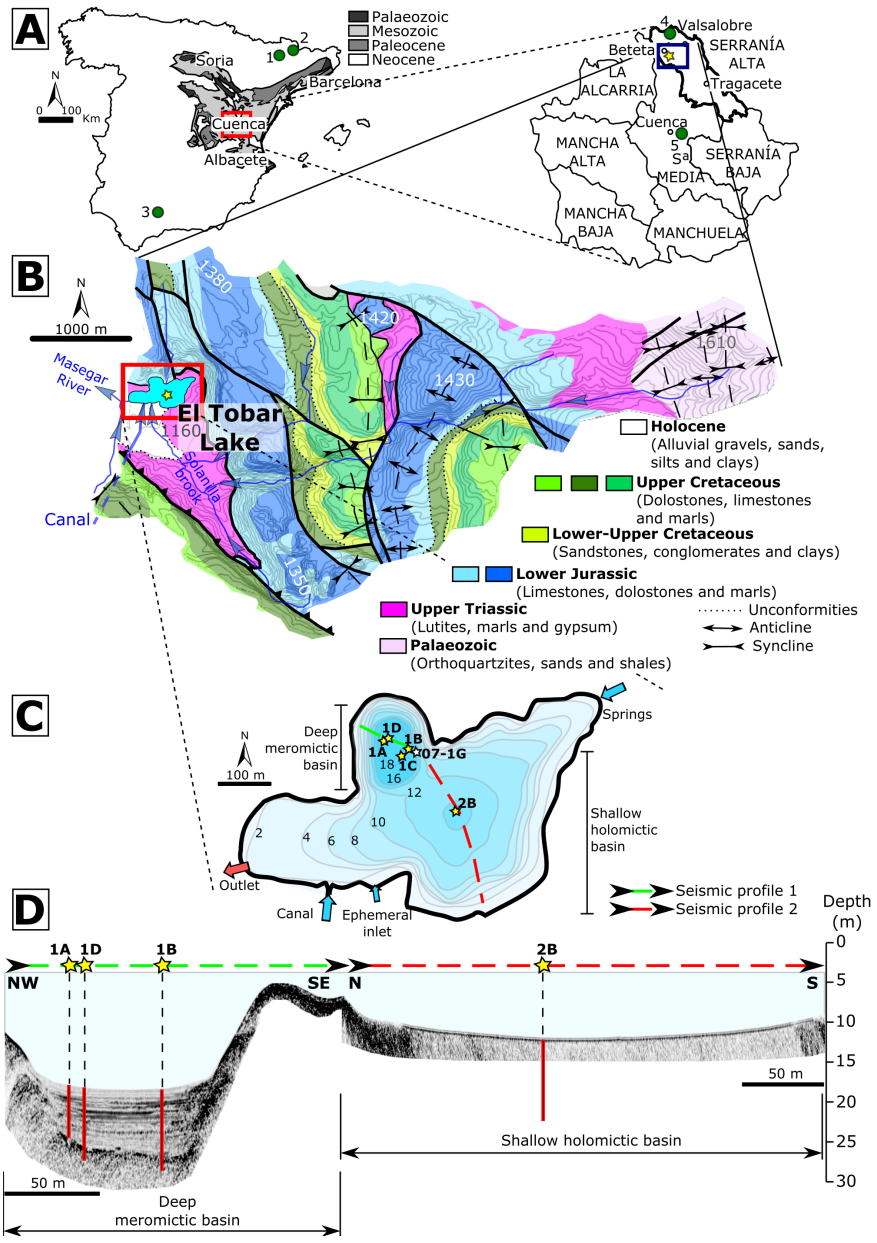

Figure 1: A) *Left: Iberian Peninsula and main Iberian Range geological units. Right: Subdivision of the Iberian Range in the study area: Serranía Alta, Media and Baja. Green dots represent the locations of main regional records in the Eastern Iberian Peninsula discussed in text: Pyrenees (1, Estaña, 2, Montcortès), South (3, Zoñar) and Iberian Range (4, Taravilla, 5, Cañada del Hoyo).* ***C)*** *Bathymetric map of El Tobar Lake showing the main water inlets and outlets and the geometry of the small meromictic sub-basin and the large holomictic sub-basin. Number indicates the depth of the isobaths in meters. Yellow stars indicate the position of the recovered long-cores, while white star mark the collected ^{210}Pb-^{137}Cs short-core. Green and red dashed lines indicate the trace of the seismic survey in the deep and shallow basins respectively.* ***D)*** *Seismic lines from the deep sub-basin (green dashed line) and from the shallow sub-basin (red dashed line) and the location of coring sites.*

2.2 Modern climate and vegetation

According to nearby meteorological stations (Beteta, 4 km NW, for the rainfall period 1945-2011 and Cañizares, 20 km SW, for the temperature period 1951-2010), the area has a Mediterranean climate, although modulated by continental influences, with harsh long winters (3 ºC mean monthly temperature) and hot short summers (19 ºC) (*figure 1B*). Average annual precipitation is relatively high (956 mm) mostly controlled by the westerly winds associated with cold fronts in late fall and winter, but inter-annual variability is large. July and August are the driest months and December the wettest, but during summer and at the beginning of the fall, highly convective storms typically occur. Meteorological records show a small mean annual temperature increase (~2 ºC) and a significant mean annual precipitation decrease since 1980s Current Era (CE), from 1600-1200 to 1000-800 mm.

Vegetation in the El Tobar watershed belongs to the supra Mediterranean sub-humid type with Central Europe tendency (Peinado-Lorca and Martínez-Parras, 1987). Pine trees dominate, with *Pinus nigra salzmannii*, *Pinus sylvestris* and *Pinus pinaster* as the main species; *Quercus ilex rotundifolia, Quercus faginea, Juniperus faginea* and *Juniperus communis* are also present as secondary species in the sunny slopes. Abandoned cereal fields occur at lower watershed elevations and abandoned *Salix* crops, used in the past for an artisan industry, surround the southern lakeshore.

2.3 The El Tobar Lake

El Tobar Lake is the largest karstic lake in the region, with a surface area of 16 ha, and a maximum depth of 20 m. It is divided into two sub-basins (*figure 1C*): (i) a smaller funnel-shaped, deeper (2 ha, 20 m depth) meromictic basin with an anoxic hypersaline hypolimnion (NaCl, brine, TDS = 19116 ppm), and (ii) a larger shallower holomictic basin (12 m depth, 14 ha) with fresher waters (TDS = 408 ppm) (López-Blanco et al., 2011b; Miracle et al., 1992; Vicente et al., 1993; Vicente and Miracle, 1988). The hypolimnion waters are dominated by Cl^- (305 meq/L) and Na^+ (261 meq/L) with pH = 7.6, while in the epilimnion these concentrations decrease until 1.7 and 1.9 meq/L respectively, with higher CO_3^{2-} (3.7 meq/L) and pH = 8.3. The lake is hydrologically open, with subaquatic spring inlets in the eastern shore (TDS= 428 ppm; pH = 7.7) and ephemeral inlets (pH = 8.2) from a small brook (Valle Solanilla creek) in the southern shore. In 1967 a connection with the nearby La Tosca reservoir (3 km southwest, fed by the Cuervo River) was established by an underground canal and since then El Tobar acts as a regulatory water reservoir (Esteban Cava, 1994). This canal provides the freshest waters (TDS = 268 ppm) dominated by CO_3^{2-} (3.6 meq/L) and Ca^{2+} (1.4 meq/L) and Mg^{2+} (0.9 meq/L). The only surface

outlet is the Masegar River, a tributary of the Guadiela River. A quantitative water balance for the lake is not available, but groundwater and the artificial canal are the main inputs. Subaquatic springs and ephemeral inlet waters have similar compositions to epilimnetic waters (IPE laboratory measures, not shown). However, the occurrence of a stable hypersaline hypolimnion suggests an active groundwater input from saline spring draining evaporitic Keuper facies (Vicente et al., 1993).

3. Materials and methods

3.1 Compilation of historical documents

In Spain, documentary evidence since medieval times is abundant, although in sparsely populated areas such as the headwaters of the Tagus River, information is scarcer. For our purposes we have used some recent compilations as Esteban Cava (1994) and the review of Valbuena-Carabaña et al. (2010). Both provide an integrated and dynamic account of the evolution of the geographical landscape, the socio-territorial, industrial and economic changes in this area for the last millennium.

3.2 Bathymetric and seismic survey

A bathymetric map from El Tobar Lake was obtained by using a SonarMite echosound connected to a DGPS. A total of 42 N-S and E-W depth-transects with a total length of 9 km were processed with the hydrographic software HYPACK, providing the bathymetry shown in *figure 1C*. Maximum depths of 19.5 and 13 m were found respectively in the deep and shallow sub-basins.

The seismic survey was conducted with an Edgetech 424-SB sub-bottom multi-frequency profiler using a frequency range of 2-10 kHz for 20 ms. A total of 5.8 km distributed in 24 seismic profiles were obtained. Penetration was very limited in the shallow sub-basin (0.5 m) but reached up to 8 m in the deep sub-basin. Seismic processing workshop software (EdgeTech Discover SB3200 XS) was used for the processing of the pinger data (bandpass filter, flat gain). Two of the seismic profiles with the best resolution and penetration have been selected to characterize the main structure of the sedimentary sequence (*figure 1D*).

3.3 Sedimentology and geochemistry

Four parallel piston cores (TOB04-1A-1K, 5.4 m; TOB04-1B-1K, 7.7 m; TOB04-1C-1K, 7.4 m and TOB04-1D-1K, 7.5 m) were recovered in the deepest part of the deep lake sub-basin (20 m); and one in the shallow sub-basin (TOB04-2B-1K, 7.1 m) with the Limnological Research Center (LRC, Univ. of

Minnesota, US-MN) floating-platform, equipped with a Kullemberg piston corer. In 2007, a short gravity core (TOB07-1A-1G, 52 cm) and its replica were retrieved with the UWITEC gravity corer for ^{210}Pb and ^{137}Cs dating assays in the deep subbasin.

The piston cores were scanned for sediment gamma density (ρ) and magnetic susceptibility (MS) at 1 and 0.5 cm of resolution respectively, with the Geotek Multisensor Core Logger (MSCL) from the LRC. Then were split longitudinally and imaged with the GEOTEK attached CCD camera at 10 pixel/mm. Sedimentary facies were described following the methodology established by Schnurrenberger et al. (2003), including smear slides microscope observations. A composite sequence was obtained (Supplementary information *figure A1*) correlating all cores using distinctive sedimentary facies and MS values.

Two main types of geochemical analyses were performed in the main cores TOB04-1B-1K, TOB04-1D-1K-2, TOB07-1A-1G (deep sub-basin) and TOB04-2B-1K (shallow sub-basin): (i) ITRAX X-ray Fluorescence (XRF) scanner at the University of Minnesota, Duluth (US-MN) at 0.5 mm of resolution with a Mo tube under the following working conditions: 30 kV, 20 mA and 30 s of exposition time per measurement point; and (ii) 53 samples covering all sedimentary facies, for quantitative elemental assays of major and trace elements by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), using a Perkin/Elmer Nexion 300X ICP-MS at the University of Pittsburgh (US-PA), following Pompeani et al. (2013). This double approach enables a complete geochemical description for each facies. The L* value calculated with ImageJ 1.48v graphic software (http://imagej.nih.gov/ij/) applied to X-Ray (XR) images obtained by the ITRAX XRF scanner was used to identify the light, gray and dark laminae occurring in the laminated facies.

The cores were also sub-sampled every 2 cm for Total Organic (TOC) and Total Inorganic (TIC) Carbon, and every 4 cm for Total Nitrogen (TN). TIC and TOC were measured with a LECO SC144DR and TN with a VARIO MAX CN elemental analyzer from the Instituto Pirenaico de Ecología (IPE-CSIC, Spain).

Mineralogy was determined on selected samples covering all facies variability by a Siemens D-500 X-ray diffractometer (Cu kα, 40 kV, 30 mA, graphite monocromator) at the Serveis Científico-Tècnics of the ICTJA-CSIC (Spain). Identification and relative abundance of the predominant mineralogy of the crystalline fraction were determined following Chung (1974a, b). Three samples from each sedimentary facies were analyzed for grain-size distribution using a Beckmann Coulter LS 13 320 Particle Size Analyzer and facies were classified using the Shepard diagram (Shepard, 1954).

The relationships among the geochemical and sedimentological signals were investigated with Principal Component Analysis (PCA) applied to a dataset

including LECO, XRF and facies data. Only the elements with a mean XRF counts per second (cps) > 1500 have been taken into account to maximize the quality of the interpretations. Then XRF data was re-sampled from the original resolution of 0.5 mm to 2 cm (LECO resolution) to compare both datasets. A final dataset with 12 variables per 359 samples was constructed and a Principal Component Analysis (PCA) was carried out using the R software 3.2.0 (R Development Core Team, 2015) with the package FactoMineR 1.29 (Lê et al., 2008).

3.4 Chronology

The construction of the age-model for El Tobar sequence has been a long and iterative process that involved different types of samples and techniques (see *Table 1*). Firstly, three wood macrorests were dated soon after the cores were retrieved (two *Salix sp*. at 551 and 789 cm depth, and one sample species not identified at 765 cm). As the results were contradictory, and no more macrorests were found in the sequence, we look for macro-charcoals, and although their presence in the sediments also was scarce, three samples (472, 756 and 768 cm depth) were dated. Finally, in a third attempt to improve the age-model and due to the scarcity of wood or charcoal fragments, bulk sediment (one sample at 789 cm depth) and pollen concentrates (three samples at 206, 279, and 507 cm depth) were also dated. Three different laboratories have been involved in dating the 10 samples from core TOB04-1B-1K: the Poznan Radiocarbon Laboratory (Poland), the DirectAMS Laboratory (US-WA) and the Quaternary Dating Research Unit Laboratory from the Council for Scientific and Industrial Research (South Africa). Radiocarbon dates were calibrated using the curve IntCal 13 (Reimer et al. 2013) and selecting the median of the 95.4% distribution (2σ probability interval).

*Table 1. Radiocarbon dates used for the construction of the age model for El Tobar sequence. Dates were calibrated using Clam 2.2 software (Blaauw, 2010) and the IntCal13 curve (Reimer et al., 2013). The 2σ probability interval was selected. Dates with * were discarded (reversals or stratigraphically inconsistent).*

Composite core depth (cm)	Laboratory code	^{14}C AMS age (BP)	2σ calibrated age (cal. year. AD/BC)	Material
206	Liv-155626	1070 ± 80	915 ± 144*	Pollen
279	Liv-155626	2055 ± 40	-75 ± 101*	Pollen
472	Liv-155624	140 ± 30	1844 ± 46	Charcoal
507	Liv-155628	1425 ± 45	610 ± 57*	Pollen
551	GrA-28169	750 ± 40	1254 ± 45*	Wood (Salix)
756	Liv-155625	560 ± 35	1335 ± 30	Charcoal
765	GrA-28170	695 ± 40	1289 ± 33	Wood fragment
768	Liv-153057	890 ± 35	1167 ± 51	Charcoal
789	Poz-12365	2050 ± 30	-53 ± 70 *	Bulk sediment
789	Poz-12233	410 ± 30	1476 ± 44*	Wood (Salix)

The uppermost sediments of the sequence were recovered in the short core TOB07-1A-1G and correlated with the uppermost part of the TOB04-1B-1K long core using TOC values. ^{137}Cs and ^{210}Pb profiles were obtained in the short core by gamma ray spectrometry at the St. Croix Watershed Research Station (US-MN). The ^{210}Pb dates were determined following Appleby (2001).

A final age-depth model based on four ^{14}C dates and the ^{137}Cs peak was performed with Clam 2.2 code (Blaauw, 2010). The final curve, after different fits with other regression models, was adjusted with a degree 3 polynomial regression, which provided the best-fitting curve for the dates.

4. Results

4.1 The sediment sequence

The NW-SE seismic profile shows well-defined reflections of alternating high and low amplitude, likely correlating with density contrasts caused by alternating sedimentary facies along the deep sub-basin (*figure 1D*). In the central part of the basin where the cores were retrieved, the seismic survey confirms that the sediment sequence is continuous, and not affected by large mass wasting processes. In the western margin, well - defined reflectors show an onlap structure at the top that could be related to relatively higher lake levels in the recent past. In the eastern margin, reflectors in the upper half of the sequence are chaotic and discontinuous. Thus, the occurrence of mass wasting deposits associated to slope instability, a common process in relatively deep, sinkhole lakes (Corella et al., 2014; Morellón et al., 2008) is very limited in El Tobar and restricted to the eastern margin.

Visual sediment description of structures, textures and composition, smear slide observations, mineralogical analyses, grain size and geochemical composition (both elemental and XRF) allowed the identification and characterization of seven facies in the El Tobar composite sequence. The base of the sequence (795-770 cm depth) is composed by facies 1 (brown sandy silts) and 2 (gray sandy silts), both with abundant terrestrial plant and gastropod fragments. Above them, facies 3 (black massive sandy silts) only occurs in this interval (770-750 cm depth). Facies 1, 2 and 3 have <20% of quartz and clay minerals, between 30 and 45% of calcite and between 20 and 50% of dolomite (see *figure 2*). The upper 750 cm of the sequence consists of an alternation of laminated light (facies 5), gray (facies 6) and dark (facies 7) clayey silts. Facies 6 and 7 are finer, with higher clay content (> 40 %) and with more abundant diatoms relative to facies 5 (*figure 2*). Facies 5 shows more frequent soil oxidized agglomerates and higher dolomite content (20%) than in facies 6 and 7 (~12%). Massive, light-colored sandy silt layers (facies 4) interspersed in the laminated sequence. They occur as 10-40 cm thick, homogeneous layers with no apparent grain-size gradation that can be correlated among all cores recovered in the both shallow and deep subbasins. Grain size analyses indicate they are coarser than facies 5, 6 and 7 (clayey silts) and they contain more dolomite (>30%) and less clay than facies 5.

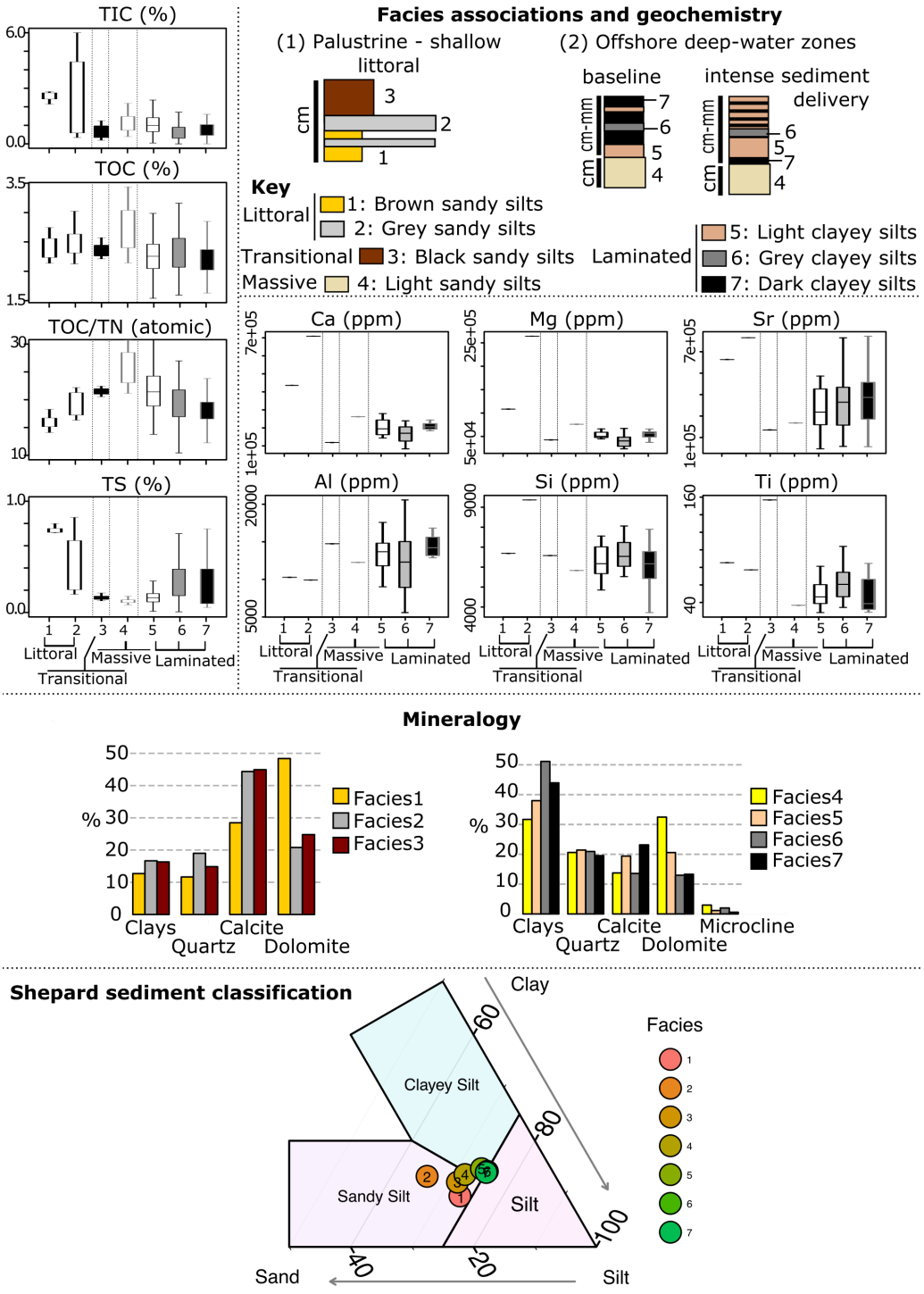

Figure 2: Main facies associations (top) and geochemical box-plots for TIC (%), TOC (%), TOC/TN (atomic) and TS (%) values (top left side) and main geochemical composition (ICP values, top right side) categorized by facies. Also XRD mineralogical analysis (middle) and textural composition of facies (bottom) are shown.

The El Tobar sediment record is organized in six sedimentary units composed of finning-upward sequences (*figure 3A*). The basal unit VI (795-770 cm) includes facies 1 and 2. Unit V (770-670 cm) starts with the deposition facies 3. It is followed by gray and dark laminated facies (6 and 7) with progressively more frequent light laminated silts (facies 5) towards the top. Units IV to I (670- 0 cm) show the same internal depositional structure (*figure 3A*): relatively coarser light colored silts (facies 5) at the base grading into more frequent finer, darker laminated silts towards the top (facies 6 and 7). The base of each unit is defined by the occurrence of thick layers (10-20 cm) of massive light silts (facies 4). The upper Unit I has been subdivided into subunit Ib (180-40 cm) dominated by light facies 5 and subunit Ia (40-0 cm) dominated by dark facies 7.

Magnetic susceptibility (MS) shows a decreasing trend from unit V (770 cm) to Ib (40 cm) (*figure 3A*). MS shows a large variability range along units, however light massive facies 4 at the base of each unit and light laminated facies 5, (low XR L* color values) have relatively higher values, than dark laminated facies 6 and 7 (high XR L* color values).

4.2 Geochemistry

Facies 1 and 2 have a distinctive composition compared to the rest. They present relatively higher TIC, TS, Ca, Mg and Sr (see *figure 2*). On the other hand, facies 4, 5, 6 and 7 have a similar composition, with only small geochemical differences. Facies 4 presents relatively higher TOC, TOC/TN and Ca and Mg compared to Facies 5, 6 and 7 that cannot be geochemically differentiated among them. Facies 3 has a geochemical signal similar to the composition of facies 4, 5, 6 and 7 but with relatively higher Al and Ti.

TIC values range between 1-5%, except for dark massive facies 3 (770-750 cm) where they reach ~3-6%. Although the values are similar from units V to I (*figure 3A*) they show an internal structure with higher values at the base of each unit and lower towards the top, following the finning-upward structure of each unit. The Ca and Mg contents in El Tobar sediments are relatively high, as usually occur in carbonate watersheds (see *figure 1C*). TOC present higher values in light laminated facies (facies 5) than in homogeneous facies 4. The highest values are reached in subunit Ia. TOC/TN values in El Tobar range between 15 and 30, and follow a similar trend as TOC. TS curve shows the highest values in facies 1 and 2 (unit VI, 795-770 cm; ~0.5-1%) and moderate values in facies 3 (unit V, 770-750 cm; ~0.5%) and from 60 to 25 cm depth (top of unit Ib and base of unit Ia). In general, TS has relatively lower values in light laminated facies and higher values in dark laminated facies.

The PCA integrating Incoherence/Coherence ratio (IC), TOC, TIC, TS and

XRF geochemical variables (*figure 3B* left) identified three end members. The first one is positively correlated to the first principal component (PC1 axis, 52% of the variance) of the PCA presenting high positive loadings for Sr, Fe, Ti, K, Rb and Ca. The second pool has positive loading for the first principal component and negative loadings for the second principal component (PC2, 18% of the variance) and includes TIC and Zr. The third end member is positively correlated with the second principal component (PC2 axis) and negatively with the PC1 and includes TOC, Incoherence/Coherence ratio (IC), Br and TS.

The addition of the sedimentological information allows mapping the distribution of the geochemical data according to facies (*figure 3B* right). The distribution of observations along negative PC1 values (affecting mainly facies 6 and 7) corresponds with individuals from the short core TOB07-1A-1G and this could be an artifact caused by higher water content in the sediments. The plot shows that facies 5, 6 and 7 have a similar geochemical signature, positively correlated with Sr, Fe, Ti, K, Rb and Ca; facies 5 is relatively stronger correlated with the last end members and facies 7 although has a high distribution range, presents a higher correlation with the geochemical elements related to the presence of organic matter (TOC, IC, Br and TS; negative PC1 and negative PC2 scores). Facies 4 is strongly correlated with Ca, TIC and Zr (positive PC1 and negative PC2 scores) and shows no correlation with organic proxies.

PC1 presents high values at the base of unit IV (650-600 cm), III (430-380 cm), II (310-250 cm) and Ib (180-150 cm). PC2 follows a general decreasing tendency from units V to Ib (*figure 3A*) with the highest values in unit V (730-670 cm), V (650-510 cm), top of unit II (230-200 cm) and unit Ia (40-0 cm).

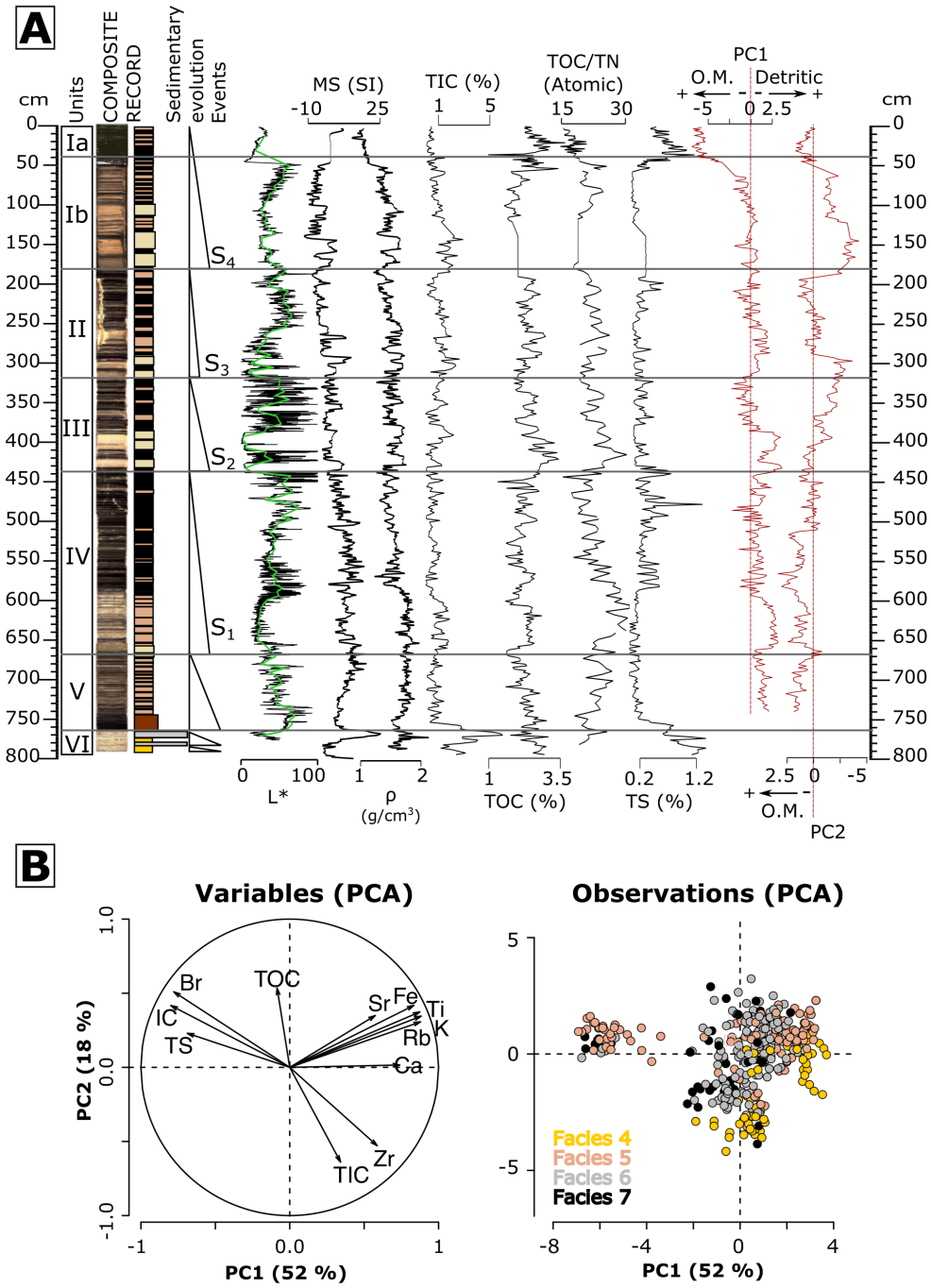

Figure 3: A) *Composite sedimentary sequence from El Tobar. From left to right: units, core image, sediment stratigraphy, facies with sedimentary evolution organized in fining-upward sequences and sedimentary events, Llightness (L*), magnetic susceptibility (MS [SI]), density (ρ [g/cm^3]), basic geochemistry TIC (%), TOC (%), TOC/TN (atomic) and TS (%), and PC1 and PC2 eigenvectors (plotted in red) summarizing geochemical XRF stratigraphy.* ***B)*** *Left: Principal Component Analysis (PCA) of El Tobar composite record using main geochemical XRF elements, elemental composition (TOC, TIC, TS), incoherence/coherence ratio (IC). The first eigenvector (PC1) highlights the detrital inputs, whereas the second eigenvector (PC2) is interpreted as changes in organic content. Right: Map of the facies distribution.*

The composition of light, gray and dark laminated facies (5, 6 and 7), which make most of El Tobar record, has been investigated using Ti and Br/Ti and Ca/Ti ratios from semiquantitative XRF analyses at 0.5 mm resolution (supplementary material *figure A2*). The three types of laminae show small differences in geochemical composition and they follow similar patterns along the record.

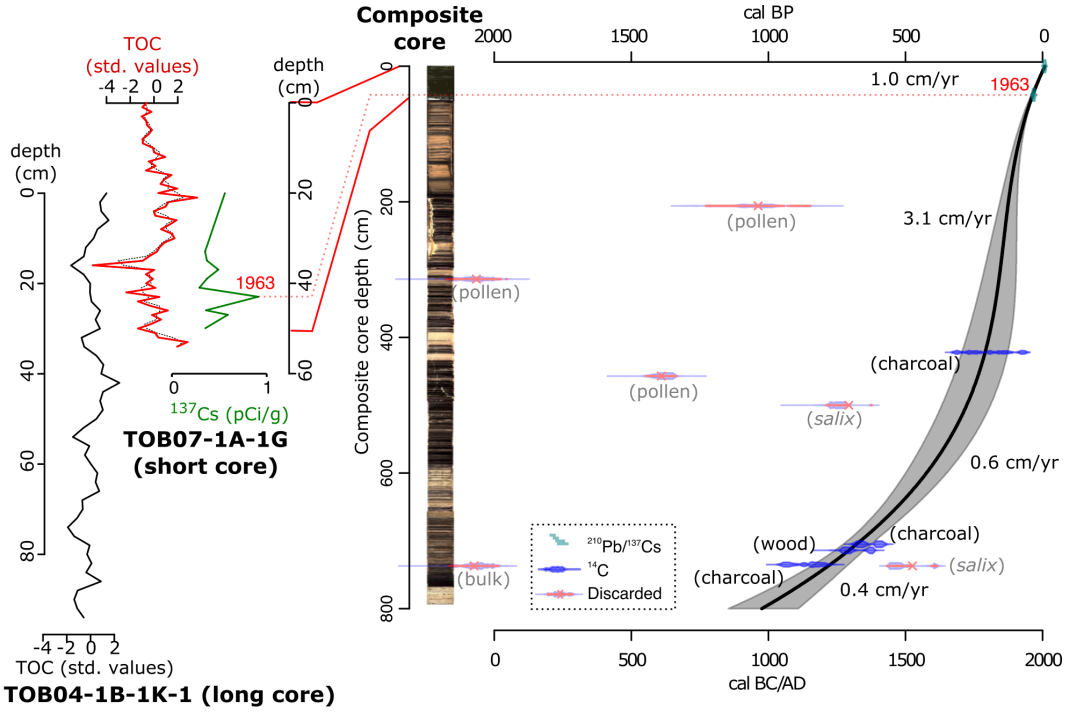

Figure 4: *Left: Correlation using TOC (%) standardized values between the short core with ^{137}Cs dates (red line, gray dotted line represents the smoothed curve) and the long-core (black line) with ^{14}C dates. Right: Age-Depth model of El Tobar sequence based on four AMS ^{14}C dates from the TOB04-1B-1K long core (blue horizontal lines) and ^{137}Cs essays (topmost green points) from the short-core TOB07-1A-1G using a weighted spline regression (Blaauw, 2010). Red crossed dates have not been included in the model. Black line represents the age-depth function framed by error lines (gray shaded area).*

4.3 Chronological model

Although 10 AMS ^{14}C dates were obtained, the chronological model for El Tobar Lake sequence is based on the ^{137}Cs peak date from the short gravity core TOB07-1A-1G and four ^{14}C dates from the TOB04-1B-1K long core (*figure 4*).

We use several criteria to select samples for the final age-model. ^{210}Pb techniques were employed to date the short core, but as López-Blanco et al. (2011b) also observed, ^{210}Pb essays show a rather constant and relatively low

radioisotope activity along most part of the core, with no clear decreasing values and thus no age-depth relationship can be modeled from this profile. This pattern can be due to both, physical sediment mixing or chemical remobilization processes in the surficial sediment layers (Appleby, 1998).

The exclusion of the ^{14}C bulk sediment sample (*Table 1*) is due to its extremely old date, which may be explained by mechanical contamination (i.e. sediment reworking). Moreover, a reservoir effect could affect lacustrine organic matter, also causing older ages. Reworking of older sediments is also an explanation for too old dates provided by wood macrorests. The *Salix sp*. from 551 cm depth was discarded in the age-model because the date is also too old, and incompatible with our final model (*figure 4*). We also excluded the *Salix sp*. sample from the bottom of the core (789 cm depth) because it provided a rejuvenate date in our age-model. Wood samples, considered traditionally excellent dating material, may also provide too young dates. As Goh (1991) shows, although wood does not exchange readily with contemporary carbon, woods buried anaerobically under natural conditions in the sediments when excavated and exposed to the air may exchange with atmospheric CO_2 and introduce young carbon into the sample. Exchanges of carbon between the sample and the atmosphere are a common cause of contamination in wood. Therefore, even if woody samples are manipulated carefully, such contaminant sources and processes may be responsible for younger dates.

The three pollen samples have been excluded from the final age-model because they provided old dates (*figure 4*) and they are not consistent among them. These inconsistencies are likely caused because the dated pollen grains are a mix from different plants (aquatics, submerged, terrestrial) and therefore a source of error for radiocarbon dating.

The ^{137}Cs assays provided some extra age constraints to the age model. The ^{137}Cs peak at 43 cm depth (1963) of the short core TOB07-1A-1G, corresponding to the 1963 nuclear tests, is in good agreement with the ^{14}C date model (*figure 4*). Moreover, the sedimentation rate provided by the ^{137}Cs essay gives a rate of 1 cm/year of the topmost 50 cm, which is in agreement with the sedimentation rate (0.8 cm/year) get from the ^{14}C for the composite core, constituted by similar lithofacies. A previously dated core (López-Blanco et al., 2011) provided a similar sedimentation rate for the recent sediments.

Therefore, the most simplistic and coherent age-depth model is based on one wood and three charcoal ^{14}C dates and is constrained at the top by the 1963 ^{137}Cs peak. In spite of the large number of discarded radiocarbon dates, the coherence between ^{14}C and ^{137}Cs dates strengthen the robustness to this age-model. These results show that the 8 m El Tobar Lake sequence spans the last 1000 years.

5. Discussion

5.1 Geochemical signature of depositional facies

The PCA allowed further investigation of depositional and geochemical processes for each facies. The elements that are positively correlated with the PC1 (i.e. Sr, Fe, Ti, K, Rb and Ca; *figure 3B*) reflect the allochtonous detrital sediment fraction originated in the catchment. Ti, one of the most representative PC1 elements, derives from detrital minerals and is not affected by weathering or diagenetic processes. Also Ti, Rb and K are often associated with clay mineral assemblages (Kylander et al., 2011). Thus, we infer that the positive values of PC1 are representing fine allochtonous detrital sedimentary inputs from the watershed. Therefore, grainsize (higher fine particles content), mineralogy (higher clay mineral content) and PCA results (relatively good correlation with the PC1) point to facies 5, 6 and 7 as dominated by fine-grained sedimentation of detrital material from the watershed.

Both facies 5 and 7 present a subset of samples with higher correlation with the organic-matter end member (TOC, TS, IC, Br) (*figure 3B*). However, as these samples with extreme negative loadings for PC1 are all from the short core, this distinctive geochemical behavior may be due to higher water content of the topmost section of the composite sequence and not too real geochemical differences. Available ICP values do not show significant differences between recent and older sediments.

Most of facies 5 samples are correlated with positive values of the PC1 and PC2 (detritic related end members). The occurrence of soil oxidized agglomerates and the relatively higher grain size and moderate amounts of dolomite also point to dominant detrital origin for this facies. Facies 7 although shows a larger dispersion, is correlated to negative PC1 loadings (less detrital). Therefore facies 5 is more dominated by the fine detritic component transported from the catchment, in some cases, relatively rich in organic soils components; facies 7 represents the out of suspension sedimentation, relatively more influenced by the autochthonous lake productivity.

The second pool defined in the PCA (TIC, Zr) is also correlated with the positive values of PC1, suggesting that carbonates in facies 4 are detrital. This interpretation is also supported by the DRX analysis that shows higher calcite and dolomite content in facies 4 likely from the highlands of the catchment, and by microscope observations (large carbonate grains, corroded textures). Zirconium is normally enriched in medium to coarse silts and sand size fraction, and is associated with weathering-resistant heavy minerals like zircon. So, in fine-grained sediments, as those of El Tobar Lake, we would expect to be relatively enriched in the coarser fraction (Kylander et al., 2011), and this would explain the relatively good relationship between clastic carbonates and Zr-bearing minerals. The opposite relationship between TOC and TIC and

between TIC and other indicators of organic content (IC, Br) also support that most carbonates in El Tobar are of detrital origin.

Facies 4 is clearly single out in the PCA biplots. It is strongly related with the second pool of geochemical elements (TIC and Zr). Therefore, facies 4 is indicating an allochtonous, relatively coarser sediment, rich in calcite and dolomite grains from the highlands of the catchment.

The third end member (TOC, Incoherence/Coherence ratio (IC), Br and TS) is positively correlated with the second principal component (PC2 axis) and negatively with the PC1. Geochemical (TOC/TN) and microscopic observations are not conclusive whether most of the organic matter in El Tobar laminated facies comes from the catchment or from in-lake productivity. Although TOC/TN values in El Tobar range between 15 and 30, indicative of dominant allochtonous, terrestrial sources (Meyers and Lallier-Vergés, 1999). Microscope observations show terrestrial plan remains occur in the soil oxidized agglomerates of facies 5 and algal matter in facies 7.

5.2 Lacustrine depositional processes

Sedimentological and geochemical features point to a shallow, littoral depositional environment for unit VI. Facies 1 and 2 are composed basically of carbonates (50-90 %) and contain bioclasts (gastropods) and terrestrial plant remains. Large size, irregular and eroded textures confirm a detrital origin for both dolomite and calcite grains. Carbonate endogenic production in El Tobar is very restricted in modern environments; charophyte meadows and encrusted macrophytes areas, common in other karstic lakes, do not occur in El Tobar, so the bioproduction of calcite in this system is small.

At the onset of Unit V, Facies 3 represents a large change in depositional dynamics. Finer darker sediments, with relatively higher TOC and lower TIC, TOC/TN and TS percentages suggest deeper environments with anoxic conditions. The transition between Units VI and V shows no stratigraphic unconformity and deformation structures (folds, microfaults) are absent in both units. Although the absence of macroscopic evidences for slumping does not preclude the occurrence of such processes -e.g., Montcortés Lake (Corella et al., 2011)-, unit V to I shows similar stratigraphy in the deep and shallow basins, and consequently slumping processes can be excluded during deposition of most of El Tobar sequence. This is also supported by the seismic survey showing continuous reflectors all over the deep basin (*figure 1D*). However, since the core in the shallow basin was not long enough to reach the depths where unit VI could be located in the shallow basin, we cannot rule out that the base of the sequence (790-770 cm, *figure 3A*) corresponds to a large mass wasting deposit affecting only the deep basin.

If there is stratigraphic continuity between Unit VI and V, this transition

was the largest change in the lake during the last millennium, in terms of morphology, hydrology and depositional dynamics: El Tobar Lake shifted from a shallow, well mixed body of water (likely a few meters deep) dominated by littoral carbonate deposition (facies 1 and 2) to a deeper water body with sedimentation of organic-rich facies under suboxic conditions. If the base of the sequence (Unit VI) constitutes a large mass wasting deposit emplaced prior to deposition of unit 3 (ca. 12th century), depositional environments in the NW areas of the Lake would have been similar (deeper, predominantly anoxic) and no significant lake level change would have occurred.

Such a large hydrological change could be related to regional (increase water availability during a more humid period) or local (sinkhole collapse) factors. The onset of deposition of Unit V occurred within the Medieval Climate Anomaly, (MCA), a period generally characterized as a more arid phase in the Iberian Peninsula (Moreno et al., 2012). However there is some evidence of humid phases with increased water availability during the 12th century with increased flooding in the Tagus River (Benito et al., 2003; 2014) and in the Pyrenees (Corella et al., 2012). A small lake level increase in the Lagunillo del Tejo (100 km southwards) (López-Blanco et al., 2011a) and a humid phase in the nearby La Parra Lake (Barreiro-Lostres et al., 2014) are also described at ~1200 CE. On the other hand, in karstic areas, both exokarstic and endokarstic processes lead to the development of new sinkholes, and the enlargement of older ones. These processes are reinforced during wetter periods. Thus, the hypothetic water-level change during 12th century CE could have been a response to higher water availability caused by climatic change, the deepening of the NW subbasin by karstic processes or, more probably, by the synergy of both forcings. Slumping could also have been favored during more active sinkhole subsidence. Since seismic survey in the shallow areas did not show the internal structure due to low penetration, only deeper coring in this basin could help to constrain if unit 6 was deposited in situ or emplaced.

In any case, in this study we focus in the lake evolution after unit 5, characterized by deposition of finer, laminated, more clay-rich facies 5, 6 and 7 with interspersed relatively coarser (sandy silts) facies 4. Laminated facies are geochemically similar, but facies 4 presents relatively higher TOC, TOC/TN and elemental Ca and Mg. Although carbonate content in facies 4 is relatively higher than in laminated facies, the absence of any components typical of shallow littoral facies (1 and 2) as bioclasts, macrophytes or large dolomite and calcite grains do not favor reworking of littoral sediments as a mayor contribution for facies 4. Thus, geochemistry, texture, mineralogy and grain size suggest a relatively different sediment source and depositional process for facies 4 than for facies 5, 6 and 7. Although some small contribution of littoral sediments may occur, the data favor an allochtonous origin (watershed) for

most of the sediment. Facies 4 layers can be traced in both the deep and shallow basins cores, so they are not restricted to depositional processes in the deeper areas (for example, associated to slumps; supplementary material figure A1). Facies 4 is thus interpreted as deposited during floods, and not related to mass wasting deposits or debris flows caused by destabilization of the lake slopes.

Although geochemically are very similar (*figure 2*), facies 6 and 7 present relatively more diatoms and lacustrine organic matter relative to facies 5, where a dilution effect (higher clastic input) could be significant. Higher calcite content and occurrence of small calcite crystal (smear slide observations) in facies 7 also suggest a limited endogenic carbonate production in facies 7. The More frequent soil oxidized agglomerates and the higher content in detritic dolomite (20%) in Facies 5 also favor a relatively higher allochtonous detritic influence than laminated facies 6 and 7. The alternation of facies 5, 6 and 7 is interpreted as baseline "normal" deposition in the lake during the last millennium.

5.3 Sediment delivery events

Since the onset of Unit V (12th century CE), significant depositional changes in the system were characterized by the intercalation of massive, thick, light-colored coarser sediments (facies 4) over the baseline lake sedimentation (alternation of facies 5, 6, and 7). The input of these materials occurred, from older to younger, during four periods: the end of 16th century CE (unit IV, 650 cm), late 18th century (unit III, 435 cm), mid 19th century (unit II, 325 cm) and beginning 20th century CE (unit Ib, 185 cm) and they have been named consecutively as sedimentary events S1, S2, S3 and S4 (*figures 3* and *7*).

The geophysical and geochemical signatures of these depositional events (low XR L* color values, high MS and ρ values, high TIC and TOC/TN, low TOC and TS, high PC1 and usually low PC2 values, see *figure 3B*) are coherent with a higher input of coarse clastic particles (Zr and silicate minerals, iron oxides, carbonates) derived from watershed.

From a sedimentological point of view, the 16th century depositional event S1 is texturally different form the rest, composed of many thin layers of light massive silts (facies 4) and light laminated silts (facies 5) intercalated within dark laminated facies 7. The other events (S2 to S4, 18th-20th centuries) show characteristically a thicker light massive layer of facies 4 with net boundaries at the base of each event.

From a geochemical perspective (see *figure 5*), events S1 (16th century) and S2 (18th century) clearly have more Ti (cps) content than events S3 and S4 (mid 19th and early 20th centuries respectively). Relatively higher Ti content is interpreted as a reflection of more siliciclastic sedimentary inputs from the

lake's watershed. Events S1 and S4 present similar Ca/Ti ratios, while events S2 and S3 have the highest values. Higher Ca/Ti ratio is interpreted as more detritic carbonatic sedimentary inputs from the watershed, since productivity of endogenic carbonates, as commented above, is almost negligible.

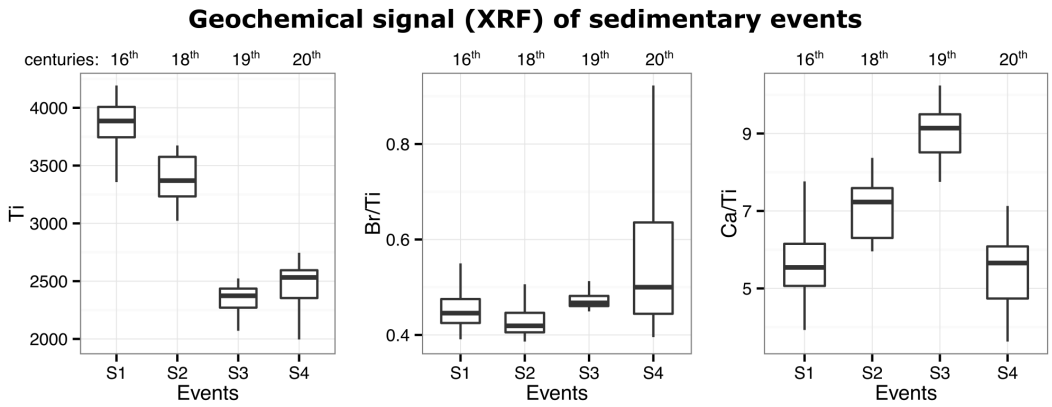

Figure 5: *Geochemical signal of sedimentary events S1 (16th century) and S2, S3, S4 (18th, 19th, 20th centuries respectively) based on XRF composition (Ti values and Br/Ti and Ca/Ti ratios).*

As the geological sketch from *figure 1* shows, the lowlands of the watershed surrounding the lake are constituted by the Triassic Keuper facies, mainly lutites and marls rocks, and they are the principal source for siliciclastic sediments. In the other hand, the highlands of the watershed are dominated by Jurassic and Cretaceous limestones and dolostones and therefore constitute the main source for detritic carbonates. So, considering that endogenic carbonate production is negligible and littoral sediment contributions should be similar in all these events, we hypothesize that changes in Ca/Ti ratio reflect changes in the sediment source – Triassic clay-rich lowlands versus Cretaceous and Jurassic carbonate highlands. A differential use of the landscape through time could explain these changes of sediment source.

5.4 El Tobar Lake and watershed evolution during the last millennium

After the onset of deposition of Unit V (12th century CE), with deeper depositional environments (facies 3), sedimentary dynamics in El Tobar Lake during the next three centuries were relatively stable, characterized by the alternation of facies 5, 6 and 7. The first large change in depositional dynamics occurred at 16th century CE (event S1) when thick, massive light silts were deposited in the basin for the first time. This increase in sediment delivery corresponds with a period of important demographic and economic development in the Serranía de Cuenca, responsible for major pressure over the whole territory (Esteban Cava, 1994). As decreasing crop and

anthropogenic taxa percentages from La Cruz record (Burjachs, 1996) show that agriculture became less important in the region from 1200 to 1700 CE (*figure 6*), and during the 16th century, the progressive deforestation for extensive transhumance stockbreeding reached a peak and changed the Serranía Alta landscape. Many examples suggest a strong relationship between grazing and increased erosion in watersheds in the past. Van der Post et al. (1997) found that recent sedimentation rate rise in the English Lake District was positively correlated with sheep densities in the catchment. Parallel changes have been detected in lakes close to El Tobar during this period (1450-1550 CE): a peak in floods frequency in Lake Taravilla (Moreno et al., 2008); the start of increasing number of floods per decade in the Tagus River at 1560 CE (Benito et al., 2003); higher sediment delivery in Lake La Parra (Barreiro-Lostres et al., 2014); increased deforestation for timber use and livestock grazing at Lagunillo del Tejo and La Cruz Lake (Burjachs, 1996; Julià, 1998; López-Blanco et al., 2011a) (*figure 6*). So Event S1 in El Tobar clearly reflects regional socio-economic changes that affected the whole area.

Afterwards, depositional dynamics in El Tobar returned to its baseline conditions with dominant dark laminated silts, up to the end of 18th century (upper part of Unit IV). Human pressure in the landscape diminished during this period owing to several demographic and economic crises, mainly due to the Black Death epidemics in 1589 and 1600 CE, and the progressive decrease of the stockbreeding industry. Another phase of increased sediment delivery (event S2) occurred at the end of the 18th century (ca. 1780±86 CE). Although live stockbreeding was greatly reduced at this time, documentary evidence (Esteban Cava, 1994; Valbuena-Carabaña et al., 2010) shows an intensification of new uses of the forest, particularly charcoal for heating and industrial purposes ("*carboneras*") peaking around 1750 CE. Again, other regional records show evidences for forest management, as a local abrupt increase in macrocharcoal at the nearby Lagunillo del Tejo record at 1800 CE (López-Blanco et al., 2011a) and more regionally, an abrupt decrease in *Pinus* pollen from Lake La Cruz (*figure 6*).

After S2 event and during the first part of the 19th century, sediment delivery decreased again and El Tobar Lake soon regained its previous depositional dynamics. A less intense use of the natural resources at a regional scale is marked by a rapid increase of pine pollen in La Cruz record during this period. This likely reflects the societal convulsions caused by decades of wars. Lower erosion in the watershed was likely due to the abandonment of croplands because of the Napoleonic wars starting at 1800 CE with the French invasion and several Spanish civil wars until 1876 CE (Esteban Cava, 1994; Valbuena-Carabaña et al., 2010).

The next sediment delivery event S3 occurred in the mid-19th century,

coetaneous with new expropriation laws in 1855 CE that forced changes in the land property. These new laws dictated the subdivision of large historical estates and infrastructures – some of them historically used communally by the villages – into smaller estates, and favored their ownership by private individuals and entrepreneurs. As a consequence, new wood clearances were practiced without an ordered plan (Esteban Cava, 1994), provoking an increasing pressure in the environment and locally new sources of clastic sediments from the watershed to the lake. The intensity of this event is relatively small compared with previous ones.

After that, a short period returning to lake's baseline sedimentation, by the late 19th century – early 20th century event S4 marks the most intense phase of sediment delivery to the lake in terms of sediment amounts. During this period, population increased all over the Serranía de Cuenca, in conjunction with a new profitable industry based on wood exploitation for building and charcoal production (Esteban Cava, 1994; Lagunillo del Tejo, López-Blanco et al., 2011a) and expansion of farm lands (Lake La Parra, Barreiro-Lostres et al., 2014; López-Blanco et al., 2011a), as shown in the increase of human-related pollen in La Cruz record around this stage (see *figure 6*), that continued till the mid-20th century.

In summary, the depositional changes in the record from lower (alternation of facies 5, 6 and 7) to higher (more facies 5) detrital input and, especially the occurrence of periods with much higher sediment delivery (sedimentary events S1, S2, S3, S4 represented by facies 4) are interpreted as a reflection of large change in sediment availability in the watershed and in the energy of sedimentary transport processes (in this case mainly flows and runoff) into the lake. During sedimentary event periods, documentary data indicate that the changes in landscape management due to agriculture and grazing had a strong impact in the watershed. Lower vegetation cover and an intensive land use would have favored an increase in erosion in the watershed and then, most likely, a high influence in the lake sedimentation. From events S1, S2 to event S3 (16th to mid 19th centuries) there is a progressive increase in the Ca content suggestive of higher highland contribution for the sediments (see figure 5), at same time that occurs the progressive decrease in the powerful stock-breeding industry in the area (*figure 6*; Esteban Cava, 1994). Event S4 (20th century) has a lower Ca/Ti signal, similar to event S1 (16th century) but relatively higher Ti cps than the previous S3 event. These changes may be attributable to a cropland increment in the lowlands due to a population maximum occurred by 1850 – 1950 CE (Esteban Cava, 1994).

However, climate has also been a significant factor controlling the sediment delivery to the lake. Higher water availability and changing precipitation patterns (seasonality) also affect the sedimentary signal by

controlling soil erodibility and sediment transport. The onset of higher sediment delivery periods in El Tobar occurred after 1200 CE, when the first evidence for wetter conditions and higher lake levels after the drier 'Medieval Climate Anomaly' has been documented (~AD 1200) in Lake La Parra (Barreiro-Lostres et al., 2014) and Zoñar (Martín-Puertas et al., 2008). The sedimentary events S1, S2, S3 occur during the wetter and colder 'Little Ice Age'. The S4 event occurs in the late-19th – early 20th centuries during relatively drier conditions, although its magnitude (is the thickest sedimentary event) and documentary data suggest it is likely due to croplands expansion between 1850 and 1936 CE.

Therefore, available sedimentary and documentary data indicate that during historical times in El Tobar Lake, the most intense sedimentary events correlate well with periods of documented high human impact in the landscape. Thus, sediment production is mostly controlled by the human landscape management changes. However, higher precipitation and run off after 1200 CE is the major responsible for an efficient and more intense transport processes in terms of energy and quantity, and thus, the final deposition of the sedimentary events.

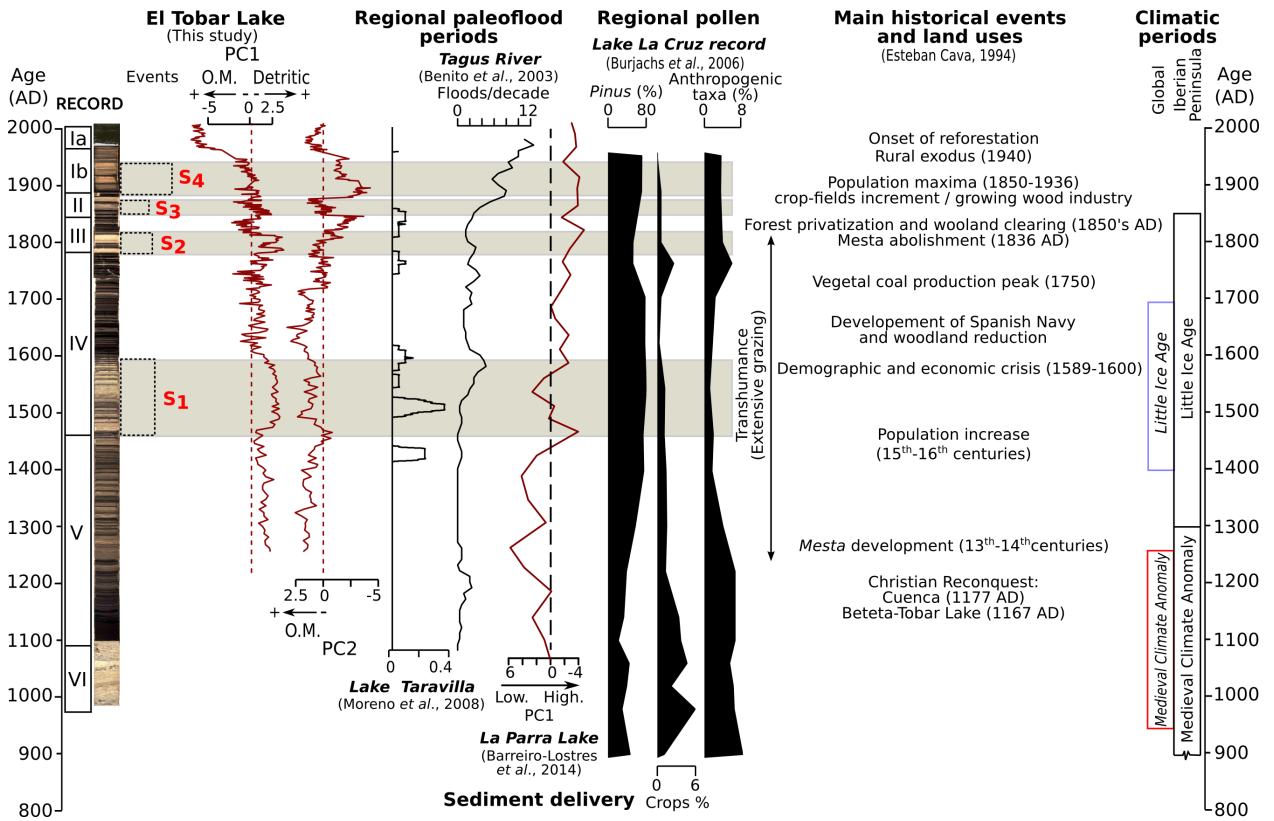

Figure 6: *El Tobar Lake depositional evolution during the last 1000 years. Main sedimentary (S1, S2, S3 and S4, brown-shaded) and changes in sediment delivery to the lake (PC1) and sediment organic content (PC2). The El Tobar record is compared with main regional flooding periods reconstructed from Taravilla Lake (Moreno et al., 2008) and Tagus River (Benito et al., 2003) records; and with available regional sequences from the nearby Lake La Parra (sediment delivery, Barreiro-Lostres et al., 2014) and Lake La Cruz (pollen record, Julià et al., 1998) in the Torcas karstic lake complex (see Figure 1 for location). Crops pollen percentage includes Cerealia, Secale, Cannabacea and Vitis. Anthropogenic pollen taxa include Artemisia, Plantado, Chenopodia, Brassicace, Urticaceae, Rumex, Centaurea and Asteraceae. Main historical events with large landscape impacts in the study area are also shown. The global North Hemisphere 'Medieval Climate Anomaly' and the 'Little Ice Age' are represented following the chronology of Mann et al. (2009). Chronology for Iberian Peninsula climatic periods is based on Moreno et al. (2012) and Morellón et al. (2011).*

After the sedimentary event deposition, the sedimentological and geochemical proxies show a rapid return to the baseline thin-layered sedimentation, without a transitional phase or significant changes in depositional features in the lake. This suggests that in this heavily human-impacted landscape, the depositional and geochemical cycles in the El Tobar Lake, had a high resilience to the variable watershed sediment inputs.

5.5. Recent Changes in a long-term perspective

The present El Tobar watershed landscape is a consequence of centuries of intense human impact and can be considered human-made. Currently, land management is characterized by farmland and grazing abandonment and forest and shrubs expansion as occurs in most Mediterranean mountain areas (García-Ruíz et al., 2011). The farmland abandonment involved a fast and increasing soil degradation of these areas as consequence, for example, of lack of maintenance of the slope bench-terraced fields, leading to new erosional processes (landslides, gullying), that can be dilated in time until shrub colonization. As García-Ruíz et al., (2013) pointed out, these fragile Mediterranean landscapes need the presence of a rural population if they are to be preserved.

Another aspect to consider in the recent evolution of Mediterranean mountain watersheds is the impact of new water infrastructures such as the canal connecting La Tosca reservoir and El Tobar Lake. Although the canal has improved the hydro-power management and facilitated the control of irrigation in downstream areas with increasing human pressure, it led to large modifications in the depositional system as changes in the water composition and lake dynamics and in the ecosystems (López-Blanco et al., 2011b). The canal opening in 1967 CE led to a large hydrological change in the lake, well marked by deposition of dark laminated silts. This depositional change represents a sharp change in the dynamics of relatively high sediment delivery since late 19th century (mainly composed of facies 4 and 5). The canal construction coincided with the peak in depopulation of the area caused by the migration to the cities started during the 1950s. As a consequence, crop-fields were abandoned and during the 1956-1984 period, cultivated area in the watershed was reduced. To better understand the magnitude of the event and to characterize geochemically the effects of the canal on the lake dynamics, we split the XRF dataset for dark and light lithofacies in unit Ia into two subsets, one pre-canal and another post-canal (pre- and post-1967 respectively; *figure 7*).

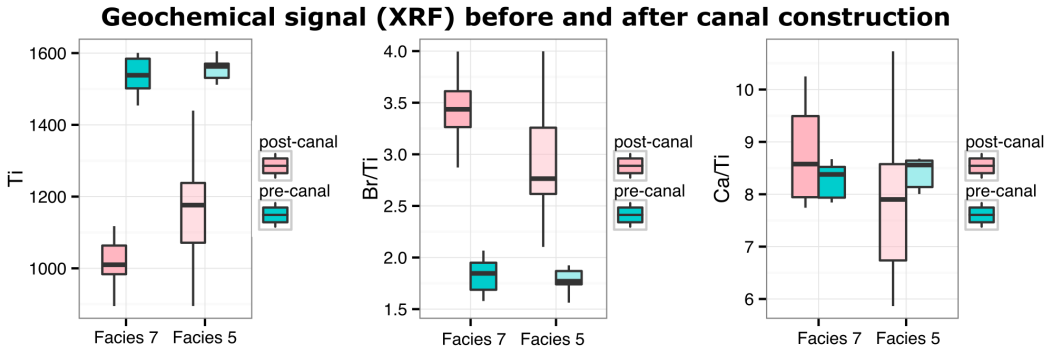

Figure 7: *Geochemical signatures of dark and light laminae prior (pre-canal, blue) and after (post-canal, pink) the canal connection of El Tobar Lake with La Tosca Reservoir in 1967.*

Although the trends are similar (lower Ti and higher Br/Ti before than after the canal opening), the range of compositional variability is higher in dark laminated facies than in light laminated facies (*figure 5*). Ca/Ti ratio does not show significant variation in any laminae types. So in the post-canal sediments higher Br/Ti and less Ti, particularly in facies 7, occur. Recent climate variability may have played a role in these changes in lake dynamics. So, deposition of black silts between 1960 and 1980 occurred during a period of higher and more intense rainfall and lower mean temperature (about 2ºC) than during the previous 1984-2010 CE period (Beteta and Cañizares meteorological stations, http://www.aemet.es). Thus, with more frequent rainfalls, likely more nutrients from the recent abandoned valley crop-fields could reach the lake and favor more in-lake organic productivity. A similar pattern has been described in Lake La Cruz (Julià et al., 1998) at the end of the LIA. A shift in Cladoceran assemblages from a dominant benthic to a progressive dominant planktonic composition, taking advantage of a nutrient enrichment, was identified during this period in a separate set of short cores from El Tobar (López-Blanco et al., 2011b). Constant low salinity water input from the reservoir also may change the lake hydrology, increasing lake levels and favoring anoxic conditions on the deep basin due to a stronger chemical gradient. Therefore, the canal opening in 1967 CE led to maintain high lake levels, fresher water inputs and a stronger chemocline. That, coupled with higher nutrient inputs form the watershed provoked a higher in-lake organic productivity and more organic matter preservation in the bottom of the lake, resulting in darker and more organic sediments during the lower half of unit Ia.

After the rapid change caused by the canal opening, in the 1980s the lake seemed to have returned to its previous depositional dynamics (alternation of facies 5 and 7) in a stage characterized by relatively higher sediment input from the watershed. In the upper 20 cm (after 1985 CE), thin laminae of facies 5 are more common. So increased bioproductivity in baseline lake sedimentation occurred at the same time as an increase in the frequency of detrital layers that

reflects changes in the watershed (increased storminess, higher availability of sediments).

6. Conclusions

The reconstruction of paleoenvironmental conditions based on multi-proxy studies are critical for understanding the dynamics of modern environmental conditions. Thus paleo-limnological approach can contribute to better define the conservation policies for long-time human influenced lacustrine systems and their environment by providing knowledge of their evolution through natural and land-use changes along time.

The geochemical and sedimentological trends identified in El Tobar record, the historical sources of regional land-use and the paleoclimate records allow the reconstruction of the lake-watershed-human interactions during the last millennium in this Iberian Range basin.

Since ca. 1200 CE no major changes in the basin configuration (accommodation space, basin morphology, drainage network) have occurred. The record shows four periods with increased sediment delivery (S1, S2, S3 and S4) that occurred at 16th, late 18th, mid 19th and early-20th centuries respectively.

The four periods of increased detrital input to El Tobar (S1 to S4) share similar geophysical, geochemical and sedimentological features; and correlate well with the main historical land-use changes in the region, mainly changes in vegetation cover due to large deforestation for grazing, agricultural and farming purposes, favoring erosion and providing sediments for transport by runoff and creeks to the lake. Sedimentologically, the most intense events in terms of sediment amount are S1 and S4, the first one corresponding to the peak in the medieval stockbreeding industry and the later occurring during the period with the highest population in the region. Increased rainfall during some phases of the LIA would have also had a positive synergetic effect with higher anthropic impact in the watershed and cause higher sediment production in the watershed and stronger erosion and delivery.

Interestingly, the transitions in El Tobar Lake from intense to low sediment delivery periods were rapid. Post-event sediments show the same previous undisturbed conditions of lower clastic inputs and relatively higher organic matter and meromictic conditions. The El Tobar Lake has shown a strong depositional resilience to periods of increased sediment influx from the watershed during the last millennium.

This study demonstrates that degradation processes in a mountain watershed such as El Tobar are strongly linked with both natural changes (water availability, flood and runoff frequency) and with anthropic activities (land use changes, soil erosion). Planning conservation strategies of water

ecosystems, as El Tobar Lake and surrounding catchment, strongly affected by degradation processes caused by hundreds of years of human activities, should take into consideration the degree of alteration they have experienced and the historical causes of such modifications, leading to site-specific intervention policies over this human-made landscape.

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Supplementary material

Table A1: *El Tobar sedimentary facies: texture, description, composition and depositional processes and environments. Geochemistry is based on MS-ICP measurements. TIC and TOC are averaged values for each facies. Mineral percentages are based on XRD analysis.*

Lithology	Facies	Description	Depositional Processes	Depositional Environments
Shallow facies				
Silts	**1 *Brown sandy silts***	Massive light brown carbonate medium sandy silts, with sharp boundaries and occasional carbonatic pebbles. They occur in few 2-4 cm thick beds. High Ca, Mg, Sr and Si; low Al. TIC: 3 % TOC: 3 % TOC/TN: 20 %. Clays: 12 %; Quartz: 11 %; Calcite: 29 %; Dolomite: 48 %.	Medium-high energy tractive currents. Oxic conditions	Palustrine to shallow depth
Sands	**2 *Grey sandy silts***	Massive light-grey carbonatic coarse sandy silts with net boundaries, sub-angulous quartz, diatoms and plant and bad preserved gastropod remains. They occur in few 5-8 cm thick beds. High Ca, Mg, Sr and Si; low Al. TIC: 4 % TOC: 3 % TOC/TN: 17 %. Clays: 17 %; Quartz: 19 %; Calcite: 44 %; Dolomite: 20 %.	Removilization of carbonatic littoral deposits under oxic conditions	Littoral to palustrine, shallow depth, with some alluvial influence
Silts	**3 *Black sandy silts***	Massive black carbonatic fine silts with dolomite and some quartz, opaque minerals, diatoms, ostracods and soil oxidized agglomerates. It is disposed in a unique 10 cm thick layer. TIC: 2 % TOC: 3 % TOC/TN: 20 %. Clays: 16 %; Quartz: 14 %; Calcite: 45 %; Dolomite: 25 %.	Out of suspension deposition and dolomite precipitation in reduced and saline conditions	Transition to relatively deep, permanently anoxic conditions
Deep facies				
Silts	**4 *Light sandy silts***	Massive light brown carbonatic fine sandy silts with some quartz grains and soil oxidized agglomerates in 10-15 cm thick beds. Geochemically similar to 1.2A. TIC: 1 % TOC: 3 % TOC/TN: 25 %. Clays: 32 %; Quartz: 21 %; Calcite: 14 %; Dolomite: 33 %.	Low energy and out of suspension sedimentation under oxic conditions	Profundal-distal dominant oxygenated conditions
	5 *Light clayey silts*	Fine to medium laminated light brown, carbonate and quartz clayey silts, in < 10 cm thick layers with a	Low energy tractive currents and out of	

	laminated structure, with some diatom, soil oxidized agglomerates and net boundaries. TIC: 1 % TOC: 2 % TOC/TN: 23 %. Clays: 38 %; Quartz: 22 %; Calcite: 19 %; Dolomite: 21 %.	suspension sedimentation under oxic conditions	
6 ***Grey clayey silts***	Massive dark grey carbonatic clayey silts with quartz and carbonatic grains in 1 cm beds with diffuse boundaries. Geochemically similar to 1.4. Clays: 52 %; Quartz: 21 %; Calcite: 14 %; Dolomite: 13 %.	Out of suspension sedimentation. Likely more saline	Profundal-distal, dominant anoxic conditions
7 ***Dark clayey silts***	Fine to medium laminated dark-grey to black carbonate and quartz clayey silts, in mm to 10 cm thick layers with diatoms, soil oxidized agglomerates and sharp boundaries. TIC: <1 % TOC: 2 % TOC/TN: 20 %. Clays: 44 %; Quartz: 19 %; Calcite: 24 %; Dolomite: 13 %.		

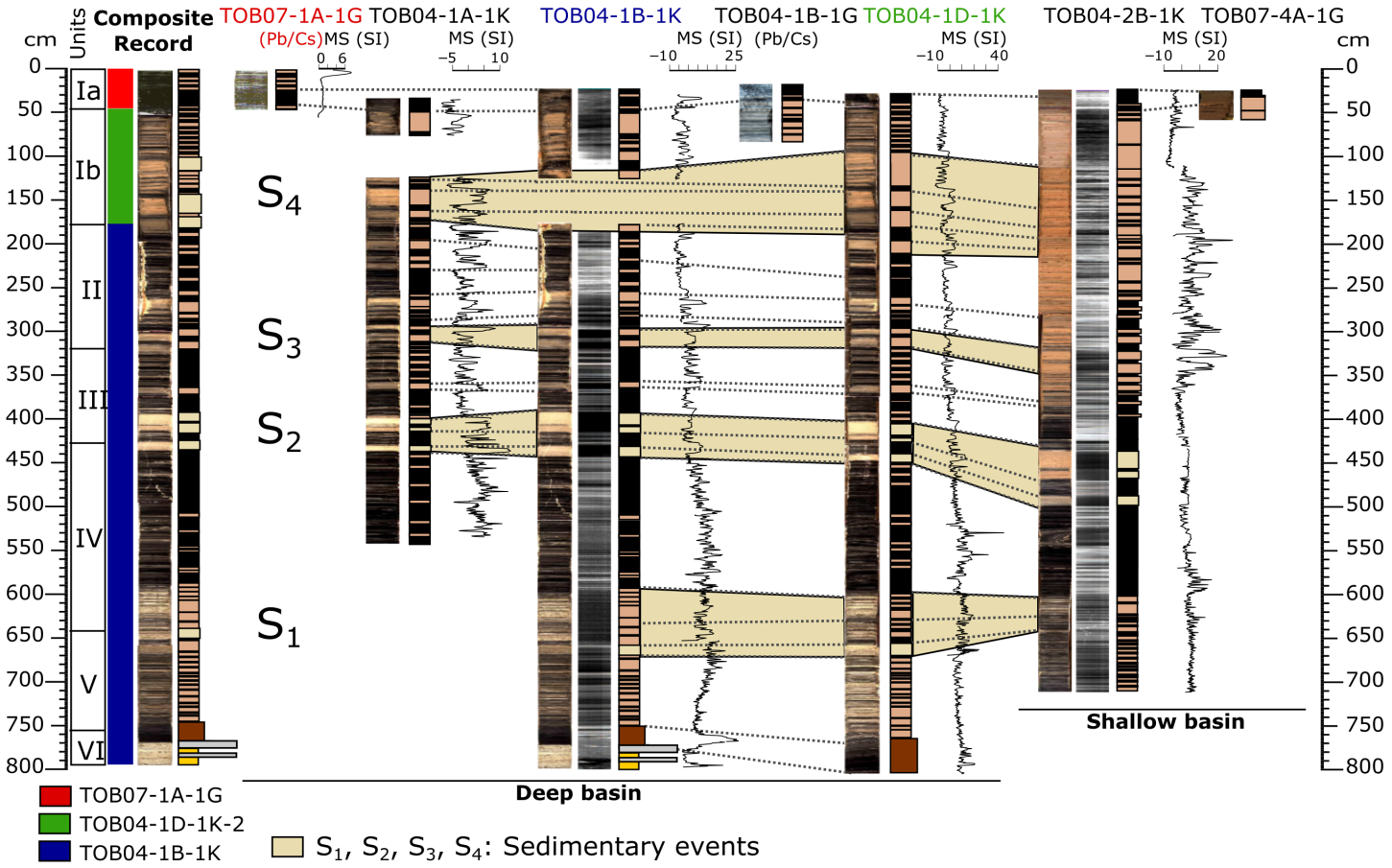

Figure A1: *Correlation panel of all cores from El Tobar Lake based on sedimentary facies, X-Ray and color images and geophysical properties (magnetic susceptibility). The composite sequence (left) was constructed using several cores to avoid gaps. The sedimentary events can be traced along both, the deep and shallow subbasins.*

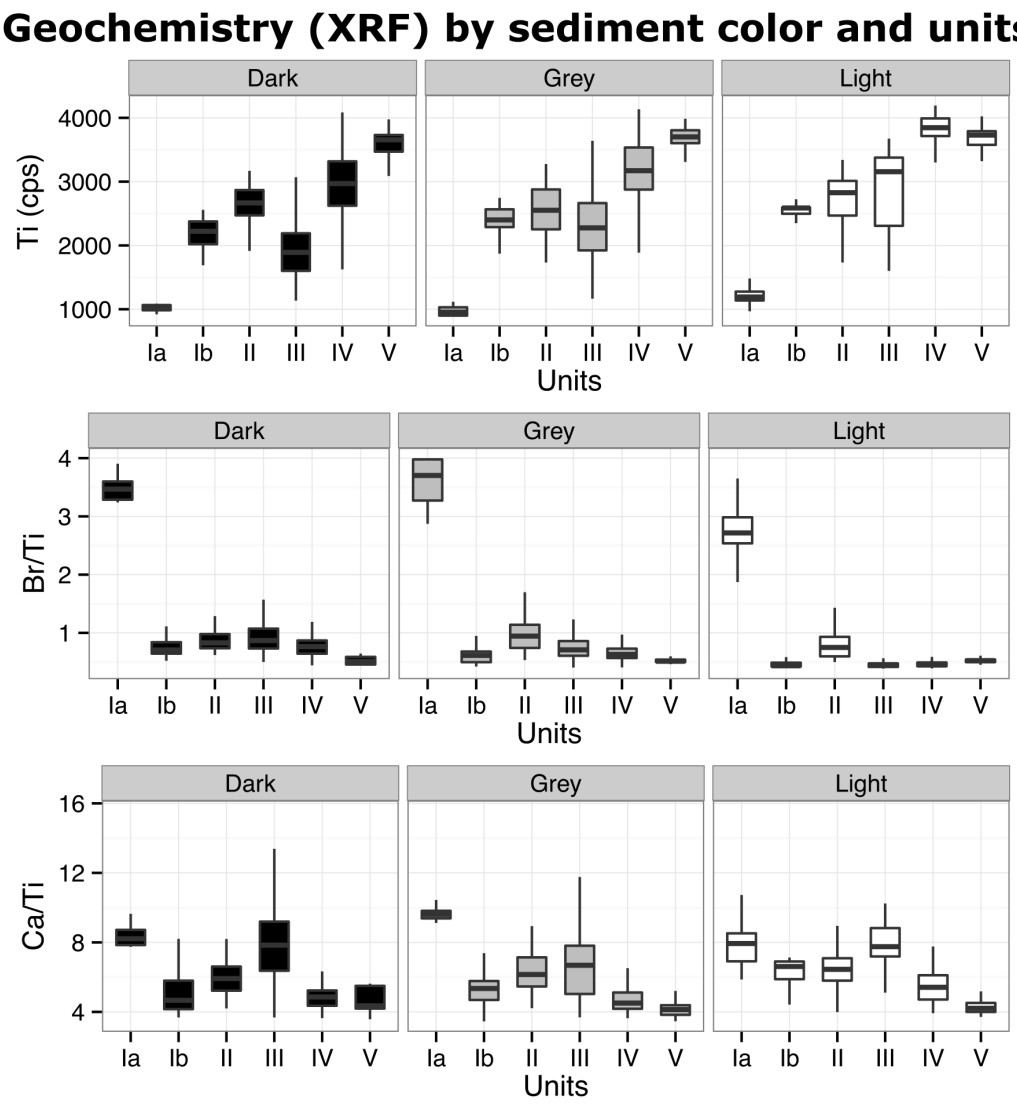

Figure A2: *Laminated facies geochemistry: Semi-quantitative main XRF ratios (Br/Ti, Ca/Ti) and Ti cps showing the evolution and trends of dark, grey and light laminae along the different units of El Tobar composite record.*

4.6 Article 4

Erosion in Mediterranean mountain landscapes during the last millennium: a quantitative approach based on lake sediment sequences (Iberian Range, Spain)

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Highlights

- Validate results obtained from Mediterranean monitored catchments in a centennial scale
- Combined methodology to quantify erosion based on long-term lake records and experimental plots
- Most sediment delivery occurs during flooding events

Abstract. Land degradation and soil erosion are key environmental problems in Mediterranean mountains characterized by both a long history of human occupation, and strong seasonality of hydrological regimes. Experimental monitored catchments have identified main controlling factors on erosion dynamics, but because of the short time span of the instrumental measurements they do not integrate the complete temporal and spatial variability of these environments. To obtain some long-term series of Mediterranean landscape evolution we propose a novel strategy based on multi-proxy analyses of lake sediments aimed to quantify sediment delivery and erosion dynamics. Karstic lakes in the Iberian Range (Central Spain) provide an opportunity to reconstruct the depositional evolution of the watersheds and to evaluate the response to both, the variable anthropogenic impacts and climate forcings during the last 1000 years.

The most significant periods of increased sediment delivery (26 - 483 T km^2 yr^{-1}) in the Iberian Range sites took place during the 15th-16th and 18th-19th centuries as a result of large land use changes and land clearing. Positive synergies between increasing human population and more humid periods led to peaks in sediment deliver during some phases of the Little Ice Age. Recent changes associated with the rural exodus and land abandonment during mid-20th century are more clearly shown in larger watersheds by decreased sediment delivery to the lakes due to the re-vegetation of the landscape (6 - 200 T km^2 yr^{-1}).

This new integrated approach based on long-term lake sequences provides a longer perspective of erosion processes in Mediterranean watersheds and validates the main factors identified in monitoring surveys (land cover and surface formations erodibility). In both settings, lakes and experimental catchments, most sediment delivery occurs during flooding events. Measured and reconstructed values show comparable large ranges, underlying the punctuated nature of sediment dynamics in Mediterranean landscapes at decadal and centennial scales.

Keywords: Lake records; experimental catchments; paleoenvironment; sediment yield; land-use changes; Mediterranean mountains.

1. Introduction

Soil erosion in the Mediterranean regions has become the focus of increasing research in recent years (Carretier et al., 2013; García-Ruiz et al., 2013; González-Hidalgo et al., 2007; Kosmas et al., 2000; Koulouri et al., 2007; Meadows, 2003; Mohammad and Adam, 2010; O'Farrell et al., 2007; Poesen et al., 1992; Portenga et al., 2016; Vanmaercke et al., 2011). European Mediterranean mountains are characterized by a large spatial and temporal variability in plant cover, usually related to marked changes in land use, which directly influences both, the water resources and the potential for soil erosion or preservation (García-Ruiz et al., 2010; 2008). Understanding the dynamics of sediment fluxes in terrestrial watersheds is also a strategic issue for the preservation and management policies of the fragile Mediterranean ecosystems and to control the threat of soil erosion to the sustainability and productive capacity of the Planet (Dotterweich, 2013; Erol and Randhir, 2012). Experimental watersheds and catchments have helped to quantify some of the main parameters in soil erosion, sediment yield and the relationships with hydrometeorological factors, vegetation cover and human activities (Ruiz-Flaño et al., 1992; Sougnez et al., 2011; White and García-Ruiz, 1998). García-Ruiz et al. (2008) demonstrated that plant cover is a key factor, influencing: flood seasonality and intensity, the annual volume of discharge, the suspended sediment concentration, the total sediment yield and the sediment composition. A recent review (García-Ruiz et al., 2015a) shows an extraordinary high variability in erosion rates, with a significant effect of land use, as agricultural lands yield the highest erosion rates, and forest and shrub-lands the lowest; the review also documents some positive relationships between erosion rates, slope and annual precipitation; and negative ones with the size of the watershed. The authors questioned the reliability of the estimated erosion rates from monitoring in experimental watersheds and plots as the involved time period is only a few years. Besides, González-Hidalgo et al. (2007) and Nadal-Romero et al. (2012) observations revealed that the sediment production in Mediterranean areas is mostly controlled by the occurrence of intense but infrequent flood events, increasing the uncertainty for the estimation of long-term sediment yields.

During the last decades, decisive socio-historical changes have occurred in the Mediterranean Iberian mountains affecting the evolution of natural systems, the availability of water resources and sediment transport and transforming the structure of the landscapes (García-Ruiz et al., 2013). In general, the abandonment of cultivated lands in mountain areas has produced a recent expansion of forests and shrubs and, as consequence, a decrease in water discharge and in erosion; only in terraced slopes, mass movements and the reorganization of the drainage network may increase erosion. In contrast,

in semiarid areas plant colonization is slow and the formation of surficial soil crusts may increase runoff and consequently, erosion (García-Ruiz and Lana-Renault, 2011).

However, those recent changes have occurred over landscapes already transformed during centuries. Recent sediment production changes (1950-present day) related to rural abandonment have occurred after centuries of intense use of mountain areas, particularly during the mid-19th century – early 20th century, when maximum cultivated area and population density were reached (García-Ruiz and Lana-Renault, 2011). The reconstruction of human-driven landscape evolution is important for understanding not only past human-nature interactions but also to constrain present variability ranges in terms of intensity, rates and structure of global changes. This is even more important in future scenarios of more intense human activities and climate with more hydrological extremes (Giguet-Covex et al., 2014). In regions with such a long history as the Mediterranean mountains, local and regional changes in cultural traditions and socioeconomic conditions have played a major role in the dynamics of soil erosion and landscape transformations (Dotterweich, 2013; Valbuena-Carabaña et al., 2010). To better understand recent dynamics in Mediterranean mountains, a long – term perspective is needed, beyond – although including- experimental data from monitored catchments and watersheds. Such reconstructions of past dynamics from centennial to millennial scale may capture all the natural and human – induced variability.

The Iberian mountains contain such records of past watershed dynamics in numerous lake basins (Valero-Garcés et al., 2014). Lake sediments have been shown to be exceptional archives of past environmental (Ambers, 2001; Bennett and Buck, 2016; Birck et al., 2013; Détriché et al., 2013; Sadori et al., 2016), climatic (Magny and Combourieu, 2013; Roberts et al., 2012), erosion (Anselmetti et al., 2007; Giguet-Covex et al., 2001; Van der post et al., 1997) and human landscape evolution (Dearing et al., 1987; De Boer, 1994; Enters et al., 2008) at regional scale (Lionello, 2012). Detail records for the last millennium are available from several karstic lakes in the Iberian Range: La Cruz (Burjachs, 1996; Julià et al., 1998; Romero-Viana et al., 2011, 2008), Lagunillo del Tejo (López-Blanco et al., 2011; Romero-Viana et al., 2009), El Tejo and La Parra (Barreiro-Lostres et al., 2014. 2013) located in the Cañada del Hoyo lakes-sinkhole system in the Serranía Media de Cuenca; and from Taravilla Lake (Moreno et al., 2008; Valero-Garcés et al., 2008) and from El Tobar Lake (Barreiro-Lostres et al., 2015) both located in the Serranía Alta de Cuenca. These lakes act as sediment traps for their watersheds and the intense depositional processes lead to high sedimentation rates and thick deposits, providing long continuous sedimentary sequences with a high temporal

resolution and an exceptional sensitivity to both regional hydrological balances and human induced land-use (Valero-Garcés et al., 2014).

In this research, we propose a novel approach to quantify sediment fluxes and denudation rates in Mediterranean watersheds based on a multiproxy study of lake sediment sequences. Using this methodology we explore the relationships between documented land use changes and climate fluctuations during the last millennium with erosion in the watersheds and sediment yields to the lakes. The results from these lake basins are compared with available data from four experimental watersheds in other Mediterranean mountain areas (Central Pyrenees) obtained during the last decades (García-Ruiz et al., 2010, 2008 and references therein).

2. Study area

2.1 The Serranía de Cuenca

The Serranía de Cuenca, is located in the Upper Tagus River valley, in the Castilian branch of the Iberian Range (NE of Spain, *figure 1*). The highest altitudes occur in the northern part of the studied area in the catchments of Lake Taravilla and El Tobar (up to 1600 m a.s.l.) and the lowest in the Southern areas (sinkhole complex of Cañada del Hoyo) with maximum altitudes around 1000 m a.s.l. The bedrock is composed of marine Jurassic and Cretaceous carbonate formations. These carbonate formations are underlain by an impervious Triassic formation (*Keuper*) containing marls and clays with evaporites, which constitute the base level of the regional and local aquifers. The karstic processes have played a crucial role in the geomorphology of the region (Gutiérrez-Elorza and Gracia, 1997), at least since the Pliocene, when most karstic morphologies started to develop (Gutiérrez et al., 1996).

Exo- and endo-karstic processes are responsible for the formation of numerous lake basins in different settings: behind travertine dams as in the Lake Taravilla (Valero-Garcés et al., 2008), due to collapse and dissolution karstic processes as in El Tobar Lake (Barreiro-Lostres et al., 2015), sinkhole formation as in the seven karstic lakes of the Cañada del Hoyo complex, which includes El Tejo and La Parra lakes (Barreiro-Lostres et al., 2014; Julià et al., 1998).

The regional climate is Mediterranean, although with strong continental influence (Romero-Viana et al., 2011). Precipitation generally increases northwards following the altitudinal gradient and westward because of the Atlantic influence. Average annual precipitation ranges between 850 and 730 mm in the Serranía Alta (northernmost sector of the study area) and about 570 mm in the Serranía Media (south of the study area). December is the wettest month and July and August are the driest, but during summer and the beginning of the fall highly convective storms usually take place, occasionally developing very intense rainstorms. Inter-annual variability is large. The mean

annual temperature increases from North to South (~10 ºC in Tobar and Taravilla; ~12 ºC in El Tejo and La Parra, Ninyerola et al., 2005; see *figure 1* for locations).

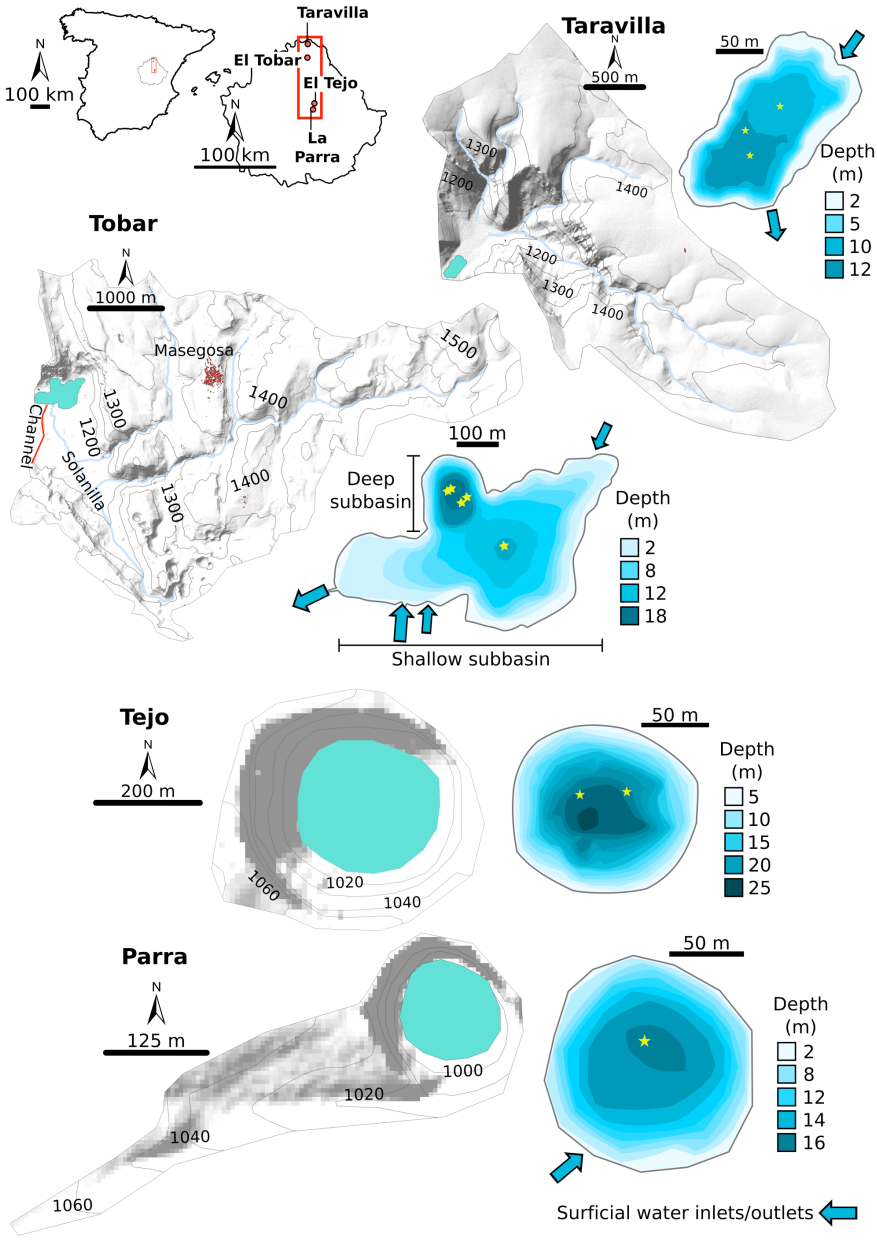

Figure 1: *Iberian Peninsula and main subdivision of the Iberian Range in the study area: Serranía Alta, Media and Baja. More detailed location and relative distance of the lakes is marked in the 3D terrain view. Also a 3D view of the lakes and their watersheds is shown and next, the bathymetric map showing the geometry of the lakes with the main surface water inlets and outlets. Yellow stars represent the coring points.*

Serranía de Cuenca soils are Inceptisols, poorly developed soils with incipient cambic horizon (Dirección General de Política Forestal y Espacios Naturales, 2015). In vegetated areas, soils are better developed, with more organic matter and differentiated horizons. Local hydrological regimes determine the occurrence of calcic and petrocalcic horizons and massive, poorly stony with moderated organic matter content. No detailed soil studies are available for the watersheds, but general descriptions in Batlle and Guerra (1987) for El Tejo, La Parra and El Tobar, and in Guerra and Monturiol (1970) for the area of Taravilla Lake indicate the presence of poorly developed soils in the carbonate formations and better developed soils in the lowlands and valleys. Regionally, vegetation is dominated by *Pinus nigra, P. sylvestris, P. pinaster, Quercus faginea* and *Q. sylvestris*. Locally, *Populous nigra* is present in Taravilla, *Q. ilex* in El Tejo and La Parra and *Buxus sempervivens* and *Q. ilex* in El Tobar. In all watersheds, except in Taravilla, cereal crop fields occur in the lowlands (GBIF-Spain, 2012). Vegetation cover has been strongly influenced by human activities since mediaeval times (Esteban Cava, 1994). After the 1960's most cultivated fields were abandoned in the slopes and forest as well as and shrub surface has increased in all watersheds.

2.2. The Lakes

The four lakes selected for this study are of karstic origin, but they are in a mature stage and karstic processes are not very active. El Tejo and La Parra lakes are flooded sinkholes with a circular morphology and both are small (0.02 and 0.01 km^2 respectively) but relatively deep (Tejo 25 m, Parra 14 m), with marked funnel-shape morphology. The littoral area in both lakes is narrow and the margins are very steep. The smallest catchment corresponds to El Tejo (0.09 km^2, see *table 1*), with almost vertical dolostone scarps, covered by dense vegetation in the north-facing and shrubs in the south facing slope. The La Parra catchment is elongated SW-NE and relatively large for the lake size (0.1 km^2) and is formed entirely by dolostones, except a small outcrop of marlstones near the lakeshore. The watershed is mostly vegetated by shrubs and trees, although there are some zones with more open vegetation, and some evidence of abandoned fields now occupied by small shrubs (see *figures A1 and A2*). Both lakes have no outlets, and only La Parra has an intermittent small inlet creek.

Table 1. Main physiographic characteristics of the lakes and their catchments.

Lake	El Tejo	La Parra	El Tobar	Taravilla
Location	39°N, 1°52′W	39°59′N, 1°52′W	40°32′N, 3°56′W	40°39′ N, 1°58′ W
Depth (m)	25	14	Deep subbasin: 18; shallow subbasin: 12	12
Lake area (km^2)	0.02	0.01	0.17	0.04
Drainage area (km^2)	0.09	0.1	20	13.3
AD/AL	4.5	10	118	333
Surface hydrology	Closed, endorheic	Closed, ephemeral inlet	Open, permanent inlets/outlets	Open, permanent inlets/outlets
Maximum elevation (m a.s.l.)	1050	1050	1600	1490
Minimum elevation (m a.s.l.)	1010	900	1150	1130
Mean elevation (m a.s.l.)	1030	975	1375	1310
Mean slope (º)	23	20	11	17
Precipitation (mm/a)	542	542	956	560
Dominant rocks in drainage area (%)				
Siliciclastic	0	0.1	32	13
Carbonate	100	99.9	68	87
Land cover (%)				
Woodland	76	77	42	84
Cropland	0	0	19	0
Abandoned cropland	0	0	3	0
Lake	24	16	0.9	0.3
Bare soil	0	0	27	1.4
Shrubs	0	6	7	14
Wetland	0	0	0	1

El Tobar and Taravilla lakes are bigger than the sinkhole lakes and both are open systems with permanent inlets and outlets. El Tobar is the largest lake in the region with two subbasins (0.17 km^2; deeper subbasin 18 m depth, shallower subbasin 12 m depth), and also has the largest catchment (20 km^2), composed of limestones and dolostones (68%) and siliciclastic formations (32%) (see *table 1* and *figure A1*). It has several intermittent creeks as inlets and also saline and freshwater springs. The Masegar River (tributary of the Guadiela River) is the only outlet of the lake. The lake is dammed and was connected in 1967 with a nearby reservoir, so currently acts as a regulatory water reservoir. The El Tobar catchment has the most diverse land occupation

of the four lake catchments: 19% of its surface area is dedicated to crops and about 3% of lands are abandoned fields, while 27% consist of bare lands, 7% of shrubs and about 47% are woodlands (*table 1* and *figure A2*). Thus, the El Tobar catchment can be considered the most anthropogenically affected compared with the rest of lake catchments.

Taravilla Lake (0.04 km^2) lies behind a travertine barrage. The inlet is only functional during the rainy season (*figure 1*) and drains a relatively large watershed (13.3 km^2). The catchment is mainly formed by dolostones and limestones (87%), and siliciclastic formations (13%) close to the lake. Not very dense woodlands cover almost entirely the catchment (84%) with only small areas of shrubs (14%) and minimal barelands (0.3%) deeply affected by erosion processes (see *table 1* and *figure A2*). The occurrence of thick Pleistocene-Holocene travertine build-ups in the SE margin of the lake and some fluvial tufas in the inlet (Valero-Garcés et al., 2008) are a significant source of sediment for the lake. The occurrence of a large palustrine-wetland area (0.12 km^2) between the main inlet and the lake basin is a unique feature of this lake. It acts as a barrier for sediment delivery to the lake and also as a temporary sediment accumulation area. The outlet, located at the southeastern margin of the barrage tufa, drains the Taravilla waters into a small tributary of the Tagus River, and becomes non-functional during dry periods.

Hydrologically, Taravilla and La Parra lakes are well mixed (holomictic). El Tejo has summer thermal stratification and during some periods, bottom waters may become anoxic. El Tobar has a deep meromictic subbasin (13 % of the lake's area) with a hypersaline hypolimnion and a shallow holomictic subbasin (87 % of the lacustrine area).

Lacustrine sediment cores are available for all of the lakes. The dominant sediments mainly consist of exogenous clastic carbonates, surface Quaternary formations and soils eroded from the watershed. Thus, the lake sequences show a large variability of facies, pointing to varied sediment sources and depositional processes, dependent strongly on hydrological conditions (Valero-Garcés et al., 2014).

La Parra and El Tejo records span the last 1600 and 3000 years respectively. They present very similar facies, mainly massive to banded clastic carbonate-rich silts and muds in fining-upward sequences, occasionally interbedded with intervals with endogenic calcite laminations (Barreiro-Lostres et al., 2014). The El Tobar Lake sequence spans the last 1000 years and is mainly composed by alternation of laminated to banded, fine to medium carbonate-rich silts. Coarser, massive carbonate-rich silts layers punctuate the sequence, marking intense depositional events during the Little Ice Age (LIA) and recent times (Barreiro-Lostres et al., 2015). The Taravilla record spans the last 1600 years. The bottom half consists of finely laminated carbonatic facies,

and the top half coarse massive to banded carbonate-rich silts and muds, punctuated by sandy to coarse-silty massive beds originated by flooding events. These flooding events mark seven phases of intense flooding during the LIA (Moreno et al., 2008; Valero-Garcés et al., 2008).

2.3 The Pyrenean experimental catchments

The four experimental catchment used for the comparison with the lake's watersheds are located in the central-western Spanish Pyrenees and have been monitored since 1986. *Table 2* summarizes their major physiographic characteristics. San Salvador, Arnás and Araguás catchments are sited in the Upper Aragón River basin (in the middle mountain belt), while the Izas catchment is located in the Upper Gállego River basin (in the transition zone between the subalpine and the alpine Belts; see *figure 2*).

Izas is the smallest catchment (0.33 km^2) located at the highest altitude (2060 m a.s.l.) and with the highest annual rainfall values (2000 mm) (Alvera and García-Ruiz, 2000). The dominant geomorphic processes are related to mass movements (solifluction, gelifluction terracettes). Subalpine and alpine grasslands cover most of the slopes, which were deforested some centuries ago to provide summer grassland for the cattle. More detailed descriptions of geomorphic processes, soils and surface processes can be found elsewhere (Nadal-Romero et al., 2012a).

The Araguás catchment (0.45 km^2, Nadal-Romero and Regüés, 2010) comprises a very active badland area (25% of the total area), intensively disturbed by runoff erosion, gullying and rilling. It has high values of annual sediment yield (see *Table 2*). Soils descriptions are found in García-Ruiz et al. (2008) and Lana-Renault et al. (2014).

The San Salvador catchment (0.92 km^2, Serrano-Muela et al., 2008) is covered entirely by a dense undisturbed and mixed forest with well developed soils. Past agricultural activity is evident only on the lowest part of the south-facing slopes. Soils and landscape formations are described in García-Ruiz et al. (2008) and Lana-Renault et al. (2014).

The Arnás catchment is the largest (2.84 km^2, Lana-Renault and Regüés, 2009) and it was entirely cultivated until the 1950s and then abandoned, so shrubs have colonized the field crops and some forest patches have developed. Arnás catchment soils are described in detail in Navas et al. (2005). This catchment is a complex geomorphic and vegetation mosaic that explains its variable hydrological response.

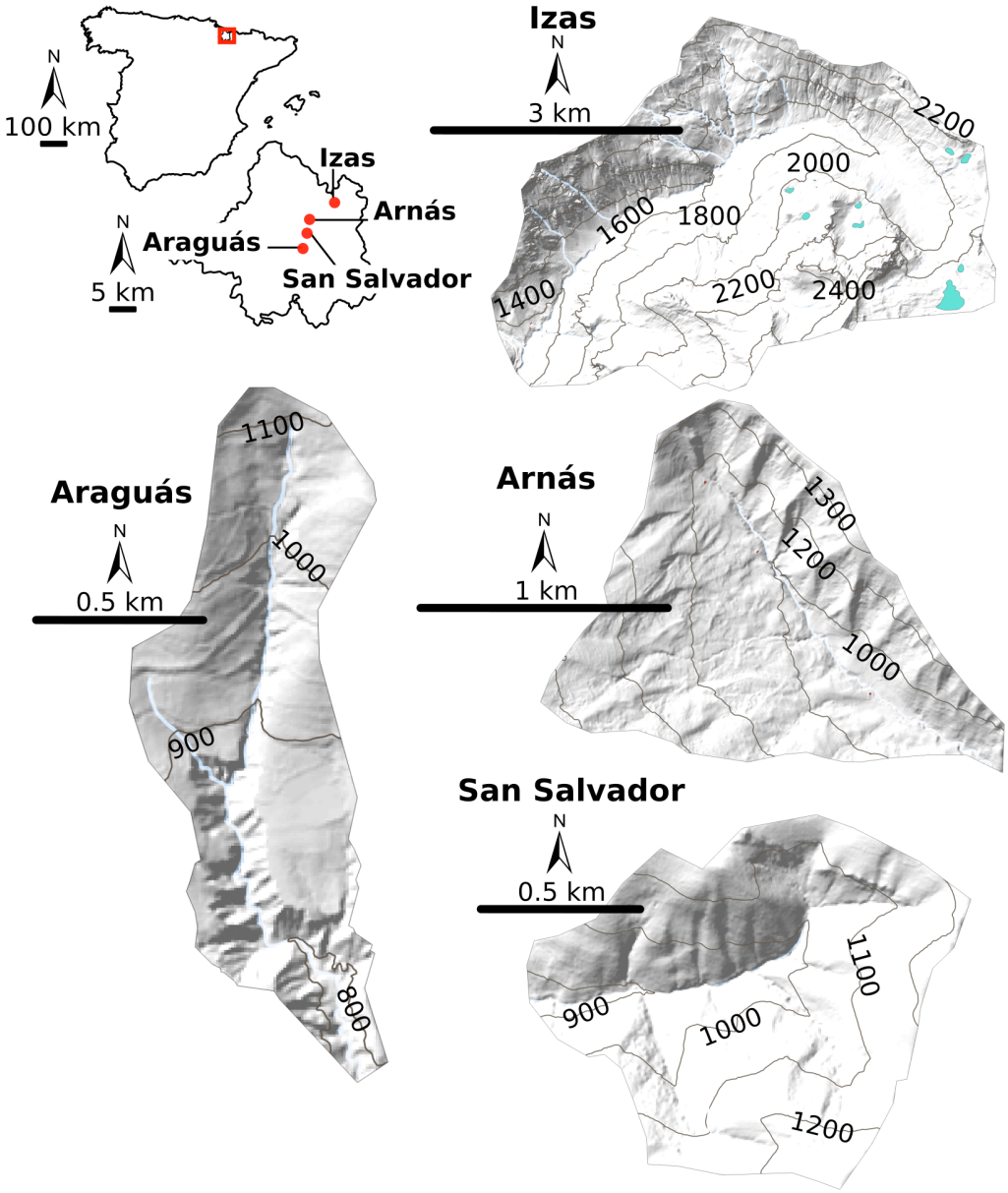

Figure 2. Iberian Peninsula with the location of Pyrenees Mountains. More detailed location and relative distance of the catchments is show in the 3D terrain view. Also a 3D view of the catchments and their watersheds is shown.

Table 2. *Main physiographic characteristics of the experimental catchments. Data based on Lana-Renault et al. (2014).*

Catchment	San Salvador	Arnás	Araguás	Izas
Location	42°37′N, 0°36ºW	42°38′N, 0°34′W	42°35′N, 0°37′W	42°44′ N, 0°25′ W
Drainage area (km^2)	0.92	2.84	0.45	0.33
Maximum elevation (m a.s.l.)	1295	1340	1105	2280
Minimum elevation (m a.s.l.)	830	910	780	2060
Mean elevation (m a.s.l.)	1063	1125	943	2170
Mean slope (º)	14	12	12	16
Precipitation (mm/a)	935	926	718	2000
Dominant Geology	Flysh	Flysh	Marls	Schist, sandstone, shales
Land cover (%)				
Woodland	98	20	30	0
Bare soil	1	2	26	5
Shrubs	1	71	38	0
Badland	0	0	25	0
Sediment yield				
T yr^{-1}	128.8	454.4	6885	82.5
T km2 yr^{-1}	140	160	15300	250
Exceptional rainfall event				
Sed. yield (T)		195.8	1392.2	5.3
Sed. yield (T km^2)		68.9	3093.7	16.2

3. Data and methods

3.1 Depositional Processes in Lakes

The sedimentary sequences and geochemical data for Lake La Parra, El Tobar and Taravilla have already been published (Barreiro-Lostres et al., 2015, 2014; Moreno et al., 2008; Valero-Garcés et al., 2008). Work in El Tejo sequence is in progress and here we summarize some of the main results (see supplementary material). Details for methodologies and results can be found in these publications.

All sequences have been studied following the same multiproxy strategy, including detailed sedimentological, mineralogical (XRD) and geochemical analyses -Total Organic Carbon (TOC), Total Inorganic Carbon (TIC) and Total Nitrogen (TN) and elemental geochemistry by by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) - and absolute dating techniques. Sediment cores were scanned for sediment gamma density (ρ) and magnetic susceptibility (MS) at 1 cm of resolution with a Geotek Multisensor Core Logger (MCL).. The composite sequences were analyzed for semi-quantitative XRF at 5 mm resolution Principal Component Analysis (PCA) was carried out to investigate in each record the relationship between chemical elements by using R software 3.2.0 (R Development Core Team, 2014) and the package FactoMineR 1.29 (Lê et al., 2008).

The age models of the sequences are based on ^{14}C, ^{210}Pb and ^{137}Cs radioisotope techniques; details can be found in the following references: La Parra (Barreiro-Lostres et al., 2014), El Tobar (Barreiro-Lostres et al., 2015) and Taravilla (Moreno et al., 2008). For the El Tejo sequence see not previously published *supplementary material A3*.

Bathymetric and seismic surveys were conducted in all lakes. Detailed bathymetric maps were obtained by using a SonarMite echosound connected to a DGPS. The seismic surveys were conducted with an Edgetech 424-SB sub-bottom multi-frequency profiler using a frequency range of 2-10 kHz for 20 ms. Penetration in La Parra, Taravilla and El Tejo was limited to the upper few meters. At the El Tobar 24 seismic profiles were obtained. Penetration was very limited (0.5 m) in the shallow sub-basin, but reached up to 8 m in the deep sub-basin. Proprietary software (EdgeTech Discover SB3200 XS) was used for the processing of the pinger data (bandpass filter, flat gain).

3.2 Calculation of sediment fluxes and denudation rates in the lake-watershed systems

The quantitative relationships between denudation in the drainage areas with respect to the sediment accumulation in the lakes have been approached following the methods described in Einsele and Hinderer (1998). From known sedimentation rates, the average denudation rate and mass denuded for a determined time interval can be calculated. Here we calculate the total denudation rate (DRt) and do not distinguish between mechanical or chemical denudation, as mechanical denudation prevails over chemical denudation in regions of high relief and is less dependent on climate or rock type than on relief (Einsele and Hinderer, 1998). In mountainous lakes, biogenic sediment production is limited and can often be neglected in relation to the rapid input of terrigenous material (Einsele and Hinderer, 1998). As sedimentological analyses have shown in these lakes, most sediments are delivered from the watershed (Barreiro-Lostres et al., 2015, 2014; Moreno et al., 2008). Thus,

terrigenous carbonate and siliciclastic are the dominant mineral fraction in the sediment.

We make the assumption that in closed systems, the mass denuded (Md) is equal to the mass accumulated in the lake (Ml) for a given unit of time. This approach has two main caveats: sediment efficiency and sediment storage in the watershed. In open systems, Md is greater than Ml, because part of the load entering the lake is lost through the outflows (Einsele and Hinderer, 1998) and so sediment efficiency may not approach 100%. The assumption is strictly valid for the two lakes located in sinkholes (El Tejo and La Parra), because of their especial funnel-shaped morphology without outlets and their large lake size in relation to their watersheds. Thus, in both cases, the lake sediment trap efficiency can be considered 100 %. In Lake El Tobar, the location of the main water inputs (channel and Solanilla brook) at the center of the south shore, in relation to the water output (west shore) facilitate the re-circulation of waters towards the East, allowing the distribution of the sediment plume counter-clockwise way and redistributing the sediment in the whole basin. Detailed sediment logs from both subbasins show similar cm-scale stratigraphy and demonstrate the homogeneous distribution of the sediments in the basin (limited focus in the deeper areas). Although it is possible that part of the fine sediment fraction is exported through the outlet, we consider the sediment efficiency to be very high. Lake Taravilla is a tufa barrage lake where both inlet and outlet are only functional during wet episodes. The large palustrine-vegetated area located after the inlet has a significant impact as diminishing the energy of the floods and consequently facilitating the deposition of the finer sediments along the lake basin before reaching the tufa barrier. In general, lake sediment trap efficiency for El Tobar and Taravilla may not approach 100% or experiment small changes trough time, but the sediment loss only concerns to fine sediments and it has been considered as negligible for the purpose of our calculations.

In large watersheds as El Tobar and Taravilla, sediments may also accumulate in some parts of the watershed area due to the variety of geomorphological landforms (i.e. channels, slopes, palustrine areas, low areas disconnected from the main hydrological network, etc.). Moreover, in the Taravilla catchment, a relatively large wetland area surrounding the NE part of the lakeshore also may act as a primary sediment trap. Thus, only relatively high-energy floods are capable to erode these trapped sediments and transport them into the lake. Therefore, the actual mass denuded could be greater than the mass accumulated in the lake (Ml).

A detailed lake bathymetry is also key for the calculations, as we need to know the lake area (Al) for each sediment interval analyzed in the sediment cores. Lake area (Al) was calculated from the bathymetric maps using GIS

software. In the smaller lakes (Tejo, Taravilla, La Parra) the lake surface area with slopes < 11º was considered the depositional area, to avoid over estimation due to some sediment focusing in the deepest areas. In El Tobar, the seismic survey and the long cores demonstrates that main depositional events occur with similar thickness in both the deep and shallow basin. Consequently to simplify calculations, the total El Tobar lake area was considered the depositional area.

To obtain the minimum mass denuded (Md) in the catchment of each lake, we calculated the mass accumulated in the lake (Ml) using the sedimentation rate (SR), the lake area (Al) and the density of the sediments (ρ):

$$Md \geq Ml = SR\ Al\ \rho = [T\ yr^{-1}]$$

Knowing the mass accumulated in the lake (Ml), we calculate the sediment yield from the catchment (Sy) based on the denuded mass (Md) and the drainage area (Ad):

$$Sy = Ml/Ad = [T\ km^{-2}\ yr^{-1}]$$

The temporal variations of denudation rate can be assessed from the total denudation rate (DRt) using the sedimentation rate (SR), the lake area (Al) and the drainage area (Ad):

$$DRt = SR\ Al/Ad = [cm\ yr^{-1}]$$

These calculations based on simple assumptions provide information about the mass denuded in the whole lake watershed (Sy), the mass reaching the lakes (Ml) and the rates of the denudation (DRt) during the long-term time span of the records or selected time intervals. When using this approach, we are aware that only approximations to erosion rates are possible, as these retain a very large degree of uncertainty due to errors involved in the estimations (Einsele and Hinderer, 1998). However, our objective is to go beyond the last decades of monitoring on experimental catchments and to obtain values for DRt and Sy for the lake watershed that could be compared with present-day direct measurements.

Another important parameter for the calculations is the sediment density. El Tejo, El Tobar and Taravilla lake sequences have been scanned with a Geotek MCL and gamma density values were available. However, the Lake La Parra cores were not logged prior to splitting. However, because El Tejo and La Parra facies are so similar, it has been possible to compared them (see *table A3*), calculating the mean value of gamma density for each facies of El Tejo sequence and assign that same value to the equivalent facies in the La Parra record. This approximation gives an estimate of the density values of the facies

along the La Parra sequence that we use to calculate the denudation values for this watershed.

3.3 Experimental catchment data

No experimental catchment data are available for the Iberian Range. Therefore, for this study we have selected four experimental catchments, located in the Central Spanish Pyrenees which have been monitored and studied during the last decades (see instrumentation in García-Ruiz et al., 2010, 2008): Izas, Arnás, San Salvador and Araguás catchments (see *figure 2 and table 2*). Although they are located in the Central Pyrenees with some differences in physiographic and meteorological conditions, they share similar characteristics with the Iberian Range lake catchments: i) a similar elevation range (~1000 m a.s.l.); ii) a dominant carbonate lithology, iii) a comparable Mediterranean hydroclimate regime. The Pyrenean sites present higher rainfall (720 to 1125 mm, except Izas) than the lacustrine watersheds (540 to 960 mm) because of the Atlantic influence; nevertheless the hydrological regime is similar, with large pluviometric and thermal differences between summer and winter. Although the Izas experimental catchment does not share some of these similarities (higher elevation: 2170 m a.s.l., higher rainfall: 2000 mm, and shale and sandstone lithology) we have included it in our comparisons to extend the sediment yield range.

Experimental catchments in the Pyrenees also share a similar history of human pressure (deforestation, grazing, cultivation in steep slopes, land clearing and abandonment) and a comparable range of recent land-uses. Because of these similarities, sediment yield measured in the experimental catchments are compared with those reconstructed from lake sediments, and the implications for the surface processes dynamics investigated.

4. Results

4.1 Event stratigraphy from lake sequences

Sedimentological and geochemical profiles allow identification of intervals of increased detrital deposition and discrete clastic layers. Usually these intervals consist of fine sediments (coarse silts to clays) without clear sedimentological boundaries but well identified by their geochemical signatures. We refer to these intervals as higher sedimentation *periods* and named them “s”. We have also identified layers in the sediment sequence corresponding to events of rapid deposition, i.e. coarse-grained sediment layers (coarse silts, sands or gravels), fining upward sequences, discrete fine-grained layers intercalated within the baseline organic-rich lacustrine sediments. These layers represent rapid allochtonous deposition originating from stronger energy transport processes (floods) and we have named them *events*. At lake El Tobar, event layers are massive, relatively coarser and easily

distinguishable from the baseline laminated fine-grained sedimentation (Barreiro-Lostres et al., 2015). In Taravilla, these events occur as thick massive, coarser carbonate-rich sediment layers interspersed within the laminated and organic-rich sediments (Moreno et al, 2008). They are coarser-grained than in the other lakes because the Taravilla watershed presents tufa formations, relatively easy to erode during high-energy events. Although some of the lakes have steep margins (El Tobar and El Tejo), mass wasted deposits and associated turbidites caused by margin destabilization have not been identified by seismic and coring techniques.

In *figures 3, 4, 5 and 6* we have summarized the most important proxies to describe the respective temporal evolution for the El Tejo, La Parra, El Tobar and Taravilla lakes. We have selected C/N ratios and the two main axes of the principal component analysis. High C/N values are related with dominant exogenous organic matter and correspond to periods of higher sediment delivery (Meyers and Lallier-Vergés, 1999). The main PCA axis is usually related with elements linked to the allochtonous, fine silicate detrital fraction derived from the catchment (i.e. Fe, K, Ti, Rb, Si) and to the allochtonous detrital carbonate fraction (i.e. TIC, Ca, Mg). The plots of event thickness show the thickness of the recorded flood sedimentary layers and their temporal distribution. In the El Tejo and La Parra lakes these events are usually composed by carbonate sands or microconglomerates that stand out from the dominant fine silt. In the case of El Tobar, where dominant deposition is finer-grained and more homogenous, these periods are highlighted by the presence of coarser silty facies with higher Zr and TIC (Barreiro-Lostres et al., 2015). In the case of the Lake Taravilla, these events correspond to previously described flood layers (Moreno et al., 2008). The time interval needed for the deposition of these layers is likely very variable, from days to weeks and even months, depending of the intensity of the runoff generation processes. Finally, the evolution of the sedimentary rate (SR in cm yr^{-1}) is calculated from the age models.

The positive end of the PC1 in El Tejo record explaining the 42 % of the total variance, is related with Fe, Si, Ti, K, Rb, C/N and Ca, linked with the external inputs of the allochtonous fine-grained and carbonate sediment fraction (see *figure A3*). Combining the information of the C/N ratio and the PC1, El Tejo record shows eight episodes of higher sediment delivery from the watershed to the lake during the last 2000 years (*figure 3*): s1 (80-250 CE), s2 (500-860 CE), s3 (940-1050 CE), s4 (1100-1140 CE), s5 (1350-1400 CE), s6 (1450-1600 CE) and s7 (1700-1800 CE) and s8 (1900-1970). Interestingly, the main sedimentary events with deposition of the thickest layers occurred prior to 300 CE and about 1300 CE during periods of relatively low sediment input. The SR remained low from 0 to 1400 CE (from 0.14 to 0.11 cm/yr), experienced

an increasing trend up to 1800 CE and a rapid increased up to 0.66 cm/yr in recent times, the highest value for the entire record.

In La Parra record, negative values of the PC1 which explains the 26 % of the total variance, highlight six episodes of higher sediment delivery along the last 1600 years (*figure 4*): s1 (300-350 CE), s2 (400-450 CE), s3 (550-670 CE), s4 (970-1070 CE), s5 (1230-1330 CE) and s6 (1430-1900 CE). Since 1900 CE, episodes of higher sediment supply to the lake have decreased. Sedimentary events occur in three separated periods: about 400 CE, from 700-800 CE and from 1200 to 1600 CE. The last period comprises smaller but more frequent events. Comparatively, the SR of the La Parra sequence is relatively higher and present a decreasing trend from 0.60 cm/yr about 300 CE to 0.10 cm/yr at 1800 CE, with a peak of higher values between 1300 to 1600 CE (0.5 cm/yr) and an increasing trend since 1800 CE up to 0.4 cm/yr. No sedimentary events are registered since 1600 CE.

The El Tobar sequence spans the last 1000 years. The positive end of the PC1, that explains the 52 % of the total variance, represents higher detrital inputs. The sequence records four periods of fine higher allochtonous sediment input to the lake (*figure 5*): s1 (1500-1620 CE), s2 (1790-1820 CE), s3 (1840-1860 CE) and s4 (1880-1920 CE). Sedimentary events concentrate in two periods: from 1450 to 1600 CE and from 1800 to 1900 CE. The last period includes the highest magnitude event and correlates with the SR trend, which is relatively low from 1000 to 1600 CE (0.5 cm/yr) and increases from 1750 to 1900 CE to 2.5 cm/yr. The SR of El Tobar is the highest of the four lakes.

In Taravilla Lake, the negative end of the PC1, that explains the 61 % of the total variance, represents the carbonate detrital inputs. The negative end of the PC2 (16 % of the total variance) is linked to the siliciclastic detrital inputs. Up to six higher sedimentation periods have been differentiated during the 1600 year time span of the Taravilla record (*figure 6*). The first two (s1, 300-400 CE and s2, 490-510 CE) correspond with increases in carbonate inputs and the following four periods are linked with increases in siliciclastic inputs: s3 (560-630 CE), s4 (810-830 CE), s5 (1000-1250 CE) and s6 (1430-1530 CE). In this case, the sedimentary periods coincide with the flooding events. These events bring coarse sediment inputs into the lake and can be grouped into four stages: 780-880 CE, 1430-1620 CE, 1780-1860 CE and one event in 1975. The first two flooding stages match well with higher C/N ratios and with the s4 and s6 periods of higher detritic inputs defined by PC1 and PC2. The Taravilla SR range is similar to those of the El Tejo and La Parra lakes, with lower but increasing values from 250 to 1200 CE (0.15 cm/yr), a period of rapid increase between 1200 and 1400 up to 0.3 cm/yr and relatively higher and stable values from 1500 to 2007 CE (0.3 cm/yr).

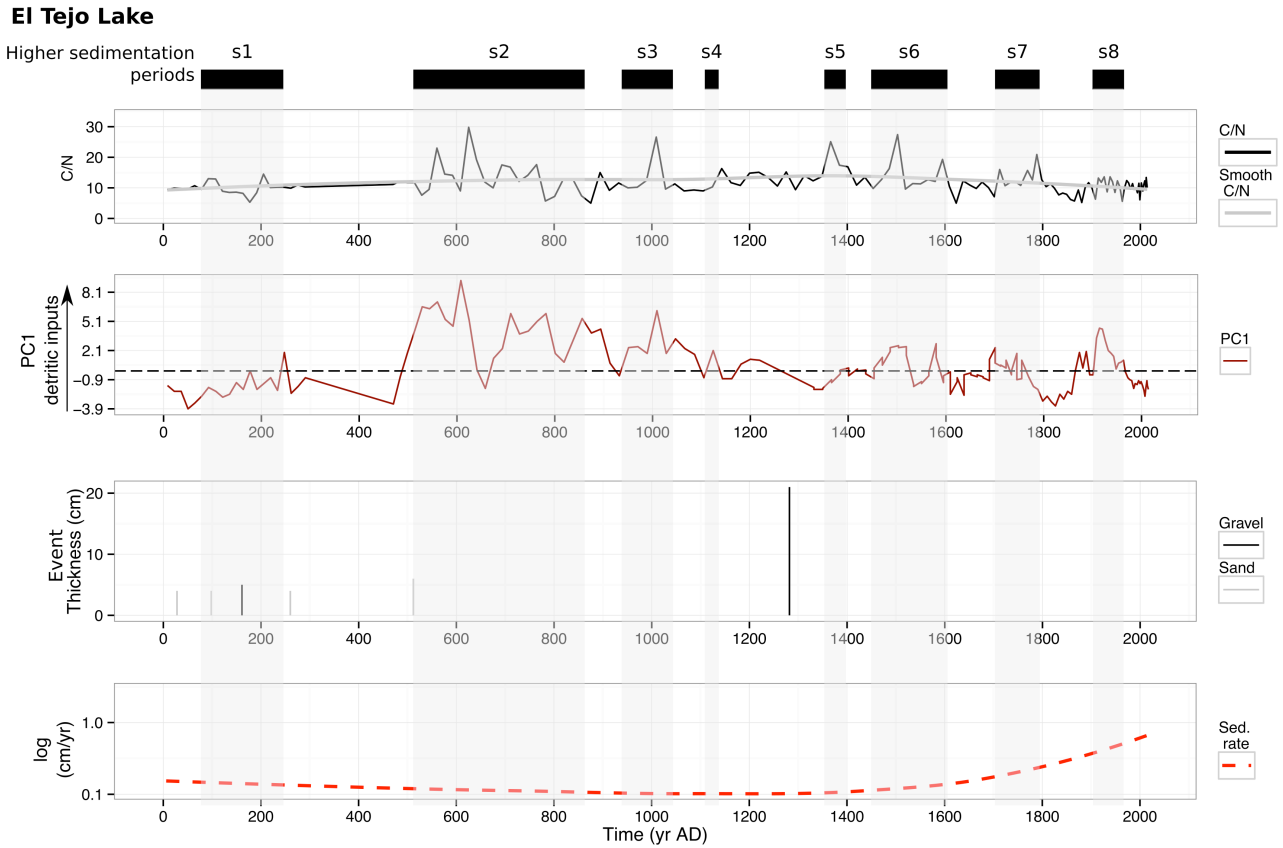

Figure 3. *Higher sedimentation periods for lake El Tejo (black rectangles) based on the total organic carbon and nitrogen ratio values (C/N, continuous black line; gray line represents smoothed values) and on the first Principal Component axis (PC1, continuous red line) or second Principal Component axis (PC2, continuous green line, see figure 6) derived from the XRF analysis, which is related with detritic sedimentary inputs. The event thickness (in cm) of the flood layers (gray vertical bars represent sands and black bars represent gravels) and the sedimentary rate (red shaded line) are also shown.*

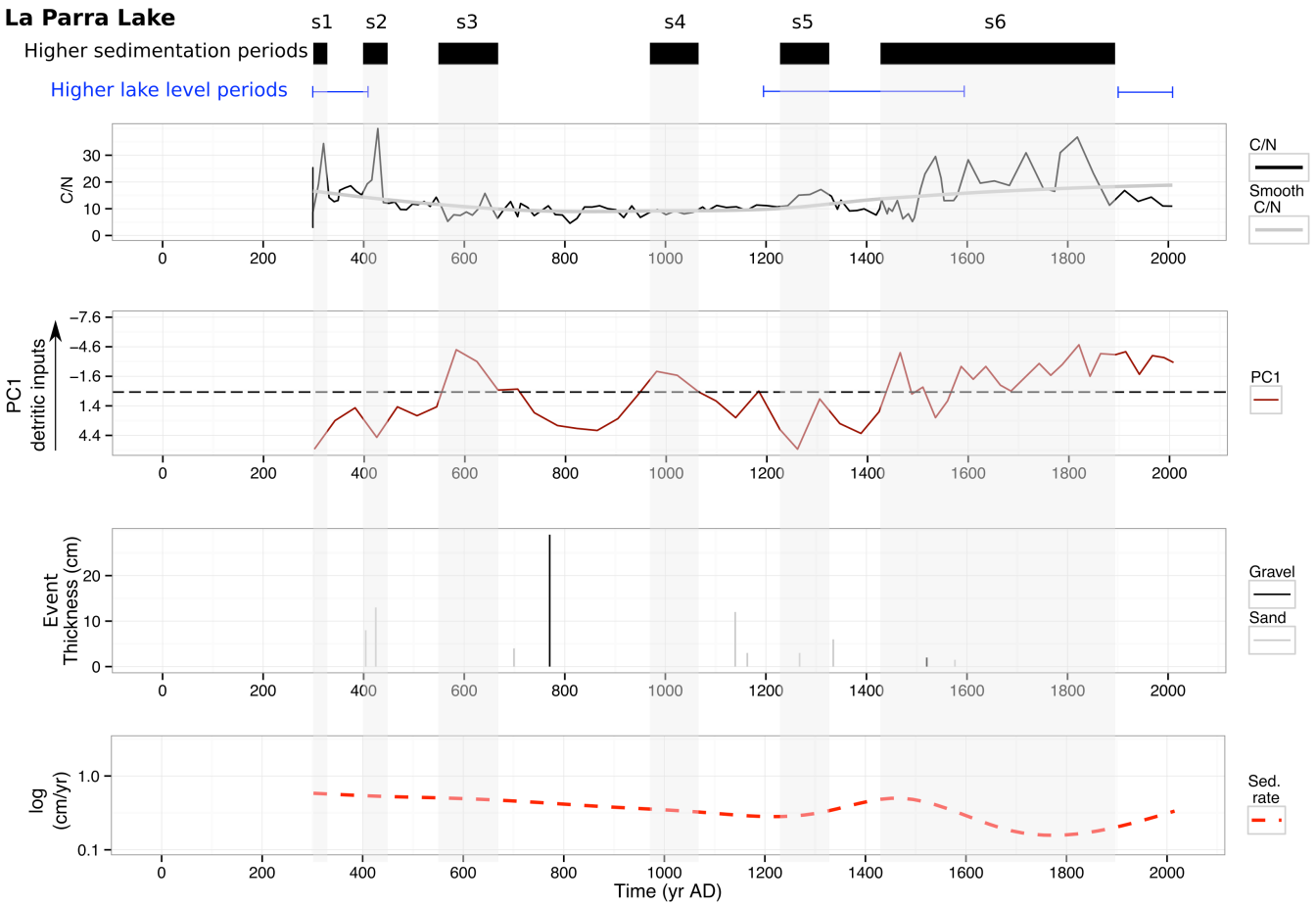

Figure 4. *La Parra Lake main higher sedimentation periods. See caption of Fig. 3 for details.*

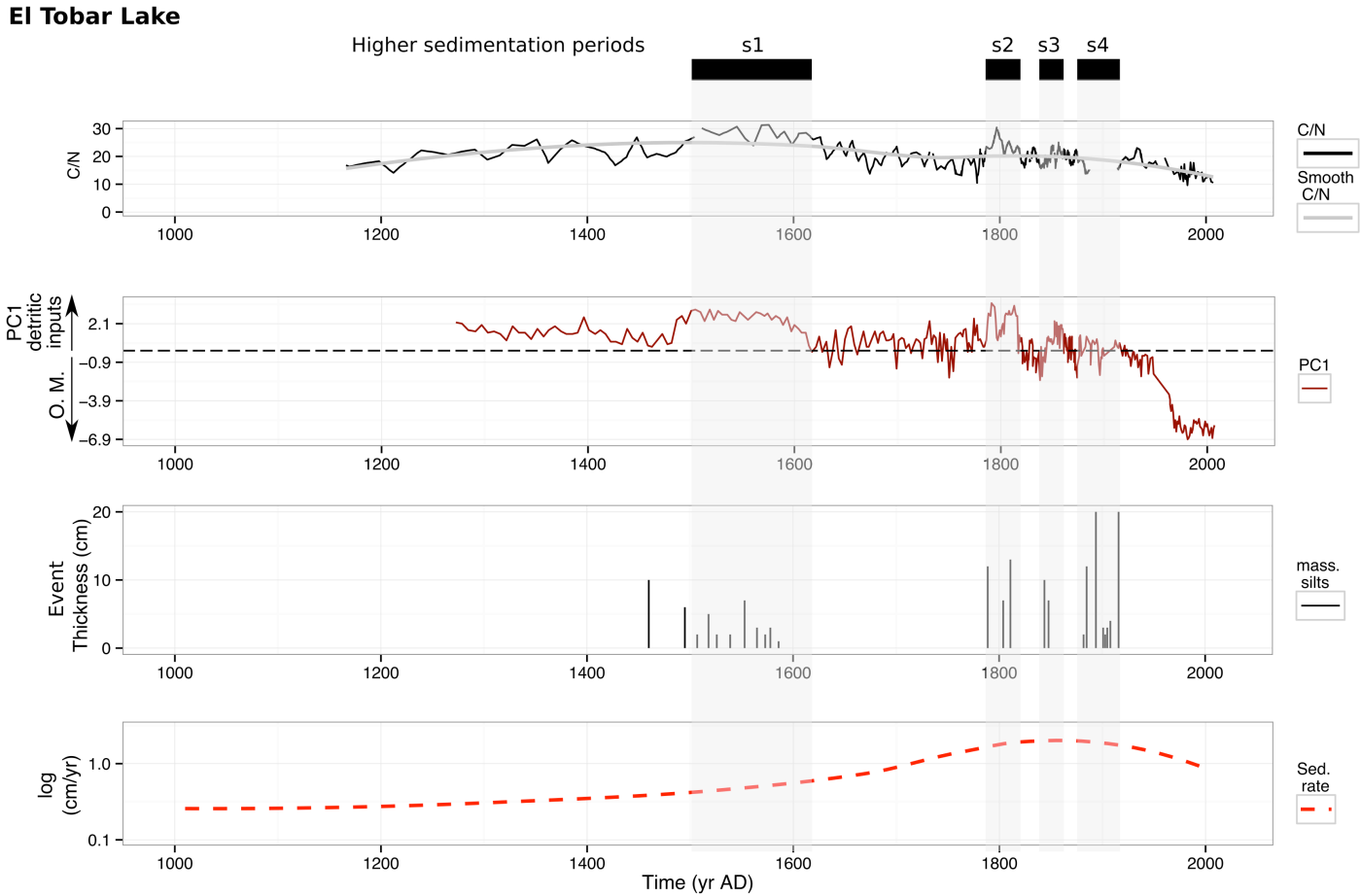

Figure 5. *El Tobar main higher sedimentation periods. See caption of Fig. 3 for details. Low values of PC1 are related with exogenous organic matter inputs.*

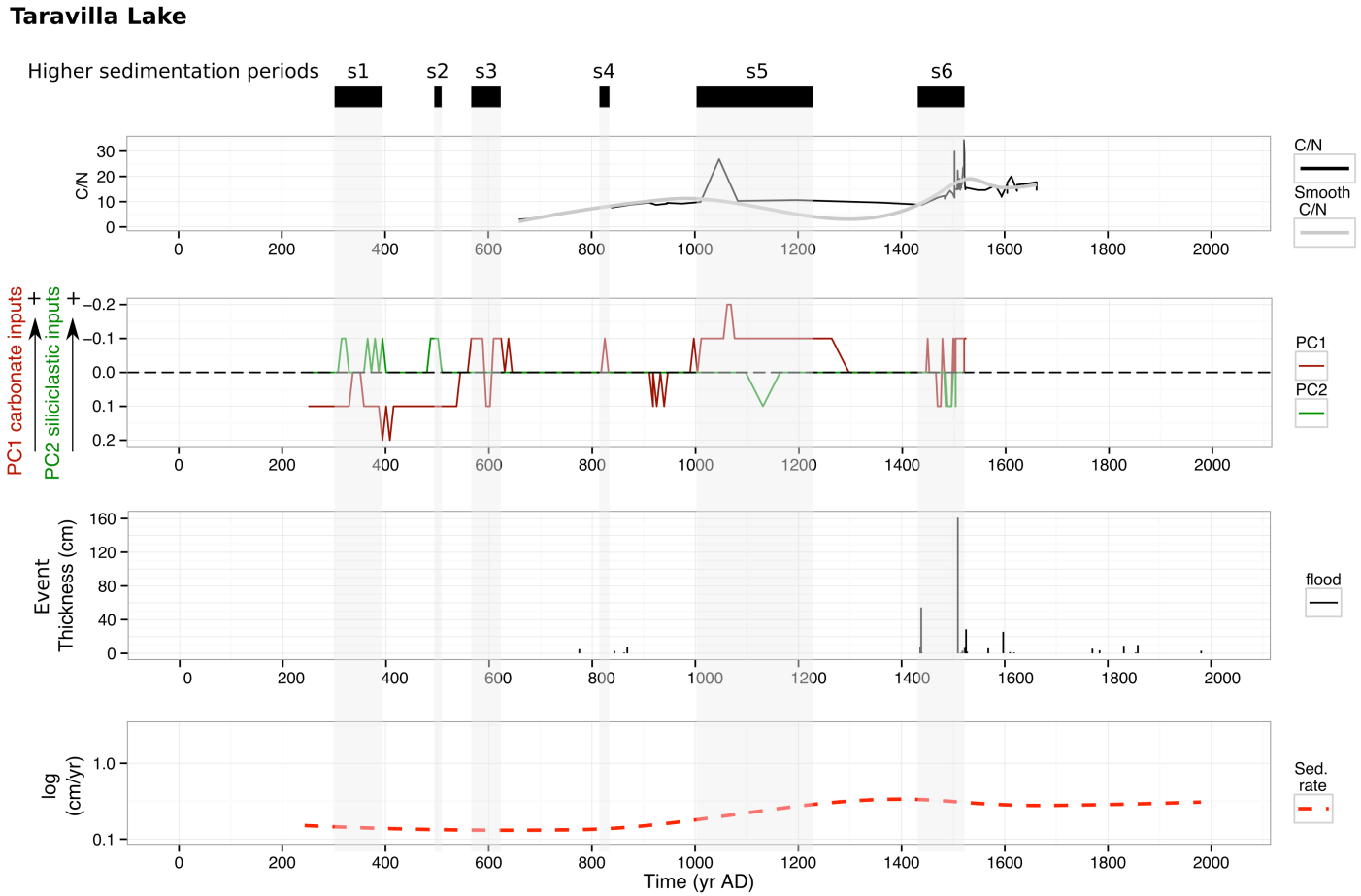

Figure 6. *Taravilla Lake main higher sedimentation periods. See caption of Fig. 3 for details. Low PC1 values (continuous red line) are related with exogenous carbonatic sedimentary inputs, and low PC2 values (continuous green line) are linked to fine siliciclastic sedimentary inputs.*

4.2 Sediment yield

Figure 7A summarizes the results obtained after applying the calculations described in section 3.2 for the lakes catchments during recent times (1960-2010) and the comparison with the sediment yield (Sy) of the experimental catchments. The La Parra and the El Tobar watersheds have the highest Sy (~100 T km^{-2} yr^{-1}) and Taravilla the lowest Sy (7 T km^{-2} yr^{-1}) among all the lacustrine watersheds. These values are lower but in the same order of magnitude than to those of the Arnás, San Salvador and Izas catchments (160, 140 and 250 T km^{-2} yr^{-1} respectively), independently of the size of the watershed. The Araguás catchment has values several orders of magnitude higher (15,300 T km^{-2} yr^{-1}). However, the data demonstrate that the calculated average sediment yield in the lacustrine watersheds during much longer periods of time (centuries to millennia) is comparable in magnitude with the sediment yield measured in the experimental catchments during short periods of time (decades) (*figure 7A and B*). Only the Araguás catchment has much higher sediment yield, attributable to the large area occupied by badlands (*table 2*; Nadal-Romero et al., 2008).

Figure 7B shows the relation between the mass accumulated in the lake (Ml) and the Sy by surface area along four main climatic periods identified in the Iberian Peninsula: the Dark Ages (DA: 500-900 CE), the Medieval Climate Anomaly (MCA: 900-1300 CE), the Little Ice Age (LIA: 1300-1850 CE) and recent times (RT: 1960-2010 CE). During these climatic periods the Ml and Sy have changed, but within the same orders of magnitude. Smaller watersheds – El Tejo and La Parra lakes - present very slight differences between climatic periods. El Tejo (smallest watershed area) reaches the highest values during RT while the highest values for the lake La Parra occur during the DA and the LIA. As expected (higher watershed, surface inlet), La Parra values are higher than El Tejo. Larger watersheds - Taravilla and El Tobar – show higher values during the LIA.

We have also investigated the relationships during the recent period (1960-2010 CE) among erosion, precipitation (*figure 8C*) and woodland cover (*figure 8D*). It appears that there is a relationship between the sediment yield and rainfall: areas with higher precipitation (Izas, Arnás, San Salvador, El Tobar) have also higher sediment yield. In a similar way, although less apparent, *figure 8D* also shows that vegetation cover affects sediment yield: with increased woodland area, sediment yield decreases.

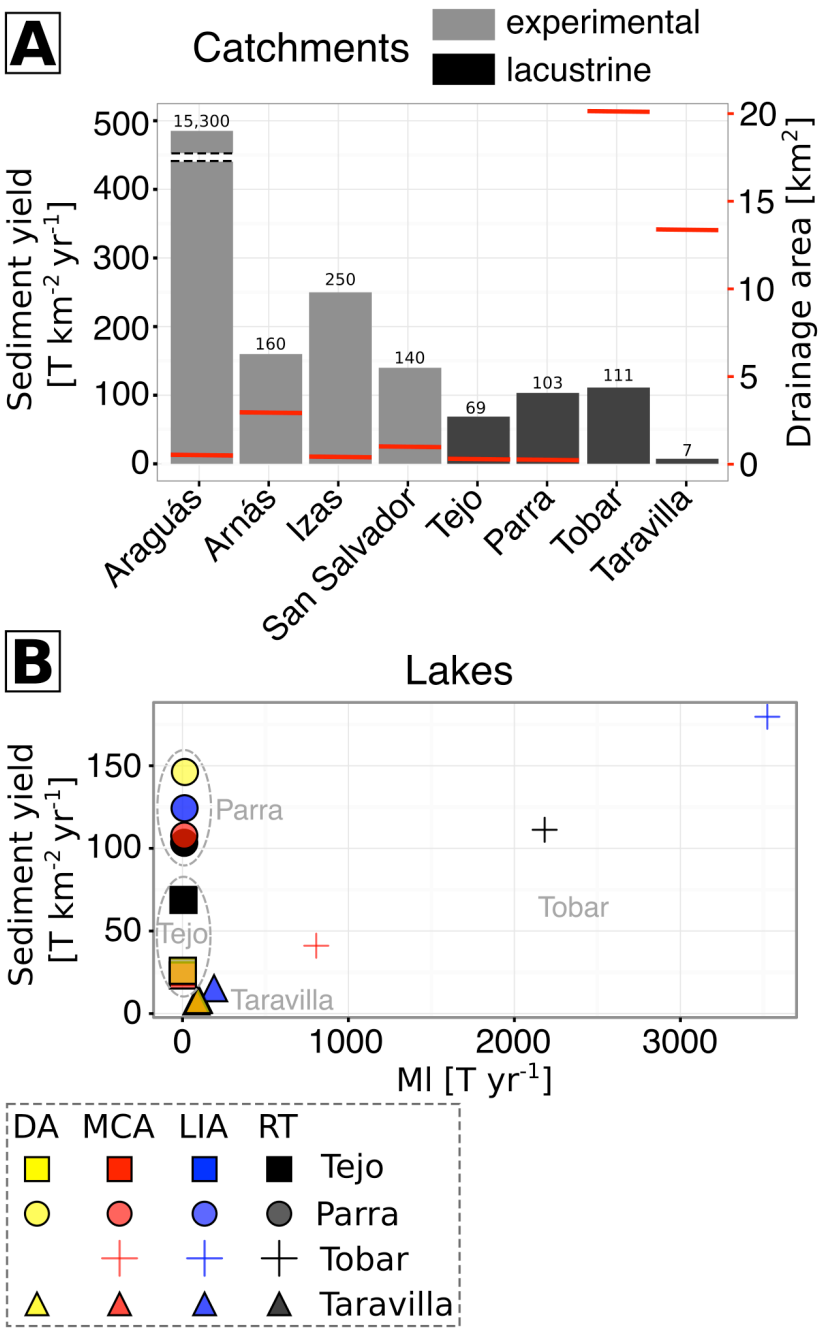

Figure 7. A) *Comparison between experimental catchments (grey bars) and lakes watersheds (black bars) sediment yield during the last 50 years (left ordinate and top-bar digits) and drainage area (right ordinate, red lines).* ***B)*** *Sediment yield versus mass accumulated for the lakes. Colors represent calculations for different climate periods from older to more recent: yellow, Dark Ages (DA, 500-900AD); red, Medieval Climate Anomaly (MCA, 900-1300 AD); blue, Little Ice Age (LIA, 1300-1850 AD); black, recent times (RT, 1960-2010 AD).*

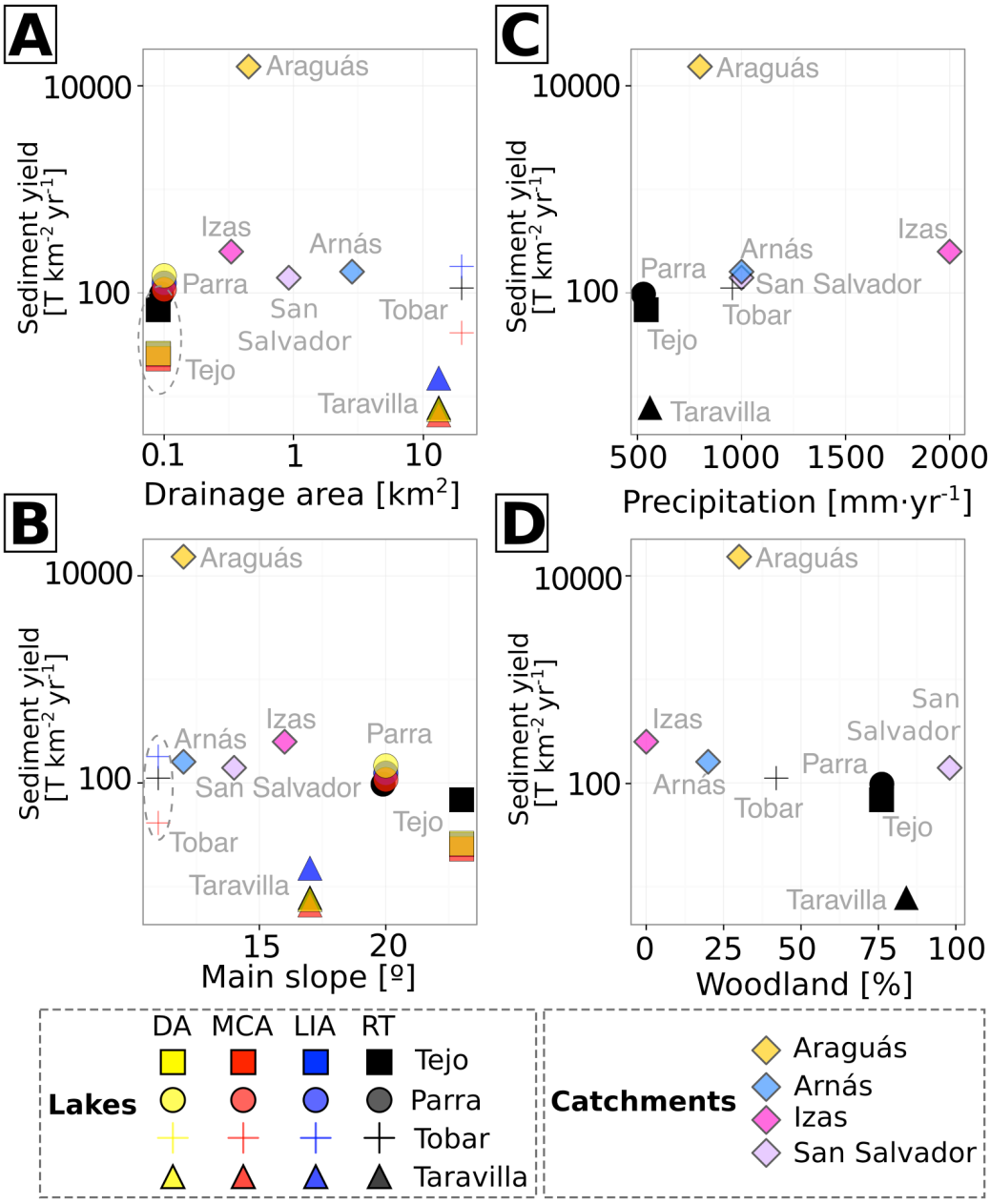

Figure 8. A) *Sediment yield related to the drainage area extension for lakes and experimental catchments.* ***B)*** *Sediment yield and mean watershed slope relationships.* ***C)*** *Sediment yield relationship with precipitation.* ***D)*** *Sediment yield relationship with woodland area cover. Lakes are represented by squares (El Tejo), circles (La Parra), triangles (Taravilla) and crosses (El Tobar); experimental catchments are plotted as diamonds. For lakes calculations, colors represent different climatic periods: see caption from figure 7.*

4.3 Main sedimentary events

The sediment yield in the watershed for each sedimentary event from each lake has been calculated and plotted in *figure 9*. The watersheds with lower Sy during sedimentary events are El Tejo (20-34 T km^{-2} yr^{-1}) and Taravilla (6-26 T km^{-2} yr^{-1}), with slightly higher values for El Tejo. These values are in a similar range than the values recorded in the Izas experimental catchment sedimentary event during the exceptional rainfall event of 2012 (Lana-Renault et al., 2014; see *table 2* and *figure 9*). La Parra watershed, although higher in general, shows a similar Sy (94-195 T km^{-2} yr^{-1}) than El Tobar (64-100 T km^{-2} yr^{-1}) during the first sedimentary events in the period around 1500 CE. This Sy value is also comparable to that of the Arnás catchment during the same exceptional rainfall event of 2012. El Tobar values slightly increase with time. The second event period for El Tobar (1800-1900 CE) shows the highest Sy values for all the lacustrine watersheds and presents increasing Sy values from 1800 to 1850 CE and decreasing from 1850 to 1900 CE. The Sy for the Araguás experimental catchment for exceptional rainfall events includes very high values due to the large extension occupied by badlands.

5. Discussion

The inference of sediment yield from the lake watersheds during recent times (last 50 yeras) is based on the sediments effectively deposited in the lakes. Thus, it is probably underestimating the true sediment yield because the entire denuded sediment may not have reached yet the lake during the last 50 years. Most likely this is the reason why the sediment yield in the lake watersheds (Sy) are in general lower than the sediment yield obtained from the experimental catchments, as some sediments are stored in other areas on the watersheds and do not reach immediately the lake basin (*figure 7A*).

Our results show that the main factor affecting the sediment yield (Sy) appears to be linked more directly with the amount of precipitation and inversely with vegetation cover (see *figures 8C and 8D*). García-Ruiz et al. (2015b, 2008) also found that differences in runoff production are related to internal characteristics of the catchment, particularly rainfall intercepted and used by the vegetation and the particular physiographic characteristics (mainly effectiveness of transport networks). Consequently, vegetation is an important buffer for precipitation/discharge relationships and the main slope gradient does not show a clear pattern related to the Sy Previous reviews in Mediterranean catchments also highlight the relation between watershed area, dominant erosion processes and sediment yield (de Vente and Poesen, 2005; Nadal-Romero et al., 2012c, 2011). El Tejo and La Parra share similar characteristics, as both are flooded sinkholes in the same geologic and human disturbed context and with a similar lake size; but the relatively larger La Parra watershed is responsible for the larger sediment delivery to the lake.

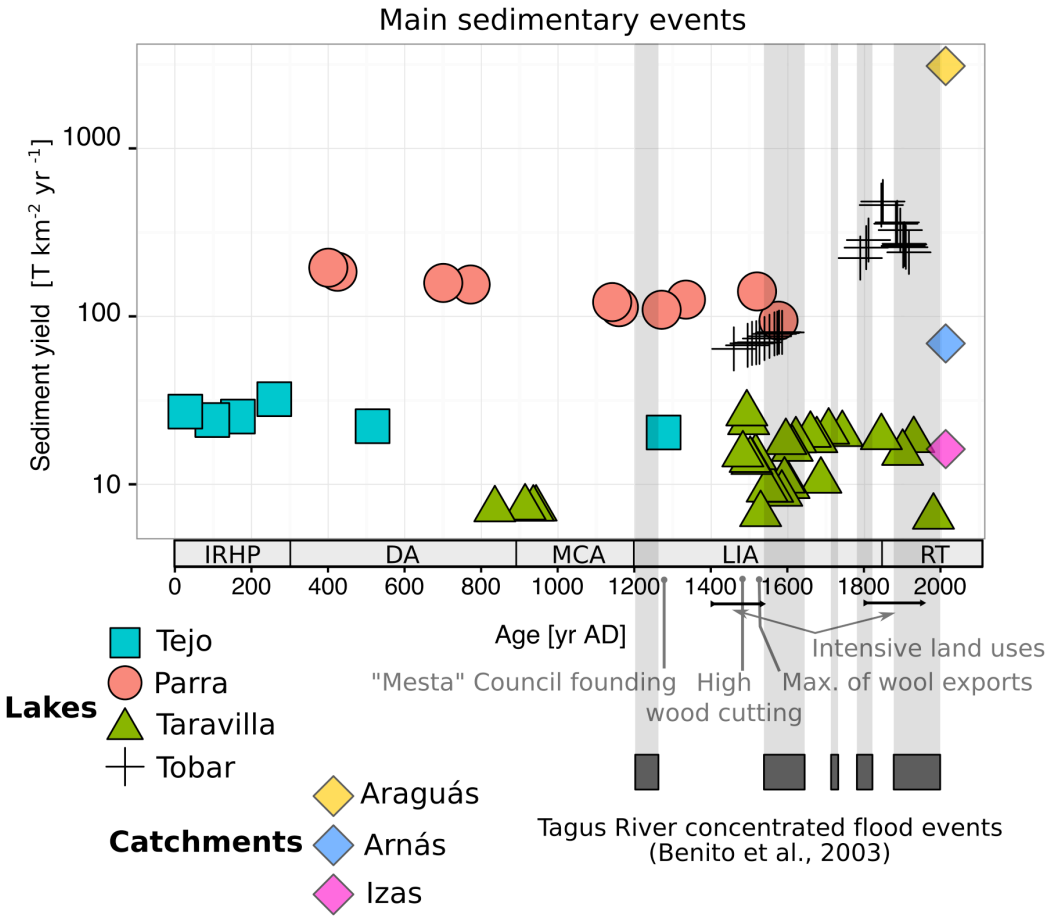

Figure 9. *Sediment yield for each lacustrine sedimentary event along the last 1000 years. Lakes: El Tejo (blue squares), La Parra (salmon circles), Taravilla (Green triangles), El Tobar (crosses). Diamonds represent experimental catchments including data from the exceptional 2012 rainfall (Lana-Renault et al., 2014): Araguás (yellow), Arnás (blue) and Izas (pink). Gray shadow rectangles mark the main Tagus River flooding event periods (Benito et al., 2003).*

However, it seems that the Sy is independent of the size of the drainage area, and the values are similar in all catchments, experimental or lacustrine, except for the Taravilla watershed with low values (*figure 8A*). The Taravilla and El Tobar lakes have much larger watershed sizes with more varied land covers than the other sites. Consequently both lakes store higher masses of sediments. The Taravilla watershed exhibits the lowest Sy among all these catchments, although the Taravilla Lake traps a relatively high mass of accumulated sediments. This may be related to the temporal storage of coarse-grained sediments in the bottom of the creeks draining the watershed (direct field observations), but also to the presence of a large palustrine vegetated area located at the NE margin of the lake (see table 1 and figure A2) serving as

an effective sediment barrier. This wetland may be acting as a sink or source of sediments depending on the intensity and energy of transport and erosion processes. Between flood periods, the sediments accumulate in the watershed (channels) and in the palustrine belt waiting to be transported into the lake during the floods. The El Tobar watershed has a variety of geomorphic areas (*figure 1*) that may be activated as sediment sinks and sources at different times depending of the environmental, climate and human conditions: sediment eroded from the highlands could be temporarily stored in the zones of changing slope and the valley bottom until conditions become favorable for their evacuation. The varied geochemical signature of some event in El Tobar sediments supports a varied provenance within the watershed (Barreiro-Lostres et al., 2015).

Differences in the hydrological functioning of the catchments (runoff generation processes and seasonality), the efficiency of the hydrological drainage nets and the provision of erodible landscapes (lithology and geomorphological landforms) would also account for differences in the Sy values. The San Salvador catchment has a relatively lower Sy than the other catchments likely due to its denser vegetal cover. The Araguás catchment has the highest Sy because a large percentage of its surface area is formed of badland regoliths. Exceptional rainfall events in the Araguás experimental catchment cause large Sy due to the presence of soft regolith and the occurrence of fast Hortonian runoff generation (Nadal-Romero and Regüés, 2010).

However as Lana-Renault et al. (2014) showed, catchments that have been subjected to farmland abandonment tend to have hydrological behaviors that are similar to forested catchments, although the hydrological activation of eroded areas, resulting from past agricultural uses, explains a significant contribution of overland flow, and subsequent intense hydrological and sediment responses. Comparing the experimental catchments with the lacustrine watersheds, we found that the Izas catchment -deforested during Medieval times to provide summer grasslands - the Arnás catchment - entirely cultivated until the 1950s - and the San Salvador catchment -covered by an undisturbed vegetal cover - all have similar range of Sy in the catchments. And interestingly, those values are similar to the four lacustrine watersheds affected by a long history of agriculture and livestock intensive uses.

Human activity has transformed the vegetation cover and landscapes deeply in Spanish Mediterranean mountains mainly by deforestation, the use land for crops, livestock or as wood resource for building (Esteban Cava, 1994; García-Ruiz, 2010; Ntinou et al., 2013; Simonneau et al., 2013). These activities have varied significantly both in time and space, providing heterogeneity in the hydrological response (Benito et al., 2015). All the lacustrine and experimental

catchments, except San Salvador, constitute a highly modified landscape by anthropogenic activities (agriculture and livestock industry) during the last 1000 years. As a consequence, significant impacts on runoff production, soil conservation and erosion should have occurred during the last millennium as vegetation cover has dramatically changed (García-Ruiz et al., 2015b). These landscape changes have been extraordinarily intense in the Castilian Branch of the Iberian Range during two periods, first from 1400 to 1600 CE and second from 1800 to 1950 CE (Esteban Cava, 1994). The first period comprised the time when cattle transhumance industry and the Mesta activity were most intense in the whole region, coincident with a peak of population in the city of Cuenca (see *figures 9 and 10*, used as an indirect measure of human occupation in less populated areas of the region) and a peak in the number of cattle heads in the Province. The second period of intense use of the territory coincides with another rapid population growth parallel to the industrialization and the consequent increased land use for crops or wood resources.

As previously observed (Bathurst et al., 2005; Boix-Fayos et al., 2006; Cammeraat et al., 2004; de Vente and Poesen, 2005) and García-Ruiz et al. (2015a) in experimental watersheds the denudation rates (DRt) vary in relation to spatial and temporal scale. We have found an inverse relationship between the size of the catchment and DRt in the lake basin, but only restricted to the recent times DRt (RT: 1900-2010). *Figure 10* shows that sedimentation in the El Tejo, El Tobar and Taravilla lakes depict relatively higher values of total denudation rate (DRt in cm yr^{-1}) during these two periods of increased human impact. The DRt is relatively low and constant between these two periods. Denudation of the Lake La Parra watershed is highest in an earlier period (300 to 700 CE), but also increases during these periods of higher anthropic disturbance. Historically, increased frequency of sedimentary events (*figure 9*) took place after an important period of regional increase in woodcutting and the maximum of grazing cattle transhumance documented by a peak in international wool exports around 1500 CE (Esteban Cava, 1994). The first and second period of increased sedimentary events in the largest watersheds, El Tobar and Taravilla, also coincides with two periods of regional intensive land uses, the first from 1400 to 1600 CE and the second from 1800 to 1960 CE (Esteban Cava, 1994). *Figure 10* illustrates how since 1900 to recent times a rapid increase of the DRt has occurred in the small lacustrine catchments (La Parra and El Tejo), while the opposite pattern is found in the large watersheds (El Tobar and Taravilla). This effect may be related to: i) the DRt during the LIA is higher for the larger watersheds, giving the appearance that DRt decreases fast; ii) the progressive and massive abandonment of the agriculture lands since 1950's linked to the revegetation of the larger watersheds, that has a higher impact in larger watersheds than in smaller ones.

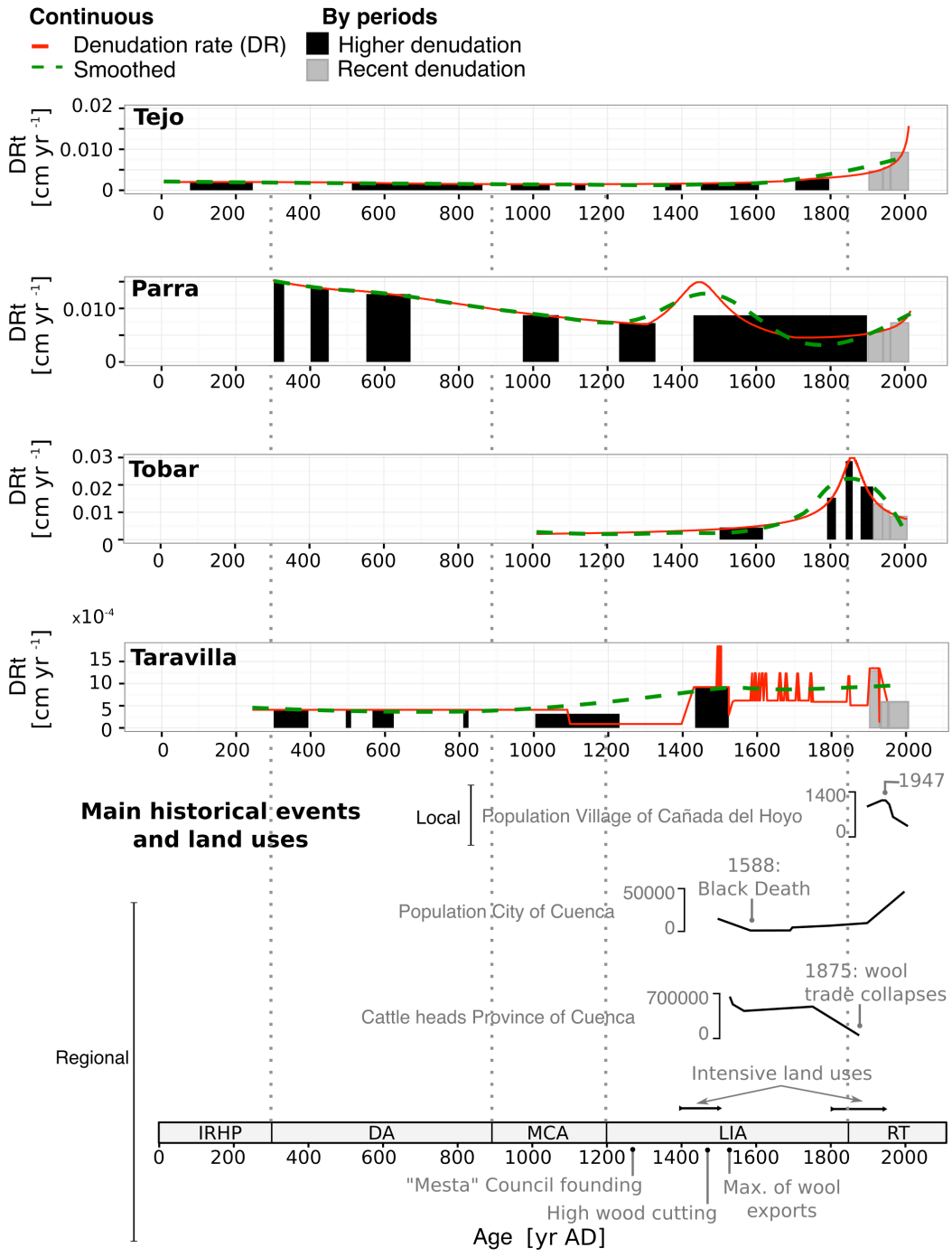

Figure 10. *Total denudation rates (DRt) for El Tejo, La Parra, El Tobar and Taravilla lakes during the last 1000 years (continuous pink line; dashed green line represent smoothed values). Sediment yield for periods of past higher denudation (black rectangles) and during recent denudation (grey rectangles) are also plotted. Below, main historical events, land use and population changes at local and regional scales are located along the time-line.*

From a paleoclimate point of view, higher denudation occurred in all watersheds during wetter climatic periods identified in the central part of the Iberian Peninsula (see figures 8 and 10): the Ibero-Roman Humid Period (IRHP), the Dark Ages (DA) and the Little Ice Age (LIA) (Martín-Puertas et al., 2008; Morellón et al., 2011; Moreno et al., 2012). Comparing the Sy with the paleoclimate periods described for the Iberian Peninsula, it seems evident that all the watersheds show sedimentary events during the LIA and those were greatly reduced during the MCA. Although only the smaller watersheds (El Tejo and La Parra) span a longer period of time, it is noticeable that their records show higher frequency and intensity of sedimentary events both prior to the Medieval Climate Anomaly (MCA) and during the first stages of the Little Ice Age (LIA). The larger watersheds (El Tobar and Taravilla) experienced the largest increase in frequency and intensity of events during the last part of the LIA and until recent times. Also, these events coincide chronologically with periods of concentrated flooding in the Tagus River (Benito et al., 2003, see *figure 9*). Both the El Tobar and the Taravilla lakes are in the Tagus River Basin and La Parra and El Tejo are close to the headwaters of this river, so a comparable hydrological behaviour is likely. During the first flooding events documented in the Tagus River (1200-1230 CE), sedimentary events in the El Tejo and La Parra lakes started again after a period of inactivity from 800 to 1100 CE. The other four Tagus River flooding events (1560– 1620; 1700–1720; 1740–1810; 1860–2000 CE) match with the highest frequency of events at Taravilla and El Tobar lakes.

If we focus on the period with historical information of landscape management - since 1200 CE - the phases of higher mass denuded in the catchments (main sedimentary events, *figure 9*) or increased denudation rate in the catchments (*figure 10*) coincide with the main territory management changes, but also match with wetter periods of major hydrological activity (LIA, Tagus River flooding periods). That is a clear indication of positive synergies between human impact and humid periods leading to increased sediment delivery and denudation. Therefore, as Benito et al. (2015) also showed, human impacts on runoff and sediment production at a catchment scale in small basins cannot be omitted at least over the last millennium.

The experimental catchment data have indicated that intense but infrequent flood events mainly control the sediment yield (Lana-Renault et al., 2014). For that reason, there is a large uncertainty in the estimation of long-term sediment production from a given catchment, and this is of critical importance for the management of the landscape-associated resources (water reservoirs, land use changes, abandon of cultivated lands, re-vegetation practices, etc.; Lasanta et al., 2015). The lakes sequences demonstrate that on longer time-scales, sediment delivered during events constitute a major

proportion of total sediment yields. The reconstructed values for the main sedimentary events during the last 2000 years for El Tejo and La Parra and during the last 1000 years for El Tobar and Taravilla catchments (*figure 9*) provide a range for sediment yield: small watersheds (El Tejo and La Parra) present narrower range of values, while relatively larger watersheds (El Tobar and Taravilla) present a wider range of values. This behavior highlights that the watershed size plays an important role in the buffering of production and transport of sediments, as a larger variety of surface accumulations and geomorphic areas occur in larger watersheds. But also the internal characteristics of each watershed (vegetation, connected hydrological channels, rock type, slope) are able to modulate better the responses to environmental changes in the large watersheds than in the small ones. Consequently, in small watersheds different environmental impacts may cause similar responses, while in large watersheds they may produce even wider range of responses.

The reconstructed values for erosion dynamics during the last millennia also help to better constrain the behavior of the watersheds at longer time scales. If environmental, climate and human conditions do not vary beyond the ranges during the last millennia in the studied areas; future sedimentary events should remain within the range of reconstructed values of mass denuded in the catchment and total mass accumulated for each lake.

The long-term erosion series also serve to put in context the recent changes in the Spanish Mediterranean Mountains. Mediterranean mountains were intensely cultivated in the past, but since mid the 20th century are affected by progressive farmland abandonment. As a consequence, most of these areas have become marginal and subject to different degrees of regrowth of shrubs and forest and afforestation practices (Lasanta et al., 2015). Such a large-scale land-cover change has had a significant impact on the availability and quality of water resources and on soil erosion and conservation. In general, sediment sources have diminished spatially and channel incision processes are occurring now. The results obtained in experimental catchment studies (Lana-Renault and Regüés, 2009; Nadal-Romero et al., 2013) are consistent with other studies in the Mediterranean region, and confirm the strong influence of land use changes on runoff generation and sediment yield. They have demonstrated a decrease in both erosion rates and runoff coefficient, as abandoned fields have been progressively re-vegetated, and as plant cover is a key factor influencing runoff generation and sediment output.

As expected from the large land use changes during the last century denudation has been progressively decreasing in the large watershed (El Tobar and Taravilla). However, it has increased in the small watersheds (El Tejo and La Parra). That contrasting behavior may reflect that farmland abandonment

and afforestation are more intense on large watersheds. In small-scale watersheds with high slope gradients as occurs in El Tejo and La Parra lakes, the effect of land abandonment and re-vegetation remains comparatively less important than climate factors. In the Cuenca region, seasonal rainfall and temperature show significant inter-decadal variability for the last 50 years. Annual rainfall variability is mainly caused by year-to-year differences in winter precipitation, highly correlated with the phase of the North Atlantic Oscillation (NAO) (Romero-Viana et al., 2008). Meteorological records show a small mean annual temperature increase (~2 °C) and a significant mean annual precipitation decrease since 1980s, from 1600–1200 to 1000–800 mm, and some evidence of increased storminess and more frequent heavy rain events. Therefore changes in the intensity and/or seasonality of the precipitation events may have had a strong impact on erosion and transport processes affecting the sediment yield in smaller basins, while in large basins, recent changes in land uses remain the controlling factor in erosion dynamics. These relationships between changes in rainfall patterns and sediment delivery implore further exploration in other lake basins.

6. Conclusions

A new methodology based on the methods described in Einsele and Hinderer (1998) has been implemented to calculate the mass accumulated in the lakes (Ml), the minimum sediment yield from the watersheds (Sy) and the total denudation rate (DRt) along the last millennium in four lake watersheds in the Western Branch of the Iberian Range. The results show a large range of values comparable to those measured in monitored Mediterranean mountain catchments in the Central Pyrenees during the last decades. In both settings, lakes and experimental catchments, most sediment delivery occurs during flooding events, underlying the punctuated nature of sediment dynamics in Mediterranean landscapes at decadal and centennial scales. The sediment yield (Sy) in all the watersheds, lacustrine and experimental, have a comparable range of Sy values for the last millennium independent of watershed size.

Precipitation (rainfall intensity, seasonality, runoff production) and land cover (forested area, degraded areas, land uses) are key factors controlling erosion in both experimental and lake watersheds. Major periods of sediment accumulation in the lakes and denudation in the catchments in the studied area during the last two millennia correspond with cooler and wetter phases (Roman and Dark Ages, 0-800 CE and LIA 1200-1850 CE) but are also detected earlier, during the Middle Ages in relation to increased human pressure in the catchments corresponding to the development of the Mesta and deforestation for grazing (12th-13th centuries).

The synergetic effects between climate and humans were particularly intense at the onset and the second part of the Little Ice Age and since the 18th

century, when the climate impact was amplified by human disturbance, resulting in higher sedimentary rates, mass of sediments accumulated in the lakes and, denudation rates in the catchments.

After the peak in erosion during the late 19th century, farmland abandonment and consequent revegetation has reduced runoff, erosion and sediment yields, particularly in the larger watersheds. In the smaller watersheds, revegetation and changes in land use are smaller and recent changes in rainfall seasonality and increase in storminess may account for increased sediment delivery to the lakes.

Most sediment delivery occurs during flooding events. The reconstructed sediment stored in the lakes during these events spans several orders or magnitude (less than 100 T to 98x10^3 T) and the denudation rate from 6 to 480 T km^2 yr^{-1}. Reconstructed sediment yield values per event in the Taravilla Lake catchment (forested) and El Tejo (smallest surface area) are similar (less than 30 T km^2 yr^{-1}) to sediment yields from high altitude experimental watersheds (Izas). Flood sediment yield values from Arnás experimental catchment (abandoned farmland) (69 T km^2) are in the lower range of La Parra and El Tobar (from 60 to 480 T km^2 yr^{-1}). No lake watershed has reached the values documented for the badland Araguás catchment (3094 T km^2). As in experimental catchments, surface area and vegetation cover exert a greater control than precipitation or mean slope. During wetter phases (LIA), higher flood frequency and intensity increased sediment delivery in lake watersheds with limited human intervention (Taravilla). Positive synergies between higher human pressure and more water available were responsible for the peak in erosion during the 19th century.

This study of sediment denudation and accumulation from four lacustrine watersheds of the Serranía de Cuenca with similar climatic and physiographic features reveals an important degree of variability in the sediment accumulation but similar response in terms of temporal frequency and intensity of catchment erosion. The results highlight the critical effect of the catchment size related to the amount of sediments that reach the lakes and confirm the paramount role of vegetation cover and land use changes as main controls of erosion in Mediterranean watersheds at centennial scales.

Our strategy to quantify erosion at centennial scales based on sedimentary sequences from lakes provides long-term series of sediment dynamics beyond the studies of experimental plots and watersheds studies. This approach is essential to understand the evolution of sediment denudation and accumulation processes along time in highly human disturbed areas and key to improve predictions of the impacts of recent socio-economic and climate changes and to design sustainable management policies.

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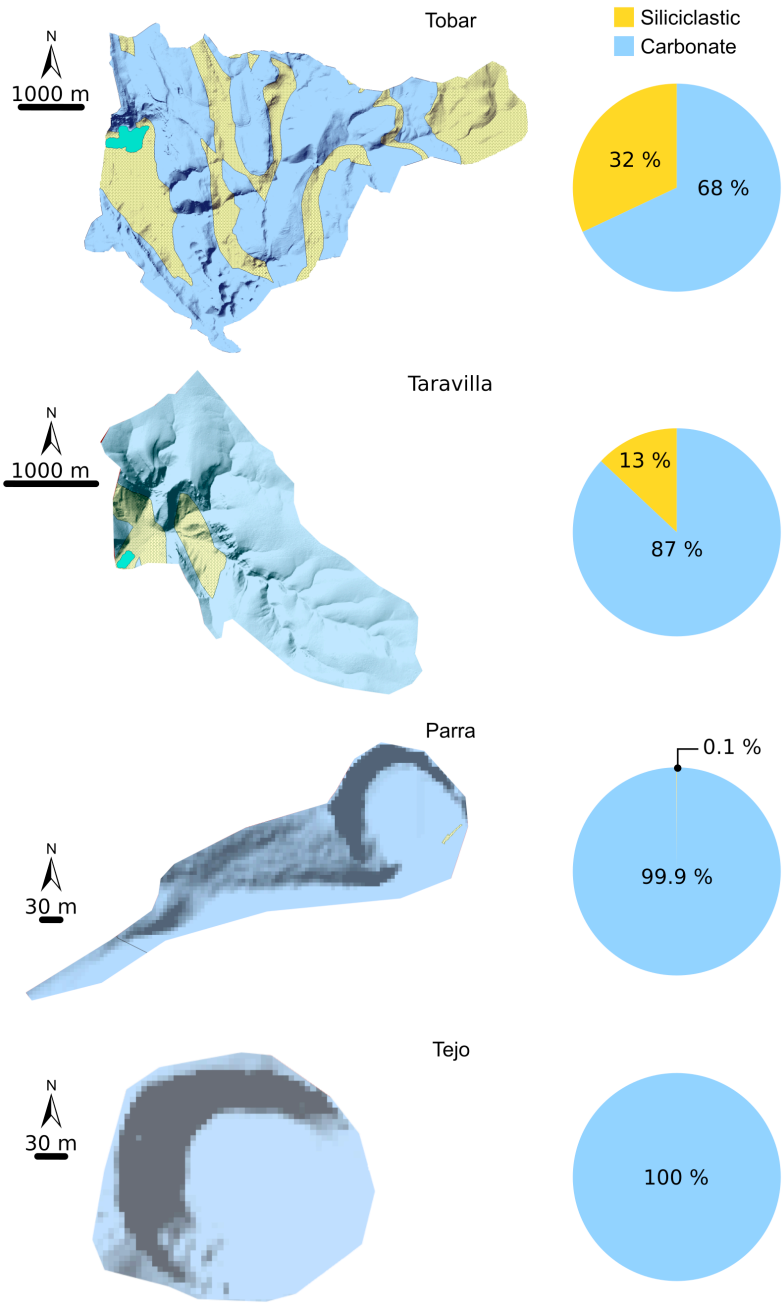
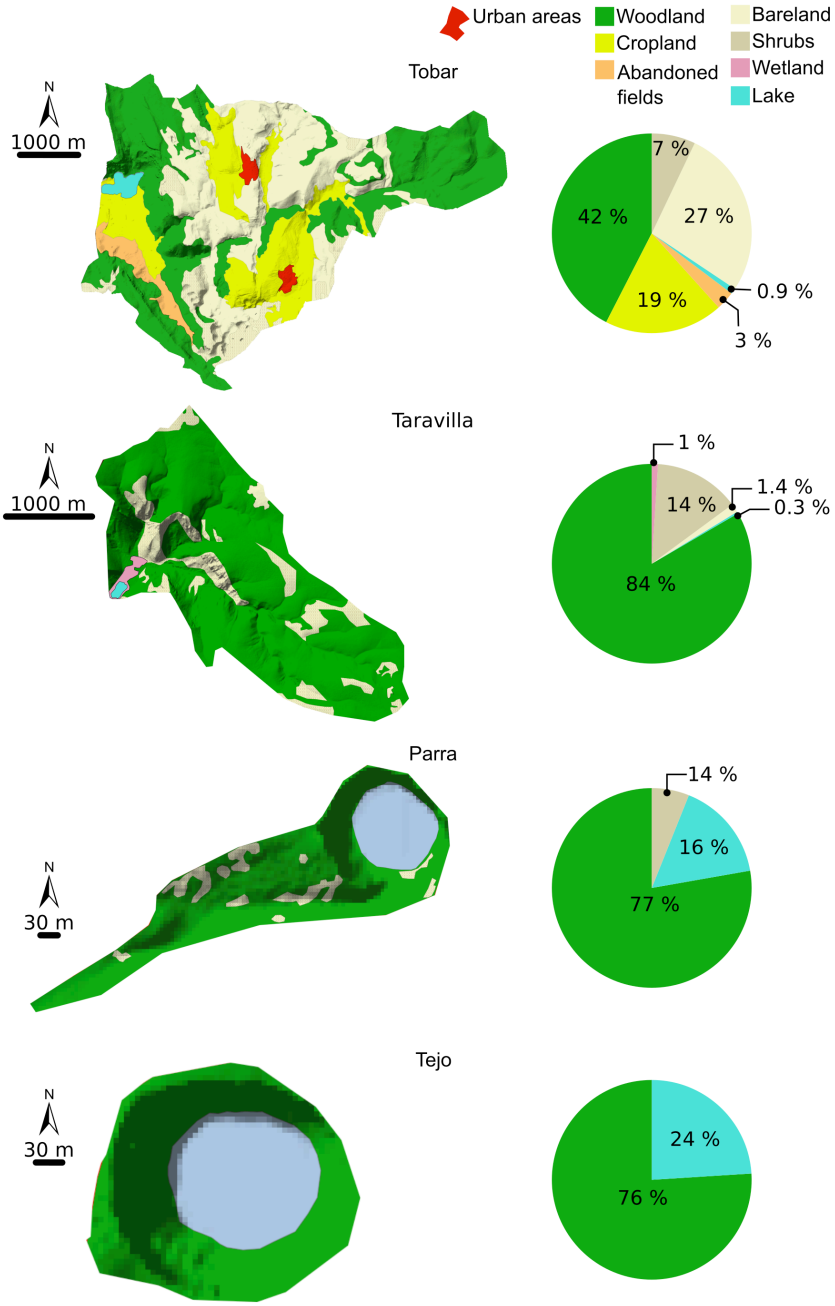


Supplementary figure A1. *Topography of lacustrine watersheds showing the area cover and percentages occupied by siliciclastic (yellow) and carbonate (blue) rocks.*



Supplementary figure A2. *Topography of lacustrine watersheds showing the main land use covers and their respective percentages.*

A3. El Tejo sequence

A3.1 Methodology

In May 2011, two long parallel piston cores (TEJ11-1A-U and TEJ11-2A-U) and two replicates from the latter site (TEJ11-2B-U and TEJ11-2C-U) were recovered in the deepest part of the lake with the IPE-CSIC UWITEC platform and coring equipment. Four short gravity cores were also retrieved to preserve the water-sediment interface. One of these cores (TEJ11-2C-1G) was sampled in the field for ^{210}Pb essays.

Once the cores were split in the laboratory for sedimentological analysis, core TEJ11-2B-U and section TEJ11-2C-4U were analyzed for semi-quantitative XRF at 5 mm of resolution using an X-ray-current of 2000 µA, with two-runs at 10 kV and 30 kV X-ray-voltage at 15 s and 25 s of exposure time-respectively per measurement point.

Core TEJ11-2B-U was sub-sampled and analyzed every 2 cm for Total Organic Carbon (TOC), Total Inorganic Carbon (TIC) and Total Nitrogen (TN) with a FLASH EA 1112 LECO TRUSPEC-CN at the Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC, Spain).

A Principal Component Analysis (PCA) was carried out to investigate the relationship between the chemical elements present on the sediments by using R software 3.2.0 (R Development Core Team, 2014) and the package FactoMineR 1.29 (Lê et al., 2008). The dataset includes XRF analyzed-elements with more than 1500 cps (counts per second) to maximize the quality of the results, and also bulk geochemistry (TOC, TIC and TN; see *figure A3 B*). The XRF data were re-sampled from the original resolution of 0.5 mm to 2 cm (LECO resolution) to compare both datasets. All variables were normalized with respect to their mean and standard deviation. A final dataset with 11 variables per 240 samples was constructed.

Mineralogy also was analyzed in the core TEJ11-2B-U every 10 cm by a Siemens D-500 x-ray diffractometer (Cu kα, 40 kV, 30 mA, graphite monocromator) at the Serveis Científico-Tècnics of the ICTJA-CSIC (Spain). Identification and relative abundance of the predominant mineralogy of the crystalline fraction were determined following Chung (1974a, 1974b).

The age model for Lake El Tejo is based on 12 radiocarbon dates from wood macro-rest samples, analyzed at Direct-AMS (US-WA) and BETA (US-FL) laboratories. Two samples were previously split and also sent to the Poznan laboratory (Poland) to double-check the results (see *table A2*). The uppermost sediments of the sequence were recovered in the short core "TEJ11-2C-1G" and correlated with the uppermost part of the composite long core using TOC values (see *figure A3 C*). ^{210}Pb profiles were obtained in the short core by gamma ray spectrometry at the St. Croix Watershed Research Station (US-MN), following (Appleby, 2001). The final El Tejo sequence age model was performed

with Clam 2.2 code (Blaauw, 2010) and is based on the 12 radiocarbon dates from the long core and on ^{210}Pb essays from the short core. Only two of the wood samples were discarded because they were stratigraphically inconsistent (too old), probably due to sediment reworking. The final age-depth curve, after different fits with several regression models, was adjusted with a degree 3 polynomial regression from the top of the core until a depth of 467 cm. From 467 to 600 cm, a linear regression model was applied.

A3.2 Sedimentary facies and units

The El Tejo composite sedimentary sequence is 590 cm long. Visual sediment description of texture, structures and composition; smear slide observations, mineralogical analyses and geochemical composition indicate that sediments are mostly composed of terrigenous carbonate grains with a relatively homogenous geochemical composition (*figure A3*). Dolomite is the main constituent of the mineral fraction (50-90%), followed by calcite (10-20%) and silicates (5-10%). Clay mineral content is low (<5%), except in some fine-grained intervals (up to 15%). Pyrite is present in most laminated facies.

MS values are low and even negative due to the dominant carbonate nature of the sediments. Magnetic susceptibility (MS) and density (ρ) show similar trends, with the lowest values at the base, the highest values in the middle sections and low, but with a large variability at the top. Higher values are associated with coarser sediments.

Despite the relatively small lake size, nine different facies have been described, ranging from microconglomerates (see *table A1*, facies 3.1); coarse, fine and very fine sands (facies 2.3, 2.2 and 2.1 respectively); coarse, medium and fine silts (facies 1.5, 1.4, and 1.2 and 1.1 respectively); to finely laminated silts (facies 1.3). As occurs in the La Parra Lake (Barreiro-Lostres et al., 2014), where deposition is controlled primarily by changes in the carbonate watershed and secondly by lake variability, clastic carbonates constitute the main sediment type: coarser facies represent deposition in littoral environments while finer facies indicate more distal settings, both influenced by variable lacustrine reworking and intensity of runoff processes. The presence of microconglomerates (facies 3.1) and coarse sands in the central areas of El Tejo Lake suggests periods of increased erosion and run-off during likely lower lake levels. Massive and banded silts represent distal to sublittoral depositional settings; and finely laminated silts (facies 1.3) are deposited under dominant anoxic conditions in the lake bottom, associated with higher lake levels or limnological conditions prone to more frequent water stratification (Julià et al., 1998; Valero-Garcés et al., 2014).

The El Tejo sediment record is structured in five sedimentary units composed of finning-upward sequences (*figure A3*). The basal unit V (590-490

cm) is organized in four finning-upward subsequences constituted by sands at the base and silts at the top. Unit IV (490-410 cm) starts with the deposition of microconglomerates followed by the alternation of sands and silts culminating with the sedimentation of silts rich in organic matter remains (facies 1.1). Three finning-upward sequences made up unit III (410-240 cm): the basal one ranges from microconglomerates to fine organic rich silts (facies 1.1); in the middle one, coarse silts are dominant; and the top one is comprised of alternating coarse sands and silts topped by facies 1.1. The lower half of Unit II is comprises by alternating coarse silts and facies 1.1 and the upper part by fine silts. Unit I starts with microconglomerates and coarse sands and silts grading upwards to coarse and finely laminated silts. It is noticeable than only units II and I present fine laminated silts (facies 1.3).

A3.3 Geochemistry

TIC shows mean values around 10%, with the lowest values (around 5%) in units IV and III. TOC presents an opposite trend, with highest values (15-20%) in unit III. In general, TOC peaks coincide with fine silts rich in organic matter (facies 1.1) and with fine laminated silts (facies 1.3). Mean TOC/TN values are about 15, with higher values (20-30%) at the base of units IV, II and I. Unit III and top of unit I have the lowest TOC/TN values (≤10).

The first principal component (PC1, see *figure A3 B*) of the PCA explains 42% of the total variance and in the positive end concentrates the elements related to siliciclastic sedimentary inputs (Fe, Si, Ti, K, Rb) and also to detrital carbonate inputs (Ca, TIC). The negative end of the PC1 is linked to the elements related to the organic fraction of the sediments (TOC, S). The second principal component (PC2) represents the 21% of the total variance and groups at the positive end the elements related to the siliciclastic inputs and at the negative end the detrital carbonate inputs.

Supplementary Table A1. *El Tejo record sedimentary facies: description, composition and depositional processes and environments. TIC and TOC are averaged values for each facies.*

Lithology	Facies	Description	Depositional Processes	Depositional Environments
Silts	**1.1 *Fine organic dark silts***	Dark brown, banded, carbonaceous fine silts with abundant aquatic amorphous organic matter (25%), diatoms (10%) and pyrite spherules (5-10%). Detrital carbonate grains (5%) are sharp and corroded. Trace quartz, pollen grains and insect parts are found. They occur in few 1-2 cm thick layers with net boundaries. TIC: 9 % TOC: 5 % TOC/TN: 13 %.	Low energy tractive currents and out of suspension. Frequent redox changes	Profundal-offshore zone with alternating oxygenated and anoxic conditions
	1.2 *Fine light silts*	Light grey, massive, carbonatic fine silts with gastropod and ostracods remains and quartz (10%. Detrital carbonates (50%) are fine and well sorted, presenting sharp limits. They are disposed in 2-20 cm layers with dark coloured at the top. TIC: 10 % TOC: 4 % TOC/TN: 12 %.		
	1.3 Fine laminated silts	Dark and light laminated carbonatic fine silts, bad preserved, and disposed in 1-5 cm thick sets with diffuse boundaries. TIC: 9 % TOC: 5 % TOC/TN: 10 %.	Out of suspension autochtonous organic deposition	Profundal-offshore areas, seasonally anoxic
	1.4 Medium brown silts	Brown, massive, carbonatic medium silts with quartz (5%), organic matter (10%: aquatic amorphous and aquatic vascular plant fragments) and diatoms (5%). They present some ostracod and gastropod remains. TIC: 9 % TOC: 6 % TOC/TN: 12 %.	Low to moderate energy tractive currents. Littoral sediments reworking	Offshore to proximal zone. Moderate depth. Oxygenated conditions
	1.5 *Coarse brown silts*	Brown, massive, carbonatic medium to coarse silts with ostracods, diatoms (10%) and amorphous organic matter (5%) and calcite (5%). Trace quartz, pollen grains and insect parts have been described. Detrital carbonates are angular and poor sorted. They occur in 1-10 cm beds. TIC: 9 % TOC: 6 % TOC/TN: 11 %.		

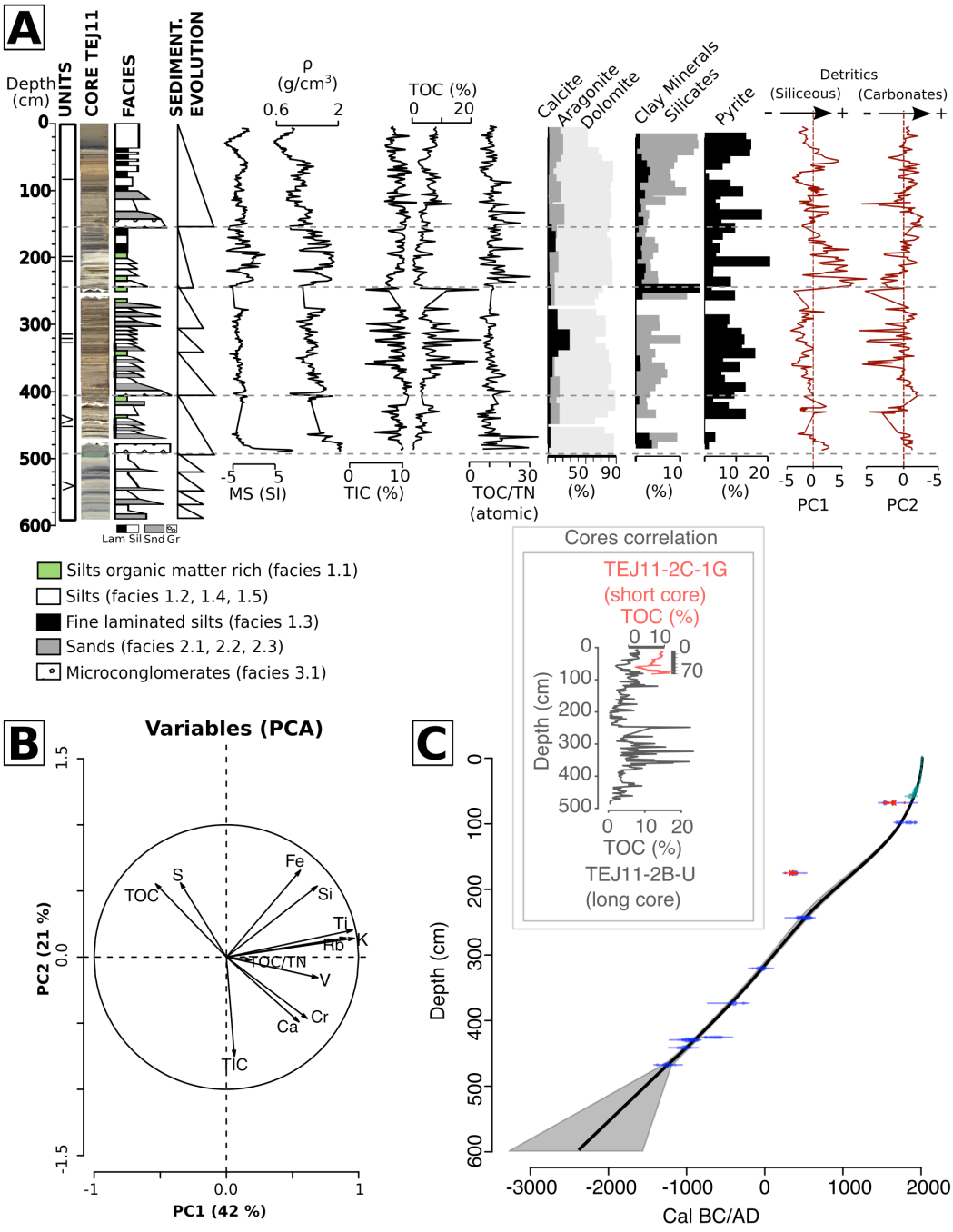
Sands	**2.1** ***Very fine brown sands***	Brown, massive, carbonatic very fine sands with aquatic amorphous organic matter (15%), broken diatoms (1%) and gastropod and ostracod remains. Detrital quartz (5%) and carbonate (20%) grains are sharp. They are present in 5 cm thick beds with diffuse boundaries. May present white carbonatic clasts of about 2mm diameter. TIC: 9 % TOC: 8 % TOC/TN: 13 %.	Medium to high-energy runoff processes with littoral sediments reworking	Proximal to littoral shallow areas
	2.2 ***Fine grey sands***	Grey, massive, fine sand with quartz (20%), detrital sharp carbonates (10%) with aquatic amorphous organic matter (5%), ostracods and trace diatoms and insect parts. They occur in 2-5 cm layer with diffuse limits and irregular bottom. TIC: 9 % TOC: 7 % TOC/TN: 11 %.		
	2.3 Coarse brown ***sands***	Brown, massive, coarse carbonatic sands with quartz (5%), corroded detrital carbonate (10%) with diatoms (10%) and ostracod and gastropod fragments. TIC: 9 % TOC: 5 % TOC/TN: 12 %.		
Micro-conglo-merates	***3.1 Fine to medium brown microconglomerates***	Brown, massive, medium to coarse carbonatic microconglomerate with white sharp pebbles < 5mm diameter in a brown fine to coarse carbonatic silt matrix. They present fragmented gastropod and ostracod remains. Boundaries are net and very irregular. TIC: 10 % TOC: 4 % TOC/TN: 12 %.	High-energy runoff and tractive currents. Intense littoral sediments reworking	Littoral shallow zones

Supplementary Table A2. *Radiocarbon dates used for the construction of the age model for El Tejo record. Dates were calibrated using Clam 2.2 software (Blaauw, 2010) and the IntCal13 curve (Reimer et al., 2013). The 2**σ** probability interval was selected. Dates with * were discarded (stratigraphically inconsistent).*

Composite core depth (cm)	Laboratory code	14C AMS age (BP)	2σ calibrated age (cal. yr. AD/BC)	Material
68	D-AMS 008006	277 ± 25	1556 ± 37*	Wood
98	D-AMS 008004	130 ± 25	1847 ± 47	Wood
175	D-AMS 1217-108	1664 ± 26	378 ± 47*	Wood
243	Poz-47637	1590 ± 30	473 ± 67	Wood
243	D-AMS 1217-109	1518 ± 23	568 ± 37	Wood
320	D-AMS 008005	2035 ± 28	-43 ± 70	Vegetal remains
373	D-AMS 008003	2309 ± 30	-384 ± 27	Wood
425	D-AMS 1217-111	2490 ± 28	-654 ± 121	Wood
429	D-AMS 1217-110	2766 ± 23	-892 ± 53	Wood
429	Poz-47638	2835 ± 30	-986 ± 74	Wood
441	BETA 301273	2860 ± 30	-1043 ± 75	Wood
467	D-AMS 1217-112	3008 ± 27	-1247 ± 58	Wood

Supplementary Table A3. *La Parra-El Tejo facies correlation. Density (ρ) is the averaged value for each facies measured in El Tejo sedimentary sequence with the Geotek MCL.*

Lithology	La Parra facies	El Tejo facies equivalent	Average ρ (g/cm3)
Silts	1.1B Fine black silts	1.1 Fine organic dark silts	1.5
	1.1A Fine grey silts	1.2 Fine light silts	1.6
	4 Fine laminated silts	1.3 Fine laminated silts	1.2
	1.2 Medium brown silts	1.4 Medium brown silts	1.1
	1.3A Coarse light grey silts 1.3B Coarse dark grey silts	1.5 Coarse brown silts	1.4
Sands	2.1 Fine green sands	2.1 Very fine brown sands	1.4
	2.2 Medium brown sands	2.2 Fine grey sands	1.3
	2.3 Coarse brown sands	2.3 Coarse brown sands	1.5
Microcon-glomerates	3.1 Fine brown gravels 3.2 Medium brown gravels	3.1 Fine to medium brown microconglomerates	1.4



Supplementary figure A3. A) *Sedimentary units, core image, sedimentary sequence and evolution with main geophysical (Magentic Susceptibility and Density) and geochemical proxies (Total Inorganic Carbon, Total Organic Carbon, C/N ratio, main mineral composition and two first PCA axis) for El Tejo record.* ***B)*** *Principal Component Analysis (PCA) including LECO and XRF geochemical analyses.* ***C)*** *Age model for El Tejo sequence spanning the last 4000 years. The long-core and short-core correlation based in TOC analysis is also shown.*

5

General Discussion

This section summarizes, integrates and highlights the implications of main results described in the research articles from the Results section. To focus the discussion according to the objectives planned in the Introduction section, it has been itemized in five main points. First the main controls affecting the lake and watersheds dynamics of El Tejo, La Parra and El Tobar systems: the sedimentological processes and main depositional environments (*subsection 5.1.1*). Second, the main paleohydrological, environmental and climatic implications based on the reconstruction from the sedimentary sequences (*subsection 5.1.2*). The third aspect discusses the relationship between historical land-use changes and anthropogenic impact and depositional dynamics in the lakes, particularly related to sediment budgets (*subsection 5.1.3*). The following *subsection 5.2* summarizes the quantitative approach for sediment input events and erosion in the watersheds. In the last *subsection 5.3* a general overview of the findings on climate-human synergistic relationships for mountain watersheds dynamics is presented.

Boarding of the coring platform in Lake La Parra.
Abordaje de la plataforma de sondeos en la Laguna de La Parra.

5.1 Controls on karstic lake-watersheds dynamics

5.1.1 Depositional evolution

5.1.1.1 Carbonate sources and processes

In the three studied lakes, the sediments reflect accurately the carbonatic geology of the watersheds. Thus, carbonates are the main component of the lacustrine sediments although the lake sequences are characterized by a large variability of facies with abrupt lateral and vertical changes. These carbonates have three main origins: chemical, biogenic and clastic.

- Chemical: Carbonate precipitation as consequence of direct chemical water concentration has been considered a main process in many freshwater and saline lakes (Valero-Garcés et al., 2014 and references therein). However biological activity (microbial, algal, macrophytes) usually plays a significant role, therefore direct chemical precipitation is usually a minor process in carbonate formation. In the three studied lakes although carbonate content in the waters is high, there is not evidence of supersaturated carbonate phases, and most likely biological activity is the trigger for most of the endogenic carbonate formation.

- Biogenic: Biogenic-mediated carbonate precipitation occurs in several depositional environments in karst lakes (Valero-Garcés et al., 2014). Littoral sediments from El Tejo and El Tobar present ostracod and gastropod remains respectively. Carbonate coatings around plants and nearshore vegetation have been observed in the three lakes, but they are likely minor contributors, as littoral zones are not very well developed due to its narrowness as described in Article 1 (*section 4.3*). In the distal zone, calcite laminae in varved facies have been found in El Tejo and La Parra, although varved intervals are thin (centimeter intervals) and only well preserved in El Tejo. A continuous varved interval since 1700 CE has been described in the nearby Lake La Cruz (Romero-Viana et al., 2011, 2008; Romero et al., 2006). Whitings in lake waters provoked by calcite precipitation have only been observed yearly in La Cruz and occasionally in El Tejo. Laminated organic facies from El Tejo include euhedral calcite grain, confirming the relationship between biological activity and carbonate formation.

- Clastic: The major proportion of sediments in the sequences of the three studied lakes corresponds to clastic carbonates ranging from gravel to clay size. The lakes have a karstic origin, 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. Clastic carbonate sediments present a relatively large facies variability depending on texture (lamination), grain-size, the proportion of carbonate and silicate minerals, and the presence of organic matter, lacustrine fossils, soil agglomerates, etc. Facies variability is controlled mainly with the amount of

carbonate particles reaching the lakes from the catchments and the depositional environment in the lake. Clastic carbonate inputs depend on several factors, as the size of the lake and the watershed, the availability of erodible sources and the type and energy of sediment transport processes involved, related to the nature of the drainage network. The availability of sediments in the catchment area of the three lakes is determined by the size of the watershed, geology, climate, vegetation cover, and during at least the last 1000 years, land uses and human impact. In this context, Lake El Tejo, that presents a small watershed with no surface drainage network, have reduced clastic input, mostly as coarse materials derived from physical erosion of the steep cliffs forming the doline. Lake La Parra, of similar size but with a larger watershed drained by a small ephemeral inlet, presents coarser facies. Lake El Tobar, with the largest watershed, is dominated by clastic facies, particularly fine-grained.

A noticeable characteristic of the studied lakes is the large increase in clastic input during historical times, particularly since the Medieval epoch, mainly caused by deforestation and changes in land uses in the watershed. A similar trend has been documented in other Iberian lakes (Valero-Garcés et al., 2014 and references therein).

5.1.1.2 Controls on sedimentation

As stated above, the three studies lakes present a large facies variability, which is mainly controlled by hydrology and modulated by lake morphology, surface hydrology, watershed size, climate and water chemistry and thermal regime (Valero-Garcés et al., 2014).

The three lacustrine systems are in a karstic mature phase, as the sinkhole has been plugged with sediments and active karstic processes are greatly reduced. In this case, lake morphology and size imply variability in sedimentation patterns. Circular-shaped sinkholes with a funnel-shaped morphology as occurs with lakes El Tejo and La Parra, develop very steep margins and consequently very restricted littoral areas. On the other hand, Lake El Tobar has a relatively large basin with a larger littoral realm. These differences are important, because 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. Similarly, the organic components in the littoral zone sediments are a mixture of terrestrial, submerged macrophytes and algal material, while in the distal environments the contribution of algal sources is higher.

Table 5.1: *Main characteristics of the lakes studied in this research, including physical, limnological and hydrochemical parameters and main literature references.*

Lake	*Geologic setting*	*Location (N, W decimal º)*	*Altitude (m a.s.l.)*	*Water surface area (km^2)*	*Max. depth (m)*	*Watershed surface area (km^2)*	*Hydrochemistry*	*Thermal regime*	*Surface hydrology*	*Main references*
El Tejo	Sinkhole, dominant carbonate formations	39.986618 -1.877637	1000	0.02	25	0.09	Alkalinity: 3.1 $mEqL^{-1}$ pH: 8.7 $[Mg^{2+}]>[HCO_3^{2-}]>[Ca^{2+}]$ EC: 540 μScm^{-1}	Monomictic Occasionally meromictic	Closed, Endorheic	Valero-Garcés et al. (2014); Barreiro-Lostres et al., 2016; this research
La Parra	Sinkhole, dominant carbonate formations	39.982557 -1.866921	1014	0.01	14	0.1	Alkalinity: 6.0 $mEqL^{-1}$ pH: 8.3 $[HCO_3^{2-}]>[Mg^{2+}]>[Ca^{2+}]$ EC: 335 μScm^{-1}	Holomictic	Closed, Endorheic	Barreiro-Lostres et al. (2013, 2014); this research
El Tobar	Sinkhole in carbonate/ gypsum formations. Two sub-basins.	40.544502 -2.049254	1200	Meromictic: 0.03 Holomictic: 0.14	Meromictic: 20 Holomictic: 12	10.8	Hypolimnion: Alkalinity: 4.3 $mEqL^{-1}$ pH: 7.6 $[Cl^-]>[Na^+]>[Ca^{2+}]>[Mg^{2+}]>[SO_4^{2-}]$ EC: 2000 μScm^{-1} Epilimnion: Alkalinity: 2.1 $mEqL^{-1}$ pH: 8.3 $[HCO_3^{2-}]>[Ca^{2+}]>[Mg^{2+}]$ EC: 600 μScm^{-1}	Small sub-basin: meromictic Large sub-basin: holomictic	Open, permanent inlets/outlets	Miracle et al., 1992; Vicente et al. (1993); Barreiro-Lostres et al., (2015); this research

Although conceptual hydrological models indicate a large groundwater contribution for the three lakes, open or closed surface drainage is a key characteristic defining the water and sediment input to the lake. The lakes studied in this research include three main surface hydrological conditions: Lake El Tejo is a closed endorheic basin, Lake La Parra has no surface outlet but presents a small intermittent inlet and Lake El Tobar is an open lake, with both surface inlet and outlet (*table 5.1*). These differences are key regarding the input sediment rates and consequently, the volume of sediment reaching the lake. Thus, the presence of active inlets determines the intensity of the clastic input to the lakes (Valero-Garcés et al., 2014; Renaut and Gierlowski-Kordesch, 2010). Moreover, changes in lake level occur more rapidly in hydrologically closed lakes as a response to moisture fluctuations (Valero-Garcés et al., 2014), and consequently makes these lacustrine systems more sensitive to climate fluctuations, also reflected in a larger facies variability as occurs in lakes El Tejo and La Parra.

The size and the geology of the watershed exert a large influence in the amount of sediment delivered to the lake. For that reason, Lake El Tobar with a larger watershed compared with El Tejo and La Parra (*table 5.1*), has higher clastic (both carbonate and siliciclastic) contribution and an average sedimentation rate several orders of magnitude higher during the last millennia, specially during periods of increased human impact. This anthropogenic impact has also increased the frequency of intense sedimentary input events to the lake.

In the continental Mediterranean climatic mountainous setting where the lakes are located, precipitation is the paramount control of the hydrological cycle and the lake dynamics, and moisture variability and changes in precipitation regimes are reflected in facies variability of the lacustrine sequences. As a general rule, during more humid periods, lake level are higher and profundal facies are better developed and during more arid periods lake levels are lower and littoral environments are better developed. Higher precipitation and/or more intense rainfall events are also conducive to higher sediment transport to the lakes, although the vegetation cover and land uses of the watershed also play a determinant role. For example, higher frequency of clastic facies occurred in El Tobar and laminated facies in El Tejo and La Parra during the more humid Little Ice Age. Moreover, in the nearby Lake La Cruz, endogenic calcite lamina thickness has been correlated with winter rainfall (Romero-Viana et al., 2008).

Lakes El Tejo, La Parra and nearby lakes La Cruz and Lagunillo del Tejo that depend almost exclusively on groundwater inputs and have a relatively small size, tend to react rapidly to hydrological variability with changes in littoral and distal facies distribution (López-Blanco et al., 2011; Romero-Viana

et al., 2009). El Tobar is a unique cause because of the presence of hypersaline monimolimnion related to the input of saline groundwaters from the evaporate-rich substrate (*table 5.1*, Vicente et al., 1993; Miracle et al., 1992). Water chemistry and limnological properties are also key factors in endogenic carbonate preservation, since hypolimnetic conditions may dissolve small calcite grains before deposition (Valero-Garcés et al., 2014).

The development of seasonal or permanent thermal stratification requires a minimum water depth of 6 m (Valero-Garcés et al., 2014), so thermal stratification occurs in the three studies lakes. The preservation of fine lamination in the sediments is largely related to the dominance of anoxic conditions (Brauer, 2004; Julià et al., 1998; Larsen and McDonald, 1993; O'Sullivan, 1983). The alternation of banded/massive to laminated facies intervals in the sedimentary sequences of El Tejo and La Parra are coherent with changes in the deepest zone from slightly stratified to mixed water column conditions. Lake El Tobar is the only one with permanent meromixis in the deepest sub-basin and the sediments are frequently finely laminated.

5.1.1.3 Facies associations and depositional environments

Detailed descriptions of sedimentary facies for each lake are provided in the articles of the *Results* (*section 4*). Nine facies have been described for Lake El Tejo, seven for Lake La Parra and seven for Lake El Tobar. These facies group in finning-upwards sequences (*figure 5.1*). Considering their relatively small size, depth and the significant clastic input, two main depositional environments have been identified in these lakes: littoral-sublittoral and profundal-distal. The facies have been grouped following Valero-Garcés et al. (2014) by key sedimentological (lamination and grainsize) and compositional (carbonate, siliciclastic and organic content) properties (*table 5.2, figure 5.1*).

There are two main types of *littoral-sublittoral* sedimentary facies associations:

- *Coarse clastic (LC)*: Although they are minor components, coarse facies occurs in the three sequences. They are composed by gravel, sand and coarse silt size sediments, constituting cm- to dm-thick massive or fining upwards sequences with erosive and irregular basal surfaces.

Interpretation: This facies is indicative of high-energy transport in littoral zones with strong alluvial influence.

- *Massive to banded carbonate-rich silts and muds (LF)*: These are the most common facies found in the sedimentary records, and they are composed by carbonate-rich silts and muds, showing a large variability depending on stratification features (massive to banded), amount of carbonates, siliceous minerals and organic matter.

Interpretation: Massive or graded silty layers are interpreted as deposition in the littoral zone during periods of higher run-off. Banded silts with abundant

plant, gastropod and charophytes remains reflect deposition in carbonatic-producing littoral environments with restricted clastic inputs. Finer facies are deposited in deeper sublittoral zones.

Table 5.2: *General view of facies and facies associations in the studied lakes, including sedimentology and depositional processes and environments. Nomenclature based on Valero-Garcés et al. (2014).*

Facies association and sedimentological features	***Depositional processes and environments***
Littoral (L)	
L.C. Coarse clastic: Cm-dm thick fining upwards sequences composed of sharp carbonate-rich silty-sand to micro-conglomerates; massive to faintly laminated carbonate silt and massive to faintly laminated, dark gray carbonate silt and mud. Cm-thick layers with abundant plant, gastropod and braquipod broken organic rests are also deposited.	Littoral, high energy, high energy alluvial tractive currents
***L.F. Massive to banded carbonate-rich silts and muds*:** Cm-dm thick layers dominated by sharp-faced carbonates, although silicates may represent variable amounts. Significant content of plant and braquiopod remains.	Littoral, low energy, low alluvial influence with out of suspension sedimentation
Distal (D)	
***D.B. Banded to laminated carbonate silts*:** Dm thick layers with medium to fine silt fraction composed of carbonates, quartz and abundant clay-rich matrix. Common biogenic components as aggregates of amorphous soil organix matter or amorphous lacustrine organic matter, macrophyte remains and abundant diatoms.	Distal, variable oxygenation bottom conditions
***D.M. Massive*:** Cm-dm thick massive sandy silt layers with relatively higher magnetic susceptibility and mixed carbonate and silicate. Contains soil-oxidized agglomerates.	Distal, low energy, dominant oxygenated conditions
D.L.L. (o). *Laminites organic-rich*: Sets of mm-thick, brown to greenish, organic-rich laminae composed of amorphous lacustrine organic matter, diatoms and some macrophyte remains, with scarce amounts of clay minerals, carbonates and silicates. Includes laminated to massive microbial mats.	Distal, deep, anoxic conditions
D.L.V. (c). *Varves with calcite laminae*: Sets of dark-brown laminae (lacustrine organic matter, diatoms) and yellowish mm-thick laminae (authigenic carbonates: calcite, aragonite).	Distal, deep, permanent or seasonally anoxic meromictic conditions with endogenic calcite bioproduction

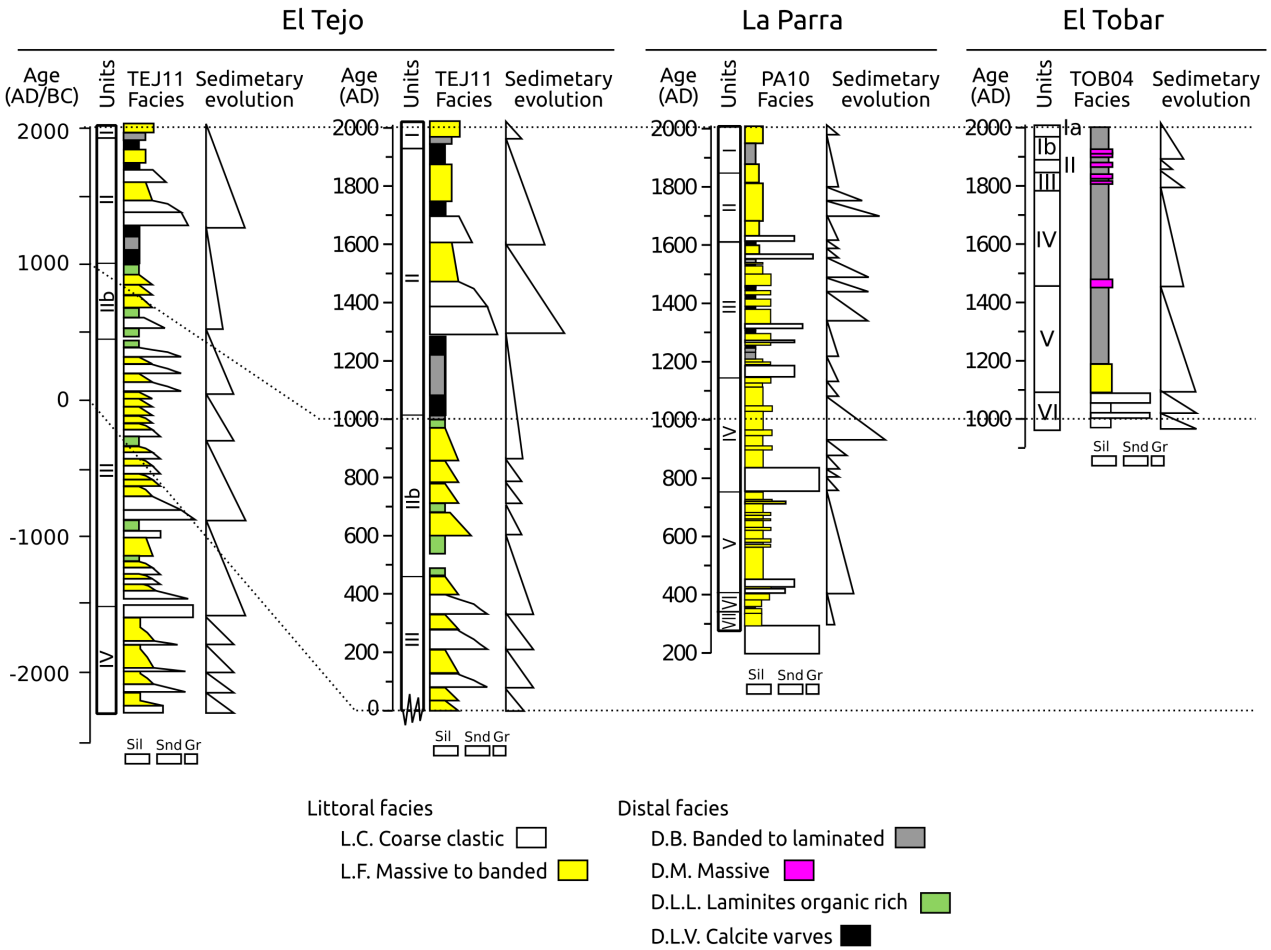


Figure 5.1: *Composite sedimentary sequence in age for El Tejo, La Parra and El Tobar lakes. Units, main facies following the unified facies and associations in Iberian karst lakes by Valero-Garcés et al. (2014) and sedimentary evolution are represented.*

These littoral facies are dominant in Lake La Parra due to the presence of the small creek and the relatively shallow nature of the lake basin. Interestingly, coarse, littoral facies are also frequent in the deep El Tejo basin, in spite of its reduced watershed and the absence of a drainage network. Periods of more intense erosion in the doline cliffs may explain the development of slope screes and the transport of coarse material to the lake basin. Littoral facies in El Tobar are a minority (only found in the basal part of the sequence) and they are of finer grain-size.

There are four *distal-profundal* facies associations:

- *Banded to laminated carbonate silts (D.B.)*: This facies includes a large variability in grain-size from fine to coarse silts, sedimentary textures from banded to laminated and color (black, brown, gray). Cm to dm thick sequences are defined by grain-size variability. Sedimentation in the distal-profundal zone of Lake El Tobar during the last 1000 years is dominated by laminated carbonate silts. In lakes El Tejo and La Parra this facies is limited to some thin intervals. Banded carbonate facies are the most common of the three lakes in distal, deeper environments. In El Tobar, these facies are more frequently laminated and interspersed by massive distal facies.

Interpretation: This facies association indicates deposition in the distal open water zones in permanently or seasonally oxygenated lake bottom waters.

- *Massive (D.M.)*: This facies in composed of homogeneous cm – dm thick massive sandy silt layers with no grain-size gradation, characterized by high magnetic susceptibility values and variable amounts of carbonate and silicate minerals. It occurs exclusively in El Tobar sequence, interspersing the laminated sediments.

Interpretation: The sedimentological features of massive facies are characteristic of turbidite-type or storm-related deposits reaching the distal low-energy zone of the lake. The fine and massive texture indicates rapid deposition in that distal zone by sediments draining the watershed during flooding episodes.

- *Laminites organic-rich (D.L.L. (o))*: This facies consist in dark-green banded, carbonaceous fine silts with abundant aquatic amorphous organic matter, diatoms and pyrite spherules. They occur only in Lake El Tejo in a few 1-2 cm thick layers with net boundaries.

Interpretation: This facies points to deposition in an environment with high microbial/algal bioproductivity. Changes in the preservation of laminae in the distal depositional environment would reflect alternating oxygenated and anoxic conditions.

- *Varves with calcite laminae (D.L.V. (c))*: Laminated facies contain both, white laminae composed by calcite crystals and dark laminae made up of amorphous organic matter and silicates. In El Tejo, La Parra and the nearby Lake La Cruz, this laminated facies are restricted to specific periods, but it is better developed and preserved in La Cruz. Some intervals in El Tejo contain varves poorly preserved. Varves are absent in El Tobar sequence.

Interpretation: This type of lamination is associated to low energy sedimentation environments, favored by water stratification during high lake levels and prone to anoxic redox conditions in the bottom (Brauer, 2004). It represents a seasonal deposition of calcite precipitated in the epilimnion in sumer during the climax of algal development (light laminae) and clastic material deposited during autumn-winter (dark laminae) seasons.

Varves are present in three of the sinkhole lakes of Las Torcas Complex (*figure 5.2*): El Tejo, La Parra and La Cruz. But the chronology for varve development is different in each case. In El Tejo varves are present in centimeter intervals at c. CE 1000, 1250, 1700 and 1900. In La Parra varves appear also in short centimeter intervals at c. CE 350 and then only from c. CE 1250 to 1450. In La Cruz they occurs as since c. CE 1700 and still persisting today. As commented above, this kind of seasonal lamination is favored with water stratification during high lake-levels and anoxic conditions in the bottom of the lakes (Brauer, 2004). The development of meromictic conditions on these karstic lakes is controlled by the synergistic effects of basin geometry, and climatic, hydrological and anthropogenic forcings. Most favorable conditions for their development are a combination of colder temperatures, higher winter precipitation, weaker winds, higher lake-levels and higher nutrient inputs (Julià et al., 1998). The relationship with higher lake levels is clear in both lakes: in Lake La Cruz, during varve sedimentation planktonic diatom dominate and in Lake La Parra the varved intervals contain with the highest concentration of diatom concentration also dominated by planktonic species.

Changes in biological productivity may also affect the development and preservation of varves. Although whiting have been documented in both La Cruz and El Tejo in recent years, only in La Cruz occur every year. In La Cruz Lake, every summer the precipitation of calcite crystals in the euphotic zone causes the 'whiting' of the lake waters that reinforces the chemically-induced stability of the monimolimnion (Rodrigo et al. 2001). These whitings also occur in Lake El Tejo, but they lack of cyclic behavior. Thus, the differences between La Cruz and El Tejo suggest that the variations on the annual algal and bacterial productivity also affect the development of a stable meromixis. Finally, other factors to take into account for meromixis instability are related with

connectivity with the karstic aquifer. Well-connected lakes would be less prone to a stable meromixis due to physical mixing of waters, as could be the case of El Tejo and La Parra. To sum up, a combination of biological, hydrological and climate parameters may trigger dominant anoxic conditions at the bottom of the lakes and the occurrence of favorable conditions for varve development and preservation at different times.

5.1.2 Paleohidrological and paleoclimate reconstruction and landscape evolution

5.1.2.1 Main paleohydrological changes for the last two millennia

A) The Cañada del Hoyo lacustrine sinkhole complex

As commented above, the paramount control on lake sedimentation is hydrology. Therefore and despite that the chronological models of the sediment records present different resolution and accuracy, the main episodes of hydrological variability during the last 2000 years should be reflected in all the lakes of Las Torcas Complex (*figure 5.2*). However, some differences should be expected as some particular lake features control the sensitivity of the system to record past hydrological changes.

The La Parra and El Tejo age models, spanning the last 1600 and 4000 years BP respectively, are most robust than other previously published records from Las Torcas Complex (López-Blanco et al., 2011a; Romero-Viana et al., 2009ab, 2007; Burjachs, 1996). La Parra record is the only one that covers the entire lacustrine sedimentation since its onset. For comparison purposes we have selected the last 2000 years of the available records (*figure 5.1*).

The most arid phase of the last two millennia occurred before c. CE 300, during the last phase of the Ibero-Roman Humid Period (IRHP, 650 BC-CE 350). Lake El Tejo presented littoral sedimentation during this stage and Lake La Parra was a dry sinkhole, with no lacustrine deposition prior to ca. CE 300. After this period, the sedimentation in both El Tejo and La Parra lakes indicate fluctuating lake-levels with a general frame characterized by more humid conditions for the last 1600 years. Lake La Parra especially supports this, since it did not experiment another drying out phase. The fact that the lake El Tejo sinkhole was flooded before than La Parra can be explained because the former is a deeper sinkhole that reaches the lower water-table levels and would be affected earlier during the rise of the regional water-table in a humid period.

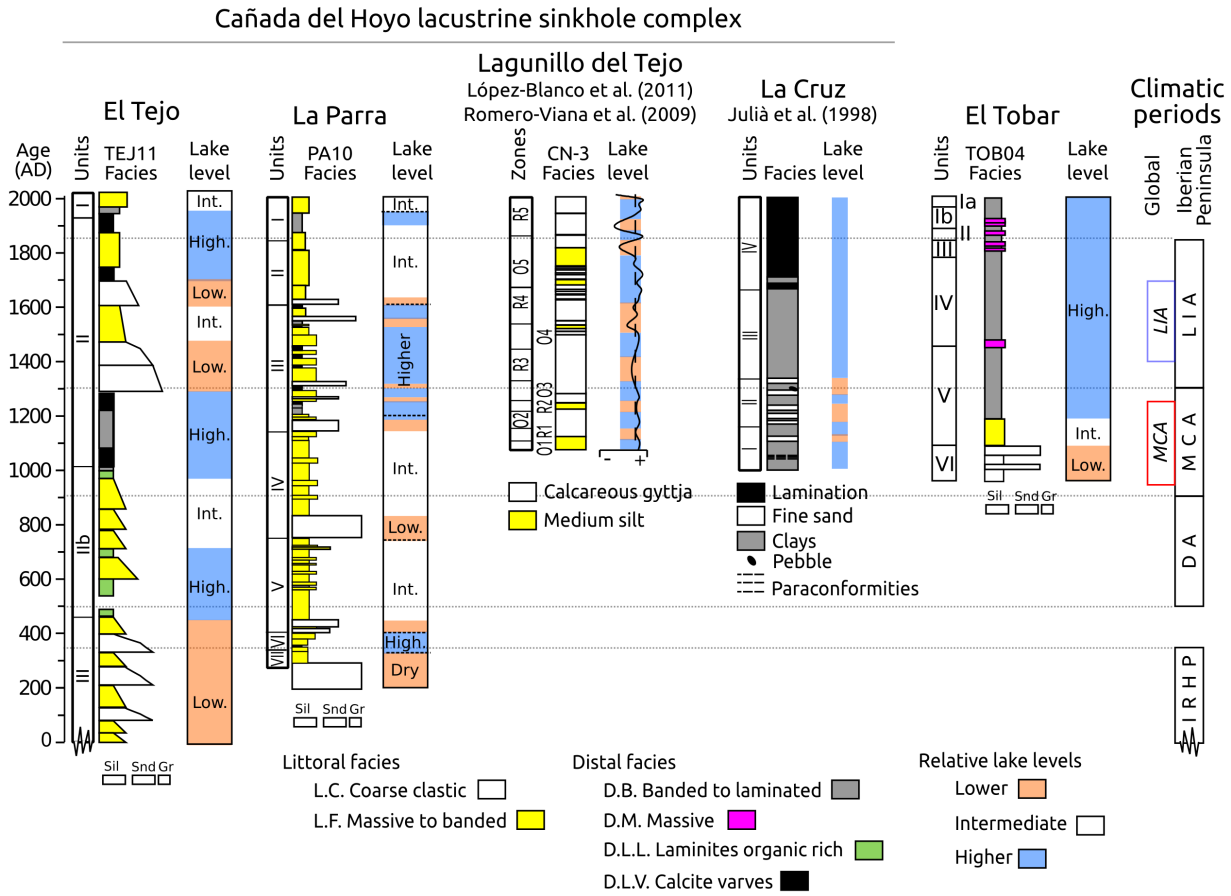


Figure 5.2: *Main units, sedimentary sequences and inferred lake levels of the three studied lakes (El Tejo, La Parra, El Tobar) in calibrated years AD. Previously studied lake records from the Cañada del Hoyo lacustrine sinkhole complex are also shown (Lagunillo del Tejo, La Cruz) for comparison. Main climatic periods of the Iberian Peninsula are based on Martín-Puertas et al. (2008), Moreno et al. (2012) and Morellón et al. (2011). The chronology of Mann et al. (2009) has been used for the main two global North hemisphere climate periods for the last 2000 years.*

After this drier episode, fluctuating hydrological conditions are inferred from both lakes´ records until c. CE 1200. Changes in sedimentation patterns (coarser sediments) indicate a relatively short and lower lake level (drier) phase. In La Parra a sharp change in sedimentation, from silts to gravels, occurred around c. CE 750 - 850. In El Tejo the transition from organic-rich laminites to coarser littoral facies seems to correlate with the deposition of gravels in La Parra.

The higher lake levels in El Tejo are interpreted by fine sediments and the presence of calcite varves, and occurred from c. CE 1000 to 1300 and from c. CE 1700 to 1950. The highest lake levels (humid period) in La Parra is also represented by the presence of calcite varves in discrete intervals and spans from c. CE 1200 to 1600. Within these periods of relatively higher lake levels, some rapid fluctuations occurred in both El Tejo and La Parra at c. CE 1300 and 1600. These lower lake level fluctuations within a wetter period are also recorded in the nearby Lagunilllo del Tejo sequence (López-Blanco et al., 2011).

In Lake La Cruz, coarse sedimentation indicative of fluctuating but lower lake-levels occurred from c. CE 1100 to 1300. Deeper lake levels occurred since CE 1300 as deposition is dominated by fine distal facies sediments. In this lake, contrarily to El Tejo and La Parra, varve deposition only occurred after c. CE 1579 and spanned till recent times (Romero-Viana et al., 2011). During the recent decades, El Tejo, La Parra and La Cruz lakes present relatively intermediate high lake levels, lower than those during the most humid period.

The rapid change in the hydrological behavior of La Parra sinkhole, and also in El Tejo, at about c. CE 300, during the end of the IRHP, is a conspicuous feature. Since no other geological agents (increase karstic subsidence, changes in geomorphological parameters as drainage networks, etc) seem capable to explain this rapid lake-level rise, we favor an increase of water-table levels due wetter climatic conditions as the most likely explanation for the rapid rise of lake levels in this area. The sensitivity of these lakes to recent water table fluctuation related to changes in aquifer-recharge patterns and local groundwater flows has been documented by Carmona and Bitzer (2001).

Lower lake-levels periods occur in both lakes during the Dark Ages (DA, CE 500-900), and during the Medieval Climate Anomaly (MCA, CE 900-1300). These arid conditions are more evident in the sedimentary record of La Parra than in El Tejo and La Cruz. The onset of the MCA is not synchronous all over the Iberian Peninsula, and even a prior phase of low lake-levels c. CE 700-950 has been documented in Central (this research; Lake Somolinos, Currás et al., 2012; Lake Taravilla, Moreno et al., 2008) and Northern (Lake Arreo, Corella et al., 2013) Iberian Peninsula.

A period of higher lake-levels (wetter conditions) occurred in lakes La Cruz, El Lagunillo del Tejo and La Parra ca. CE 1200, but started earlier in Lake El

Tejo (c. CE 1000). Interestingly, the first evidence for wetter conditions and higher lake-levels after the MCA (onset of the Little Ice Age) occurred earlier in Central (this research) and South (Lake Zoñar, Martín-Puertas et al., 2008) Iberian Peninsula (about CE 1200), and later (around 100 years) in the Northern Iberian records (Lake Arreo, Corella et al., 2013; Lake Montcortès, Corella et al., 2010; Lake Estanya, Morellón et al., 2008; Lake Redon, Pla and Catalán, 2005).

Some of the differences in the depositional response to changing hydrological conditions is related to the different configuration of the lacustrine basins: El Tejo and La Cruz lakes are the largest and also the deepest lakes of the complex, while Lake La Parra is relatively shallower and is the only lake of the complex with a surface inlet. Larges lakes may soften relatively changes in the hydrological budget derived from wetter to drier climatic conditions since due to their depth, they are better connected with the regional aquifers. On the other hand, precipitation and runoff greatly affect the delivery of sediments to Lake La Parra by the small creek. In other words, larger and deeper lakes with no surface inlet could be less sensitive than smaller lakes with ephemeral inlets to run off and sediment delivery changes. The Lagunillo del Tejo, the smallest closed lake of the sinkhole complex, shows high amplitude drops and rises in the water-levels (López-Blanco et al., 2011) not appreciable in the other lakes.

B) The Lake El Tobar

Similarly to the Cañada del Hoyo lacustrine complex, hydrology is a significant factor controlling sedimentation in Lake El Tobar; however in this case, human impact through land-use changes is also a paramount control,.

Coarse clastic littoral sediments from Unit V (*figure 5.2*) suggest shallow lake-levels between CE 1000-1100. The onset of deposition of finer massive littoral facies is interpreted as the establishment of relatively deeper depositional environments c. CE 1100 to 1200. In El Tobar, lower lake levels occurred during the MCA and deeper environments were established since the onset of the LIA (c. CE 1200), although around 100 years earlier than in northern lacustrine records (*figure 5.2*). Since then deposition in Lake El Tobar has dominated by the deposition of banded to laminated distal facies, which indicates relatively deeper water-level conditions. The most important changes in depositional dynamics during the last 1000 years in the distal areas are the sedimentation of massive distal facies, indicative of increased sedimentation delivery from the watershed due to land-use human induced changes. A remarkable aspect is that increased sedimentation episodes only occurred during the LIA and their frequency increase from c. CE 1800 to 1950, roughly synchronous with periods of peak floods frequency in the nearby Lake Taravilla (Moreno et al., 2008) and with increased number of floods per decade in the Tagus River (Benito et al., 2003).

C) The Serrania de Cuenca

In summary, this research provides three new multiproxy karstic lake sequences from the Iberian Range, with a robust, high-resolution hydrological and environmental variability record for the last two millennia. They contribute as well to fill the gap between North and South of the Iberian Peninsula. These new records constitute the longest and most complete lake sequences from this karstic area.

Lakes El Tejo and La Parra are small flooded sinkholes with a reduced watershed and highly sensitive to environmental variability, showing a rapid response to changing hydrological conditions. In lake El Tobar, hydrology controls the main long-term lacustrine dynamics, although short-term variability is related to both hydrological and anthropogenic impacts in a relatively much larger watershed. As it is discussed in the following section, human impacts were similar in intensity and activities in the three watersheds, providing increased sediment inputs to the lakes, but interestingly, each lake recorded a different evolution of that human pressure due to the combination of different factors, as land uses, bathymetry, watershed topography and extension.

The three records provide a coherent paleoclimate reconstruction at centennial scale for the Iberian Range. Comparison with other Iberian records emphasizes the heterogeneity through space and time of the main dry (MCA) and wet (LIA) climatic periods at decadal scales, supporting the existence of latitudinal gradients on the Iberian Peninsula climate variability during the last 2000 years: increased humidity during the IRHP is limited to the South (Martín-Puertas et al., 2008b) while warmer and drier signatures are more evident in Northern (Lake Arreo, Corella et al., 2013; Lake Montcortés, Corella et al., 2010; Lake Estanya, Morellón et al., 2008) and in Central (this research; Lake Somolinos, Currás et al., 2012) Iberian Peninsula. After a period of relatively higher lake levels and increased humidity during the so-called Dark Ages, some dry phases occurred prior to the MCA onset in the Iberian Range (this research; Lake Taravilla, Moreno et al. 2008). Despite some chronological inconsistencies and local differences the MCA was a drier period in the Iberian sequences (Moreno et al., 2012). The humid phases of the LIA started and ended earlier in the central Iberian Range relative to the Pyrenean and to the southern Iberian Peninsula. Although El Tobar lake-level after the end of the LIA remained relatively constant until nowadays, El Tejo and La Parra showed slight lower lake-levels after c. CE 1950.

Considering a broader context and despite differences on temporal resolution with other Mediterranean lacustrine records, Central Iberian Range hydrological climatic-related changes are in agreement with the main West and Central Mediterranean climate reconstructions (Ahmed et al., 2013, Magny et

al. 2013). The studied lacustrine records show an opposite hydrological behavior compared to East Mediterranean records, supporting the hypothesis of Roberts et al. (2012) of an East-West paleohydrological see-saw during the last two millennia in the Mediterranean area. At global scale, the main hydrological changes identified in this research coincide with the CE 800-1000 and CE 1400-1850 rapid climate changes described by Mayewski et al., (2004) during the last millennium and also are coherent with a dry and warm MCA and wet and cold LIA as suggested by global model simulations (Mann et al., 2009; Wanner et al., 2008).

5.1.3 Land-use impacts on lake depositional dynamics

Decisive socio-historical changes have occurred in the Mediterranean mountains not only during the last decades but during the last two millennia, affecting the evolution of natural systems, the availability of water resources and sediment transport and transforming the structure and main characteristics of the landscapes (García-Ruiz et al., 2013). Human intervention through land-use changes along history has been as intense to the point that many landscapes can be considered as human-made. The area of study of this research has been subjected to significant human pressure through deforestation, overgrazing, cultivation of steep slopes, fires, etc.

El Tejo and La Parra records span the last millennia (*figure 5.3*), and they show that main increase in sediment inputs started with the end of the Visigoth Kingdom and during the Moorish periods at c. CE 500-800. Two phases of higher sediment delivery occurred in the following centuries: the first one during the wars between Moors and Christians in this region between CE 1000-1200 (*figure 5.3*). The second one during the period of growing population after the Christian conquest of this area and the establishment of the important extensive livestock-breeding industry at CE 1200-1300. During this period, population increased and woodland areas were cleared for agricultural and cattle purposes, including steep mountainous lands. In the following centuries high sediment inputs become more frequent and occurred in the three lakes: in El Tejo and La Parra a general increase in sediment delivery occurred during this period, while in El Tobar the frequency of discrete events increased.

The great demographic crisis at CE 1600 caused the abandonment of some farming and grazing areas (Esteban Cava, 1994). After the recovery, environmental resources uses diversified and woodland exploitation firstly peaked around CE 1750, and later ca CE 1850 with the privatization of large woodland areas. Increased sediment input in El Tejo and El Tobar occurred from the late 19th to CE 1960, coinciding with a population maximum again (*figure 5.3*). Finally, the abandonment of rural areas due to migration to cities after CE 1940 to recent times caused the collapse of traditional land

management systems and a general reduction in sediment input into the lakes.

These periods of increased sediment inputs do not correlate with higher lake water-levels although their frequency increased during more humid phases. The intensity of these higher sediment input periods - measured as thickness of detrital layers or their frequency - although modulated by climate conditions, appears not too be directly related to the drier or wetter environmental conditions, and more to the human activities. In summary, the higher sediment delivery periods are interpreted as a reflection of changes in sediment availability in the watershed. As documentary data indicate, these higher sedimentary input periods correlate well with main changes in landscape management due to agriculture and grazing impacts.

These periods of increased human impact in the landscape are also observed in the Lagunillo del Tejo and La Cruz lake records, although with some differences. Human impact was relatively larger in Lagunillo del Tejo than in El Tejo, La Parra or La Cruz because the configuration of its watershed and depth, which facilitated the use for agricultural practices. Human impact in El Tobar watershed also produced more net differences in the sedimentary record due to the cumulative effect of a large watershed with several zones of sediment production or temporal storage. Also in El Tobar, many crop fields are located on the lowlands and surrounding the lake. This heterogeneity in the human footprint expression in the sedimentary records highlights the importance of the lake watershed configuration and the intrinsic lacustrine characteristics. Local differences within a similar socio-historical and climatic regional context are key to correctly interpret lake sedimentary records.

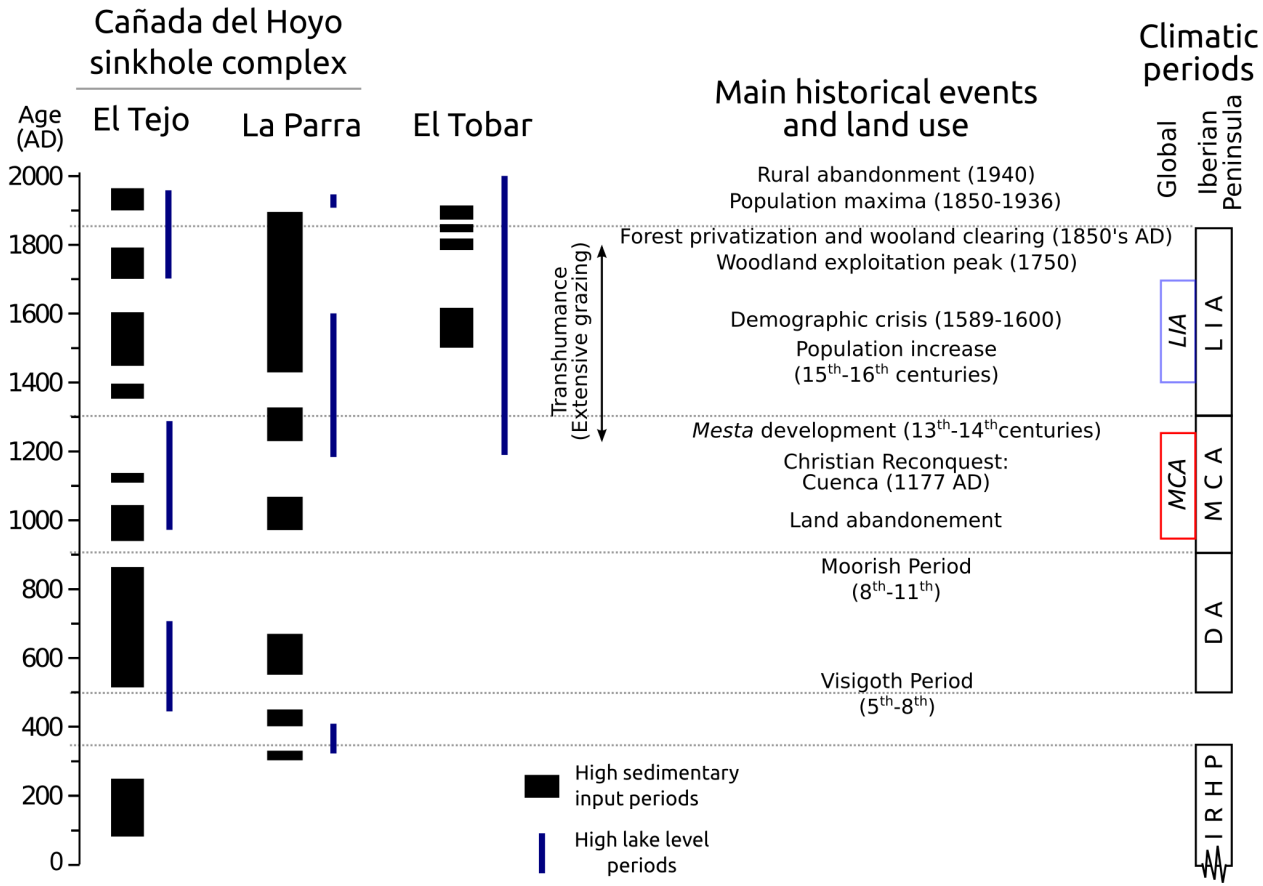


Figure 5.3: *Main sedimentary input periods in calibrated age AD (in black) for El Tejo, La Parra (Cañda del Hoyo sinkhole complex) and El Tobar lakes. Blue lines represent inferred high lake level stages. Main chronological historical events and land use changes are also added for comparison. Main climatic periods of the Iberian Peninsula are based on Martín-Puertas et al. (2008), Moreno et al. (2012) and Morellón et al. (2011). The chronology of Mann et al. (2009) has been used for the main two global North hemisphere climate periods for the last 2000 years.*

5.2 Towards a quantification of sediment inputs to lake basin and watershed erosion

Mediterranean mountains are characterized by strong seasonality of hydrological regimes and a long history of human activities. Both features make land degradation and soil erosion a key environmental problem of increasing scientific interest during the last decades. In *section 4.6* a method to quantify the mass accumulated in each of the studied lakes during the periods of higher sediment inputs has been developed. These periods of higher sedimentation (named events) have been determined for the last 1000 years following a multi-proxy geochemical approach, basically studying the signature of the conservative elements representative of detritic inputs (Ti, Si, Zr, Rb, K, Fe; following Kylander et al., 2011; Croudace et al., 2006; Richter et al., 2006), their synchrony with high values of the carbon-nitrogen (C/N) ratio, which is representative of dominant extra-lake organic matter inputs (Meyers and Lallier-Vergés, 1999) and their thickness and sedimentation rates. Once identified the intervals corresponding to these events, the mass of sediments accumulated in the lake (Ml) for each event has been calculated applying the equations described by Einsele and Hinderer (1998). From that point, it is easy to estimate the potential mass denuded from the watershed (Mdc) that produced a determined event and even the velocity at which that denudation occurred obtaining a total denudation rate (DRt). It has to be highlighted that these estimations are possible by using simple and usual field surveys and laboratory analysis of the sedimentary records. They include detailed bathymetries and sedimentological descriptions, semiquantitative XRF-scan and elemental LECO analysis, continuous density measurements and an accurate chronological control of the sedimentary sequence.

5.2.1- Quantification variability on watersheds

The main differences in the Ml and Mdc values obtained from watersheds under similar human impact and environment conditions during the last 1000 years are related with variables linked to the internal functioning of the watershed-lacustrine system: differences in the hydrological behavior, in the efficiency of the hydrological drainage net and its organization and the presence of erodible landscapes. As expected, the Ml values allow ordering the lakes by watershed size: El Tejo, La Parra, Taravilla and El Tobar. Larger watersheds produce more sediment that can be delivered to the lake. On the other hand, the Mdc is similar in magnitude in all the watersheds, lacustrine or experimental, and is independent of the size of the drainage area. It appears to be linked directly with the intensity of rainfall and inversely with the vegetation cover and other internal characteristics of the catchment (connectivity, soil type, topography; García-Ruiz et al., 2015, 2008). In this context, the existence

of relatively large palustrine areas with abundant vegetation, as occurs in Lake Taravilla, are key elements, acting as sedimentary sinks or sources depending of the intensity and organization of transport processes, which may add important masses of sediments to the lake during flooding periods (Moreno et al., 2008).

For the CE 1900-2010 period, in the relatively small watersheds of El Tejo and La Parra, the DRt experimented a rapid increase. Contrarily, in the larger watersheds (Taravilla and El Tobar) a decrease of the DRt occurred. A similar trend has also been observed in experimental catchments (García-Ruiz et al., 2010) and may be attributed to the fact that larger watersheds present higher resistance to natural or human impacts as consequence of a size effect: larger systems are more difficult to destabilize than smaller ones.

An important observation in quantifying sediment events is that large watersheds present a wider range of values for Ml and Mdc, while the small watersheds have a narrower variability range. This is also attributed to the watershed size-effect on production and sink of sediments.

5.2.2 Results, limitations and future improvements

The method for quantification of sediment events from lacustrine sequences has produced coherent results with modern experimental catchments data from the Pyrenees. This is indicative that, a priori, the method is robust enough to provide reliable estimations of Ml and Mdc for the last 1000 years. The results also underline the punctuated nature of sediment dynamics of Mediterranean mountain areas at decadal and centennial scales, confirming the idea from experimental catchments that infrequent but intense flood events may control the sediment yield (Lana-Renault et al., 2014).

Many theoretical and modeling studies assume a direct link between the generation and deposition areas of sediment. The importance of the sediment transport processes from uplands to basin also has to be taken into account on quantification studies. As illustrating example, Coulthard and Van de Wiel (2013) assert that for a given flood event, the amount of sediment released may or may not bear any relation to the size of the flood event. The difference may be only a short area of accommodation for storage and re-working of sediments, which is able to distort the climatic or anthropic signal. In numerous natural settings there is a relatively important space between areas of sediment erosion and deposition and therefore this must play a key role in how signals are transmitted from uplands to basin by actuating transport processes. Geomorphological studies indicate that this transport processes are expressed in a non-linear way as part of a complex response, acting to buffer sediment supply signals, while more recent short-term storage along the watershed may distort any upstream climate or anthropogenic impact signals (Coulthard and Van de Wiel, 2013). Therefore, processes between upland erosional areas and

the ultimate depositional setting can have a great impact on sediment delivery. At this respect, it is suggested that the shape of the basin and distance between sediment sources and sinks impart also an important control.

Additionally, Coulthard and Van de Wiel (2013) results indicate that autogenic variability of sediment yield, due to temporary storage and release of sediment within the basin, can be of the same magnitude as the spikes in sediment yield associated with the external disturbance, that at 2000 years scale may be, climate change or human activity. This mechanism of autogenic (self-organized) behavior in sedimentary systems produces fluctuations in transport processes (Jerolmack and Paola, 2010), which are especially important on large watersheds as El Tobar and Taravilla, where their extension and characteristics facilitate the probability of re-working processes. Furthermore, typical landscape systems comprising a set of linked transport subenvironments can have multiple time scales, not all of which are currently well understood. That also implies that the response of landscapes to variations in environmental forcing is also frequency dependent, because sediment transport is inherently depending on response time (Jerolmack and Paola, 2010). Moreover, there is ample evidence that sediment transport is a stochastic process even under steady forcing, and that this variability leaves its imprint on the stratigraphic record (Schumer and Jerolmack, 2009).

Thus determining how sedimentary systems respond to relatively rapid external forcing is not a simple task where numerical modeling is needed. Understanding transmission of environmental signals is crucial for predicting landscape response to climate and human impacts, and interpreting paleoclimate from stratigraphy (Jerolmack and Paola, 2010).

Other important factor that may lead to ambiguous interpretations is related with the non-linearity of sediment transport and the calculus of the sedimentary rates from stratigraphic records, which consequently affects also the induced denudation rate. Recent studies (Schumer and Jerolmack, 2009 and references therein) maintain that geologic evidence strongly supports the notion that hiatuses are common while deposition is rare, such that stratigraphy records only a very small fraction of Earth surface evolution. Regardless of their origin, the net effect of such non-linearities is that sediment transport is intermittent and rates typically vary widely in space and time even under relative steady forcing (i.e climate, human impacts, base-level variations). Several studies indicate that a large portion of stratigraphy constitute the record of the stochastic variability of sediment transport itself, rather than changes in forcing (Schumer and Jerolmack, 2009). The real problem lie in measured deposition rates decrease systemically with measurement duration for virtually all depositional environments in which there are sufficient data, with intervals ranging from minutes to millions of

years (Sadler and Jerolmack, 2015). This pattern is popularly known as the ''*Sadler effect*'' (Schumer and Jerolmack, 2009). Sadler (1981) recognized that this decrease likely results from the intermittent nature of sediment deposition. Fortunately, in the present research the time-scale of the stratigraphic sequences spans only the last 2000 years and the *Sadler effect* although present, has less influence than when studying long-term sequences, where large bias may induce complete distinct interpretations of the same records (Herman and Champagnac, 2016; Willenbring and Jerolmack; 2016). This bias could be removed if it would be possible to measure past sediment denudation and accumulation from a watershed, validating the theoretical mass conservation constraint over the time interval in question (Willenbring and Jerolmack; 2016).

Nevertheless, is has to be kept in mind that sediment quantification calculations here presented are based on simplified model assumptions (Einsele and Hinderer, 1998) and it is need to be aware that only order of magnitude estimations are possible, as these retain a very large degree of uncertainty. Fortunately, lake sequences cover the sedimentary variability along time and demonstrate that the major proportion of the total sedimentary yield is produced during sedimentary events, which helps to delimit and quantify them.

In order to improve this methodology and to obtain more accurate results in Mediterranean areas characterized by strong seasonality of hydrological regimes, monitoring on experimental watersheds that include a catchment-lake system combining traditional catchment monitoring and in-lake sediment traps is need. Besides, as indicated above, transport processes are key to establish reliable correlations between sediment yield from the uplands and sediment deposition in the basins. In this aspect, hydrological modeling of transport processes is also required in order to face a complete research on sediment quantification.

Following this idea, Las Torcas Lake Complex could be a good start-point due that they are small closed lacustrine systems with gradual differences in the watersheds, from no surface inlets to relatively larger ephemeral inlets and present also a gradation in the distance and complexity of the paths between sediment production and deposition. Additionally, they belong to a cultural landscape which quantification of human impact on landscape development would be of great importance for future management strategies.

5.3 Human impact, climate and watershed synergies

The effect of human impact on mountain ecosystems has been recognized in densely populated areas of the Alps, as well as in the less populated areas of the Scandinavian mountain range (Karlsson et al., 2007).

Understanding the history of human impact in the Mediterranean mountain watersheds and lake systems is essential for an adequate management and development of mountain regions. Nevertheless, disentangling climatic from human impact on the environment is one of the main challenges in paleolimnological research covering the last millennia. The separation of natural and human influences on the environment is even more complicated in regions affected by a long and intense history of cultural changes (Corella et al., 2011), as Mediterranean areas.

In the Iberian Peninsula since pre-historical times the anthropogenic pressure on lake watersheds has been variable, although human disturbance has been suggested as a major cause of vegetation change (Valbuena-Carabaña et al., 2010). In the area of study, particularly grazing for livestock-breeding and agriculture, have been the major human-related factors transforming the landscapes during the last 2000 years (Lozano-Sahuquillo, 2002; Esteban Cava, 1994). With each increase in population, more land has been cleared for agriculture. As population declined, cultivated land was abandoned, grazing pressure was reduced and, to a certain extent, natural vegetation grew back. However, each cycle frequently resulted in soil loss and progressive loss of plant cover (Valbuena-Carabaña et al., 2010). Although the available lacustrine records show that Iberian lake dynamics responded primarily to changes in hydrology (Valero-Garcés et al., 2014), a complex interplay of climate and the significant human impact may obscure the climate signature in some lake records (or *vice-versa*), making difficult to disentangle their effects on lake dynamics (Simonneau et al., 2013; López-Blanco et al., 2011; Moreno et al., 2008). For these reasons, karstic lakes in the Iberian Range provide an opportunity to reconstruct the depositional evolution of the Mediterranean mountain watersheds and to evaluate the response to both, the variable and intense anthropogenic impacts and climate forcing during the last 2000 years. Moreover, the proximity of the studied lakes provide the opportunity to evaluate the regional extent of reconstructed environmental changes in a context of similar climate conditions and human impact, evidencing that local and particular lake features may control the sensitivity of the system to record past changes.

From previous studies (García-Ruíz et al., 2015, 2013, 2010a,b, 2008; Giguet-Covex et al., 2014; Kosmas et al., 1997) it is known that precipitation (rainfall intensity, seasonality, runoff production) and land cover (forested *versus* retrogression of vegetated areas, mainly by changing land uses) are key factors controlling landscape erosion. The results in this study show that major periods of sediment accumulation in the three lakes and denudation in their respective watersheds during the last two millennia generally correspond with cooler and wetter phases (Roman and Dark Ages, 0-800 and LIA 1200-1850 cal.

CE). However, documentary sources (Valbuena-Carabaña et al., 2010; Lozano-Sahuquillo, 2002; Esteban Cava, 1994) demonstrate that the main period of sediment delivery to the lakes corresponds with the development of the Medieval highly complex system of sheep transhumance – the 'Mesta' Association -, which exerted a paramount control on the intense deforestation for grazing (12th-13th centuries).

Only the Lake Taravilla record, according to vegetation reconstruction based on pollen records (Moreno et al., 2008; Valero-Garcés et al., 2008) suggest that the important change in vegetation after cal. CE 1700 is more related to changes in climate (higher temperatures and wetter conditions) than related to agricultural practices. Thus, in general, is possible to conclude that for the area of study since cal. CE 1200, the periods of higher mass denuded in the catchments or increased denudation rate in the watersheds coincide with the main territory management changes, and also match with wetter periods and major hydrological activity (LIA, Tagus River flooding periods; Benito et al., 2003). This relationship is a clear indication of positive synergies between human impact and humid periods leading to increased sediment delivery and denudation stages. Therefore, human impacts on runoff and sediment production at a catchment scale in small basins cannot be omitted at least over the last millennium (Benito et al., 2015).

More recent changes on lake sedimentation, occurred during the 1960's, can be associated to the rural exodus and land abandonment during mid-20th century. These changes are more clearly shown in larger watersheds as decreased sediment delivery to the lakes due to recent afforestation. Other recent important anthropogenic influences are associated with new water infrastructures for irrigation or power stations. In the case of lake El Tobar, the construction of the canal in the 1960s led to an abrupt change in the sedimentation dynamics and the development of stronger chemocline.. These changes also coincided with the 1960's farmland abandonment and with a period of more intense rainfalls and lower mean temperature.

The sedimentary evolution of the studied lake sequences has been governed by a combination of factors, being climate and human impacts the major driving forces determining the sediment yield to the lakes. Although climate is a major driving force determining the long-term sedimentary evolution in the Mediterranean mountains, more local human impact can cause relatively short-term effects on the sedimentary evolution of the lake systems through landscape modification. Although each factor has had a strong effect in lake dynamics, the synergies between human impact and climate has a multiplying effect in landscapes evolution. Hence, a thorough knowledge of the site history is important when the lake sedimentary evolution is used as a proxy for past climate change.

6

Conclusions

The main conclusions of this research are classified in five subsections: Sedimentological and stratigraphic reconstruction (*subsection 6.1*), Paleoclimatic reconstruction and landscape evolution (*subsection 6.2*), Human impact through historical land use (*subsection 6.3*), Quantification of watershed land-uses impact (*subsection 6.4*) and Human impact, climate and watershed dynamics synergies (*subsection 6.5*).

Wader birds' reflection in Lake El Tobar.
Reflejo de pájaros limnícolas en la Laguna de El Tobar.

6.1 Sedimentological and stratigraphic reconstruction

The sedimentary sequences of lakes El Tejo and La Parra constitute the longest (6 m, last 4000 years; and 6.93 m, last 1600 years respectively) and best dated records (9 and 13 ^{14}C samples respectively) from Las Torcas sinkhole complex. The sedimentary sequence of El Tobar is the longest and best - dated record (7.90 m, 10 ^{14}C samples, last 1000 years) from Lake El Tobar. The age models based on ^{210}Pb, ^{137}Cs and ^{14}C dates are robust.

Sedimentary, geochemical, biological and mineralogical analyses allowed the definition of five units in the sedimentary sequence of Lake El Tejo, seven units in La Parra sequence and six units in El Tobar record.

The sediment sequences are characterized by a large facies variability mainly constituted by clastic carbonatic sediments. The three karstic systems have similar sedimentary facies association grouped in two depositional environments have been interpreted: i) littoral-sublittoral and ii) distal-profundal. Littoral facies (banded silt facies) dominate in the small topographically-closed basins (El Tejo, La Parra) while in larger basins (El Tobar) laminated sediments dominate in distal environments

Hydrology is the main control on facies and depositional environment patterns distribution and evolution. Paleohydrological fluctuations also controls the sediment inputs to the lakes.

6.2 Paleoclimatic reconstruction and landscape evolution

The three records provide a coherent paleohydrological reconstruction for the past 2000 years. Lakes El Tejo and La Parra are highly sensitive to short-term environmental variability, showing a rapid response to changing hydrological conditions. In lake El Tobar, hydrology controls the main long-term lacustrine dynamics, while short-term variability is related to both, hydrological and anthropogenic impacts.

All lakes from Las Torcas sinkhole complex show comparable fluctuations of environmental and hydrological conditions, although strongly modulated by particular lake features that control the sensitivity of the system as recorder of past changes.

The lowest lake levels during the last two millennia occurred before c. AD 300, at the last stage of the Ibero-Roman Humid Period (IRHP, 650 BC-CE 350)

Minor lower lake-level phases occurred during the Dark Ages (DA, CE

500-900), although the most important arid phase occurred between c. CE 750 – 850, at the onset of the Medieval Climate Anomaly (MCA, CE 900-1300).

The onset of a higher lake level phase occurred in all records in Las Torcas sinkhole complex at about CE 1200

The first evidence for wetter conditions and higher lake-levels after the MCA at the onset of the Little Ice Age (LIA, CE 1300-1850) occurred almost synchronously in Central and South of the Iberian Peninsula (about CE 1200), but it is around 100 years earlier than in Northern Iberian Peninsula. During the LIA, a complex pattern of dry-wet intervals has been found.

This research provides new paleoclimate reconstruction at centennial scale for the Iberian Range, coherent with most Iberian lacustrine sequences. The new data emphasize the heterogeneity through space and time of the main dry (MCA) and wet (LIA) climatic periods at decadal scales, supporting the hypothesis of latitudinal gradients in the Iberian Peninsula climate variability during the last 2000 years.

Comparison with records from the Central and East Mediterranean, also support the hypothesis of an antiphase behavior between West and East Mediterranean, as proposed by Roberts et al. (2012), suggesting an active role for NAO dynamics over the past two millennia in the western Mediterranean.

6.3 Human impact through historical land use

The sedimentological and geochemical trends identified in the lacustrine sequences allow the reconstruction of the lake-watershed-human interactions during the last millennium in the Western Branch of the Iberian Chain.

The main lake-watershed-human interactions are related to increased sediment delivery to the lakes.

The sediment input to the lakes has been characterized by geophysical, geochemical and sedimentological features.

The time interval needed for the deposition of these layers representing higher sedimentary inputs is likely very variable. That allowed to discriminate between *events*, of faster deposition (from days to weeks and even months, depending of the intensity of the runoff generation processes) and originated by stronger energy transport processes and *periods* of higher sedimentation (from decadal to centennial scale).

Major periods of sediment accumulation in the lakes and denudation in the catchments in the studied area during the last two millennia correspond with cooler and wetter phases (Roman and Dark Ages, 0-800 and LIA 1200-1850 cal. AD) and with increased human pressure in the catchments corresponding to the development of the Medieval highly complex system of sheep transhumance – the 'Mesta' Association - and consequent intense deforestation for grazing (12th-13th centuries).

Recent changes associated to the rural exodus and land abandonment during mid-20th century are more clearly shown in larger watersheds by decreased sediment delivery to the lakes due to recent afforestation.

The study of sediment denudation and accumulation from four lacustrine watersheds with similar climatic and physiographic features reveals an important degree on variability in the sediment accumulation but similar response in terms of frequency and intensity of erosion in the catchments through time.

6.4 Quantification of watershed land-uses impact

A new methodology based on the methods described in Einsele and Hinderer (1998) has been implemented to calculate the mass accumulated in the lakes (Ml), the minimum mass denuded from the watersheds (Md) and the total denudation rate (DRt) along the last millennium in four lake watersheds in the Western Branch of the Iberian Range.

Comparing the reconstructions from the Iberian lakes with data from experimental watersheds in the Pyrenees, the size of the watershed, the land cover and the erodibility of the geological formations and soils are key factors to control the sediment fluxes from mountains Mediterranean watersheds.

Precipitation (rainfall intensity, seasonality, runoff production) and land cover (forest area, degraded areas, land uses) are key factors controlling erosion in both experimental and lake catchments.

The results highlight the critical effect of the catchment size related to the amount of sediments that reach the lakes, confirming the paramount role of vegetation cover and land-use changes as main controls of erosion in Mediterranean watersheds at centennial scales.

The mass of sediments accumulated in the lakes (Ml) is highly variable

between lakes but with consistent values for each lake along time. This variability is associated mainly with the watershed size.

Values for minimum mass denuded from the watersheds (Mdc) and total denudation rate (DRt) from monitored Mediterranean mountain catchments and from lake sequences are comparable and they are independent of the watershed size.

In both lakes and experimental catchments, most sediment delivery occurs during flooding events. The results underline the punctuated nature of sediment dynamics in Mediterranean landscapes at decadal and centennial scales.

The reconstructed sediment delivery to the lakes and related denudation rate during these events spans several orders or magnitude (100 – 98,000 T and 6 – 480 T km^{-2} yr^{-1} respectively).

Reconstructed mass denudation values per event in the forested lake catchments are similar (< 30 T km^{-2} yr^{-1}) to sediment yields from high altitude experimental watersheds.

Flood sediment yield values from abandoned farmland experimental catchment (69 T km^{-2}) are in the lower range of lake watersheds (from 60 to 480 T km^{-2} yr^{-1}).

No lake watershed has reached the values documented for the badland catchment (3,094 T km^{-2}).

6.5 Human impact, climate and watershed dynamics synergies

Main periods and events of increased detrital input to the studied lakes correlate well with the main historical land-use changes in the region: mainly changes in vegetation cover due to large deforestation for live-stock grazing and agricultural objectives.

The synergistic effects between climate and humans were particularly intense at the onset and the second part of the Little Ice Age (LIA, AD 1300-1850) and since the 18th century, when climate signal was amplified by human disturbance, causing increased sediment production and stronger erosion and delivery, resulting in higher sedimentary rates, mass of sediments accumulated in the lakes and, denudation rates in the catchments.

This research demonstrates that degradation processes especially in

mountain watersheds, regardless of their size, are strongly related with both, natural environmental evolution and with anthropic impacts through historical land-use changes.

Planning conservation strategies of lake-watershed systems strongly affected by degradation processes caused by the consequences of an inherit cultural landscape of hundreds of years of human activities, must take into consideration the degree of alteration they have experienced and the historical causes of such modifications, leading to site-specific intervention policies.

6 Conclusiones

Las principales conclusiones de esta investigación se han clasificado en cinco subsecciones: Reconstrucción sedimentológica y estratigráfica (*subsección 6.1*), Reconstrucción paleoclimática y evolución del paisaje (*subsección 6.2*), Impacto humano a través de los cambios históricos en los usos del suelo (*subsección 6.3*), Cuantificación del impacto de los usos del suelo en las cuencas (*subsección 6.4*) y Sinergias entre impacto humano, clima y dinámica de las cuencas (*subsección 6.5*).

Aerial view of Lake El Tejo.
Vista aérea de la Laguna de El Tejo.

6.1 Reconstrucción sedimentológica y estratigráfica

Las secuencias sedimentarias de las lagunas de El Tejo y La Parra constituyen los registros más largos (6 m, últimos 4000 años; 6,93 m, últimos 1600 años, respectivamente) y mejor datados (9 y 13 muestras de ^{14}C, respectivamente) del complejo lacustre de Las Torcas. La secuencia sedimentaria de El Tobar es el registro más largo y mejor datado (7,90 m, 10 muestras de ^{14}C, últimos 1000 años) de dicha laguna. Los modelos de edad, basados en dataciones de ^{210}Pb, ^{137}Cs y ^{14}C son robustos.

Los análisis sedimentarios, geoquímicos, biológicos y mineralógicos han permitido definir cinco unidades en la secuencia sedimentaria de la laguna de El Tejo, siete unidades en la secuencia de la laguna de La Parra y seis unidades en el registro de El Tobar.

Las secuencias sedimentarias están caracterizadas por una gran variabilidad de facies, principalmente constituida por sedimentos clásticos carbonatados. Los tres lagos kársticos presentan una asociación de facies similar, que puede agruparse en dos ambientes de depósito: i) litoral-sublitoral y ii) distal-profundo. Las facies litorales (facies de limos bandeados) dominan en las cuencas pequeñas y topográficamente cerradas (El Tejo, La Parra), mientras que en la cuenca más grande (El Tobar), los sedimentos finos laminados predominan en los ambientes distales.

La hidrología es el principal agente que controla la distribución y evolución de facies en los diferentes ambientes de sedimentación. Las fluctuaciones paleohidrológicas también controlan la entrada de sedimento en las lagunas.

6.2 Reconstrucción paleoclimática y evolución del paisaje

Los tres registros lacustres proporcionan una reconstrucción paleohidrológica coherente durante los últimos 2000 años. Las lagunas de El Tejo y La Parra son muy sensibles a la variabilidad ambiental de corto plazo, mostrando una respuesta rápida a la fluctuación de las condiciones hidrológicas. En la laguna de El Tobar la hidrología controla la dinámica lacustre a largo plazo, estando la variabilidad ambiental de corto plazo influenciada a la vez por la hidrología y el impacto humano en la cuenca.

Todas las lagunas del complejo de dolinas de Las Torcas muestran fluctuaciones comparables en las condiciones ambientales e hidrológicas, aunque están influenciadas por características particulares de cada laguna, modulando la sensibilidad de cada sistema a la hora de registrar cambios

ambientales en el pasado.

El nivel de agua más bajo de las lagunas durante los últimos 2000 años tuvo lugar antes del año 300 D.C., durante el final del Periodo Húmedo Ibero-Romano (PHIR, 650 A.C. – 350 D.C.)

El nivel de agua más bajo de las lagunas tuvo lugar durante la Alta Edad Media (AEM, 500-900 D.C.), aunque la etapa más árida tuvo lugar entre 750-850 D.C., al comienzo de la Anomalía Climática Medieval (ACM, 900-1300 D.C.).

El comienzo de altos niveles de agua tuvo lugar al mismo tiempo en todos los registros disponibles en el complejo de Las Torcas, en torno al 1200 D.C.

La primera evidencia de condiciones más húmedas y mayor nivel de las lagunas después de la ACM y al comienzo de la Pequeña Edad del Hielo (PEH, 1300-1850 D.C.) fue casi simultánea en el centro y sur de la Península Ibérica (en torno al 1200 D.C.), pero cerca de 100 años más temprana que la encontrada en el norte de la Península. También, durante la PEH, se ha encontrado un patrón complejo de oscilación entre intervalos secos-húmedos.

La presente investigación proporciona una nueva reconstrucción paleocimática a resolución centenaria para la Cordillera Ibérica, coherente con la mayoría de las secuencias lacustres disponibles en la Península. Los nuevos datos proporcionados enfatizan la heterogeneidad en el espacio y el tiempo de los principales periodos secos (ACM) y húmedos (PEH) a escala de decenios, apoyando la hipótesis de gradientes latitudinales en la variabilidad climática de la Península Ibérica durante los últimos 2000 años.

La comparación con otros registros del Mediterráneo central y oriental también apoya la hipótesis de un comportamiento antifásico entre el Mediterráneo occidental y oriental, propuesta por Roberts et al. (2012), sugiriendo un papel activo en la dinámica de la Oscilación del Atlántico Norte (NAO) durante los últimos 2000 años.

6.3 Impacto humano a través de los cambios históricos en los usos del suelo

Los patrones sedimentológicos y geoquímicos identificados en las secuencias lacustres han permitido la reconstrucción de las interacciones entre las lagunas, sus cuencas y su población durante el ultimo milenio en la rama occidental de la Cordillera Ibérica.

Las principales interacciones están relacionadas con el aumento de aportes de sedimento a las lagunas.

Este aporte de sedimentos a las lagunas ha sido descrito por sus características geofísicas, geoquímicas y sedimentológicas.

El intervalo temporal necesario para la sedimentación de las capas que representan un mayor aporte de sedimentos es muy variable. Esto ha permitido diferenciar entre *eventos* de rápida sedimentación (desde días hasta semanas o incluso meses, dependiendo de la intensidad de los procesos generadores de escorrentía) originados por procesos de transporte enérgicos y *periodos* de mayor sedimentación (desde decenios hasta siglos).

Durante los últimos 2000 años, los mayores periodos de acumulación de sedimentos en las lagunas y de erosión en las cuencas del área estudiada coinciden con las fases más frías y húmedas (Época Romana, Alta Edad Media, 0-800 D.C., y PEH, 1200-1850 D.C.) y con un aumento de la presión antrópica en las cuencas relacionado con el desarrollo de la ganadería trashumante –la Mesta-, con la consecuente deforestación para la obtención de pastos (siglos XII-XIII).

Los cambios recientes asociados con el éxodo rural y el abandono de tierras durante la mitad del siglo XX son más importantes en las cuencas grandes, debido a la reducción del sedimento que llega a las lagunas por efecto de la reforestación.

El estudio de la erosión y acumulación de sedimentos en las cuatro cuencas lacustres bajo características climáticas y fisiográficas similares revela una variabilidad importante en la acumulación de sedimentos, pero una respuesta similar en términos de frecuencia e intensidad en la erosión de las cuencas a lo largo del tiempo.

6.4 Cuantificación del impacto de los usos del suelo en las cuencas

Se ha desarrollado una nueva metodología basada en los métodos descritos por Einsele and Hinderer (1998) para calcular la masa de sedimento acumulada en las lagunas (Ml), la masa mínima denudada en las cuencas (Md) y la tasa total de denudación (DRt) durante el último milenio en cuatro cuencas lacustres de la rama occidental de la Cordillera Ibérica.

Comparando los datos obtenidos de las lagunas con datos de las cuencas experimentales monitorizadas en los Pirineos, el tamaño de la cuenca, la

cobertera vegetal y la predisposición a la erosión de las formaciones geológicas y suelos son factores fundamentales que controlan los flujos de sedimentos en las montañas mediterráneas.

La precipitación (intensidad, estacionalidad, producción de escorrentía) y la cobertera vegetal (extensión de las zonas forestales, degradadas, usos del suelo) son factores clave que controlan la erosión tanto en las cuencas experimentales como en las cuencas lacustres.

Los resultados enfatizan el efecto predominante del tamaño de la cuenca en relación a la cantidad de sedimento que llega a las lagunas, confirmando el papel dominante de la cobertera vegetal y los cambios en los usos del suelo como controles principales en la erosión de las cuencas mediterráneas a escala centenaria.

La masa de sedimentos acumulada en las lagunas (Ml) presenta valores muy variables, pero coherentes en el tiempo para cada laguna. Esta variabilidad está asociada principalmente con el tamaño de la cuenca.

Los valores obtenidos para la mínima masa denudada en las cuencas (Mdc) y la tasa de denudación total (DRt) para las cuencas monitorizadas y los obtenidos por las secuencias lacustres son comparables e independientes del tamaño de las cuencas.

En ambas situaciones (lagunas y cuencas experimentales) los mayores aportes de sedimento tienen lugar durante eventos de inundación. Los resultados subrayan la naturaleza discontinua de la dinámica sedimentaria en los ambientes mediterráneos a escala de décadas y siglos.

Los aportes de sedimento lacustre reconstruidos y su tasa de denudación relacionada durante estos eventos presenta diferentes órdenes de magnitud (100 – 98,000 T and 6 – 480 T km^{-2} yr^{-1} respectivamente).

Los valores reconstruidos para la masa denudada por evento en las cuencas lacustres vegetadas son similares (< 30 T km^{-2} yr^{-1}) a la producción de sedimentos en las cuencas experimentales de alta montaña.

Los valores de producción de sedimento por inundación en las cuencas experimentales con usos agrarios abandonados (69 T km^{-2}) están en el rango inferior de las cuencas lacustres (from 60 to 480 T km^{-2} yr^{-1})

Ninguno de los valores obtenidos para las cuencas lacustres ha alcanzado los valores documentados para la cuenca experimental que presenta badlands (3094 T km^{-2}).

6.5 Sinergias entre impacto humano, clima y dinámica de las cuencas

Los periodos y eventos de aumento en los aportes de sedimento en los lagos estudiados correlacionan bien con los cambios históricos en los usos del suelo de la región: principalmente cambios en la cobertera vegetal debido a una intensa deforestación causada por la trashumancia extensiva y otros objetivos agrícolas y de aprovechamiento del entorno.

Los efectos sinérgicos entre los impactos climáticos y antrópicos fueron particularmente intensos al comienzo y durante la última parte de la PEH y desde el siglo XVIII, cuando la señal climática fue amplificada por la alteración humana, provocando una mayor erosión y el consiguiente aumento en la producción de sedimento, resultando en mayores tasas de sedimentación y masas de acumulación de sedimento en las lagunas y mayores tasas de denudación en las cuencas.

Este estudio demuestra que los procesos de degradación, especialmente en cuencas de montaña sin importar su extensión, están intensamente relacionados con la evolución medioambiental y los impactos humanos por medio de los cambios históricos en los usos del suelo.

Por último, es necesario recordar que para el planteamiento de estrategias de conservación en sistemas lacustres fuertemente afectados por procesos de degradación como consecuencia de un paisaje cultural heredado a través de cientos de años de actividades humanas, es necesario tener en consideración el grado de alteración que han experimentado y las causas históricas de dichas modificaciones, llegando a establecer políticas de intervención específicas para cada situación concreta.

7

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8 Appendix

Set up of the coring platform in Lake La Parra.
Montaje de la plataforma de sondeos en la Laguna de La Parra.

8.1. Factor de impacto y áreas temáticas de las publicaciones

Aquí se incluye el factor de impacto de las revistas y áreas temáticas correspondientes a las publicaciones que se recogen en esta Tesis Doctoral así como las cartas de aceptación de los artículos pendientes de publicar:

Below is detailed the impact factor of the journals and thematic areas related to the publications that constitute this PhD Thesis and the approval letters of the articles pending of publication:

Research article 1

Barreiro-Lostres, F., Moreno, A., Giralt, S., Valero-Garcés, B.L., 2013. Evolución sedimentaria del lago kárstico de La Parra (Cuenca) durante los últimos 1600 años: paleohidrología, clima e impacto humano. Cuadernos de Investigación Geográfica 39, 179–193.

Subject area: Earth and Planetary Sciences, Environmental Science, Social Sciences

Impact factor: 2014 Impact Factor SJR (SCImago Journal Rank): 0.272

Research article 2

Barreiro-Lostres, F., Moreno, A., Giralt, S., Caballero, M., Valero-Garces, B., 2014. Climate, palaeohydrology and land use change in the Central Iberian Range over the last 1.6 kyr: The La Parra Lake record. The Holocene 24, 1177 – 1192. doi:10.1177/0959683614540960.

Subject area: Geography, Physical; Geosciences, Multidisciplinary

Impact factor: 2014 Impact Factor JCR (Journal Citation Reports): 2.283

Research article 3

Barreiro-Lostres, F., Brown, E., Moreno, A., Morellón, M., Abbott, M., Hillman, A., Giralt, S., Valero-Garcés, B., 2015. Sediment delivery and lake dynamics in a Mediterranean mountain watershed: Human-climate interactions during the last millennium (El Tobar Lake record, Iberian Range, Spain). Science of The Total Environment 533, 506–519. doi:10.1016/j.scitotenv.2015.06.123.

Subject area: Environmental Sciences

Impact factor: 2014 Impact Factor JCR (Journal Citation Reports): 4.099

Research article 4

Barreiro-Lostres, F., Moreno, A., González-Sampériz, P., Giralt, S., Nadal-Romero, E., Valero-Garces, B., 201X. Erosion in Mediterranean mountain landscapes during the last millennium: a quantitative approach based on lake sediment sequences (Iberian Range, Spain). CATENA, accepted for publication.

Subject area: Geosciences, Multidisciplinary; Soil Science; Water Resources
Impact factor: 2014 Impact Factor JCR (Journal Citation Reports): 2.820

8.2 Carta de aceptación artículo 4

CATENA4681R1 - Editor decision

Catena para ferbalos 20 may.

Dear Mr. Barreiro-Lostres,

I can now inform you that the reviewers and editor have evaluated the manuscript "Erosion in Mediterranean mountain landscapes during the last millennium: a quantitative approach based on lake sediment sequences (Iberian Range, Spain)" (Mr. Fernando Barreiro-Lostres). I am pleased to say that it has been favourably received and publication with minor revision is recommended (see below and on http://ees.elsevier.com/catena/).

Please consider the reviews to see if revision would be feasible.To facilitate further review, add line numbers in the text of your manuscript. Should you wish to resubmit you should explain how and where (i.e. by giving line numbers) each point of the reviewers' comments has been incorporated. For this, use submission item "Revision Notes" when uploading your revision. Also, indicate the changes in anannotated version of the revised manuscript (submission item "Revision, changes marked"). Kindly note that your submission will not be accepted without the marked annotated manuscript. Please follow the order "Revision Notes", "Revision, changes marked", "Manuscript", etc. When submitting your revised manuscript, please ensure that you upload the source files (e.g. Word). Uploading a PDF file at this stage will create delays should your manuscript be finally accepted for publication. If your revised submission does not include the source files, we will contact you to request them.

Should you disagree with any part of the reviews, please explain why.

Please strictly follow the formatting requirements as presented in the Guide for Authors.

Given that the requested revisions are fairly minor the new version is required within the month.

To submit a revision, go to http://ees.elsevier.com/catena/ and log in as an author. You will find your submission record under Submission(s) Needing Revision.

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When resubmitting, please present any figures, tables etc. as separate files. See the Artwork Guidelines on the home page right menu for further file naming conventions, referencing and format issues.

I hope that you will find the comments to be of use to you and am looking forward with interest to receiving your revision.

Please note that this journal offers a new, free service called AudioSlides: brief, webcast-style presentations that are shown next to published articles on ScienceDirect (see also http://www.elsevier.com/audioslides). If your paper is accepted for publication, you will automatically receive an invitation to create an AudioSlides presentation.

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Thank you for submitting your work to this journal.

Kind regards,
LH Cammeraat, PhD
Editor
Catena

.....

Important note: If a reviewer has provided a review or other materials as attachments, those items will not be in this letter. Please ensure therefore that you log on to the journal site and check if any attachments have been provided.

COMMENTS FROM EDITORS AND REVIEWERS

Dear authors,

The reviewers consider your contribution as important. Please consider the textual suggestions for improvement in the attached document

Erik Cammeraat

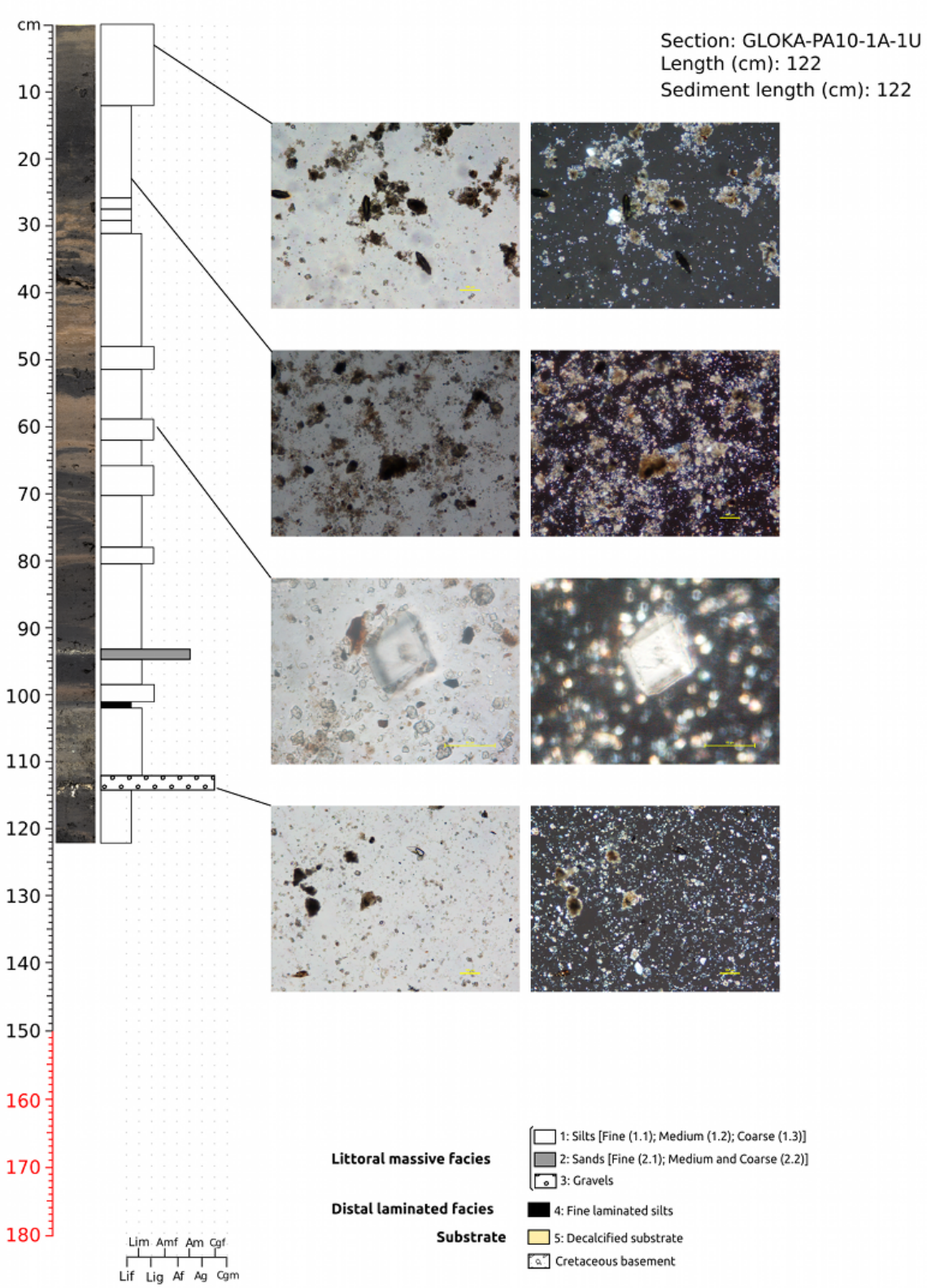
Editor

Reviewer #2: The resubmitted manuscript deserves to be accepted. Minor errata/edits are included. The authors have dealt with all my comments and suggestions.This is an important contribution.

Sincerely, Jonathan Laronne

8.3 Sediment cores used in this PhD Thesis

La Parra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Length (cm): 122
Sediment length (cm): 122
cm
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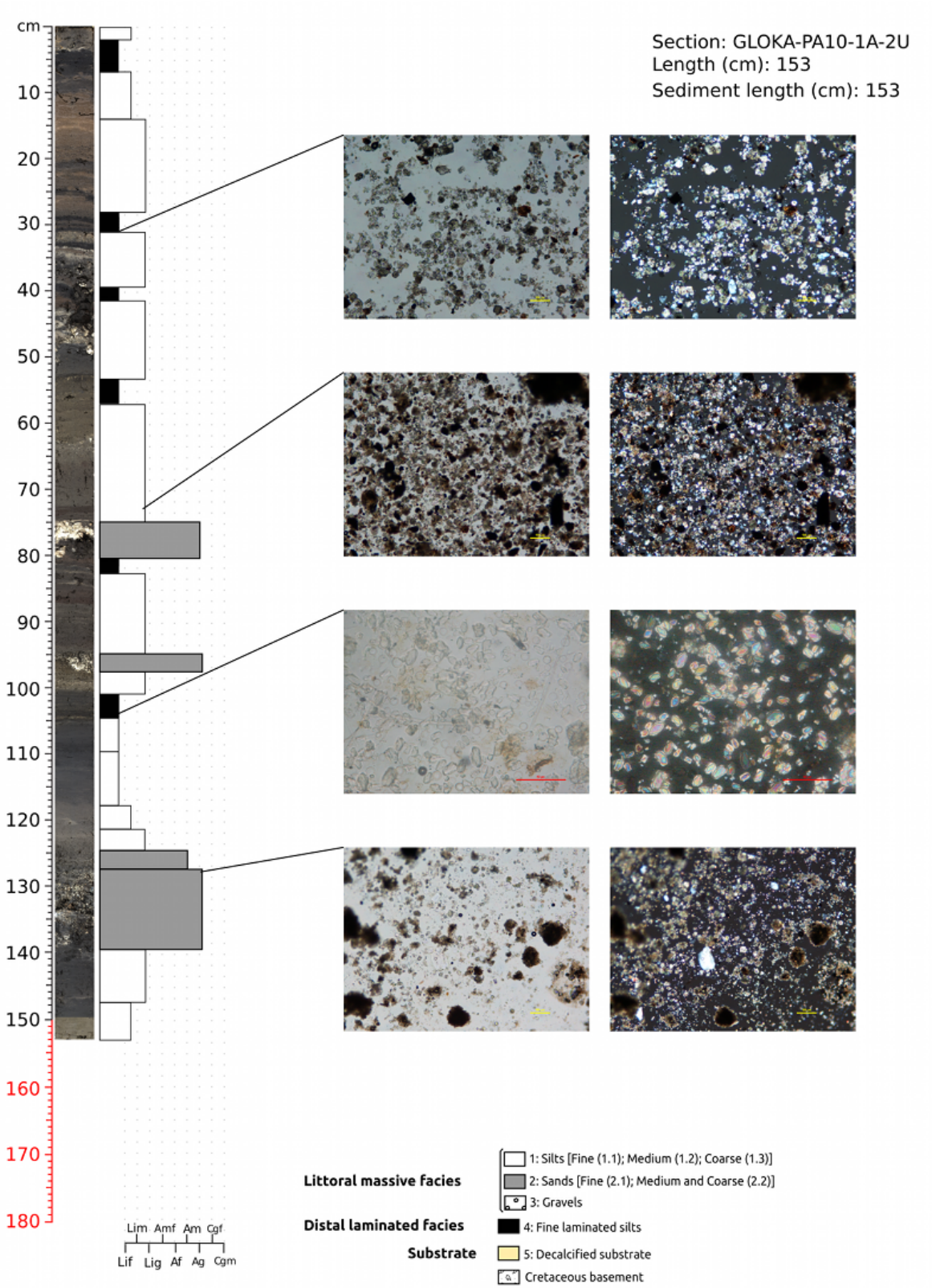
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral massive facies
1: Silts [Fine (1.1); Medium (1.2); Coarse (1.3)]
2: Sands [Fine (2.1); Medium and Coarse (2.2)]
3: Gravels
Distal laminated facies
4: Fine laminated silts
Substrate
5: Decalcified substrate
Cretaceous basement


Section: GLOKA-PA10-1A-2U
Length (cm): 153
Sediment length (cm): 153
cm
10
20
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40
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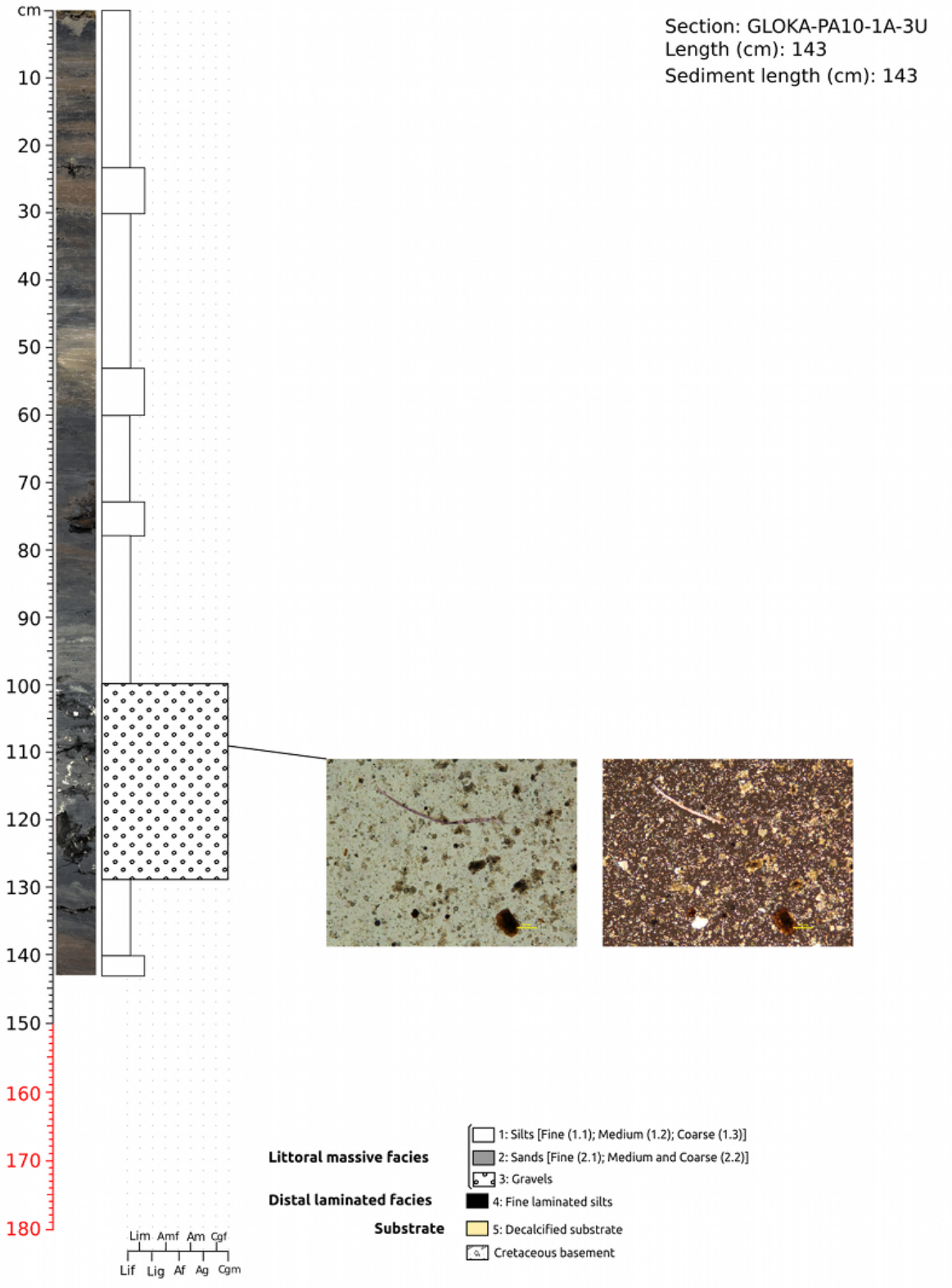
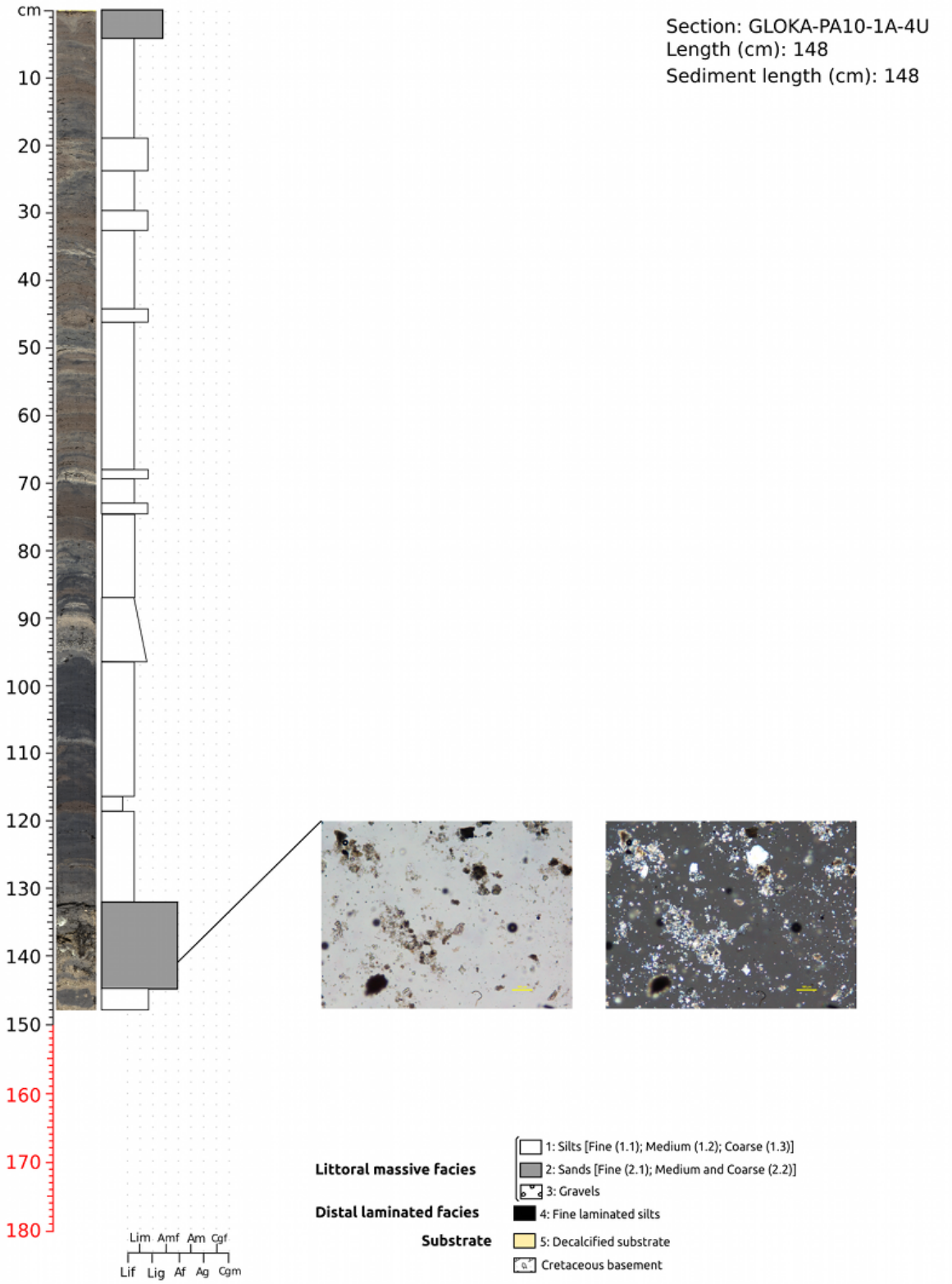
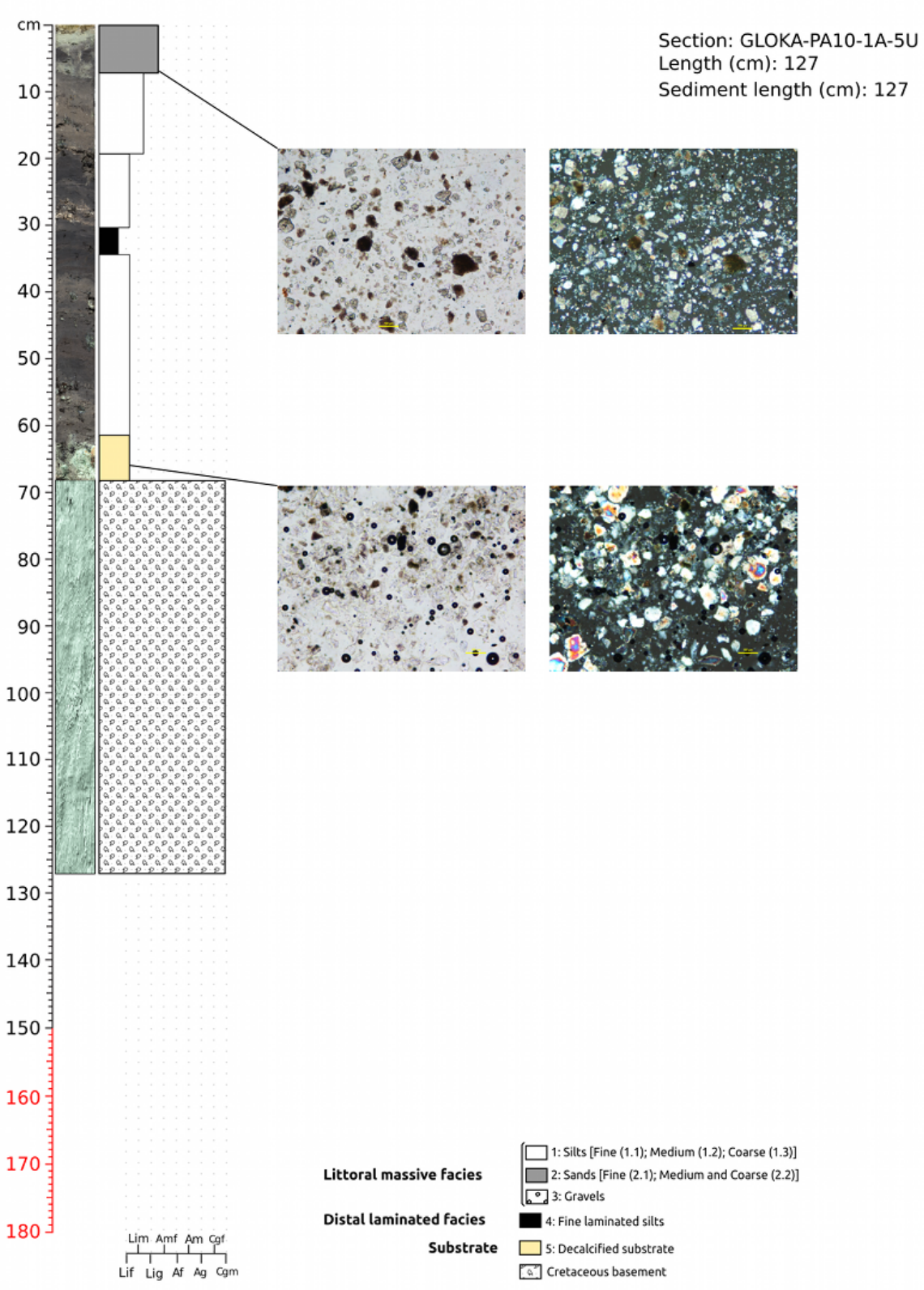
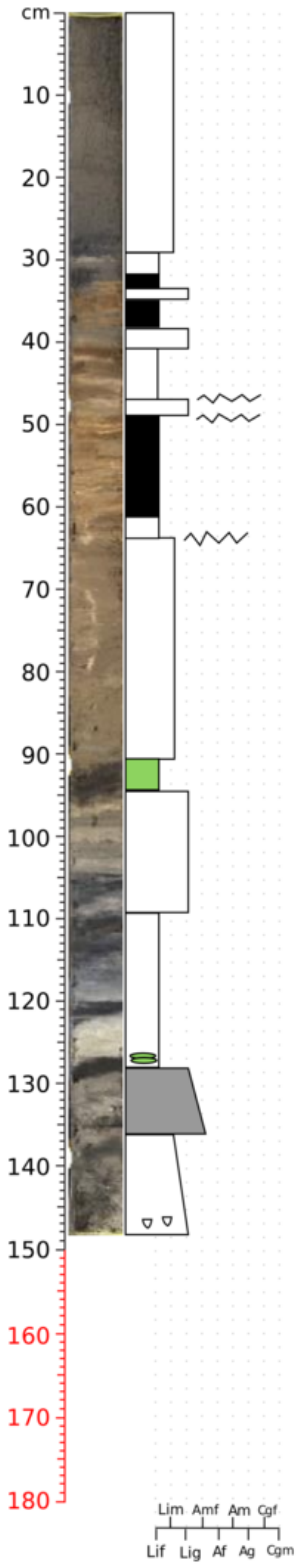
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral massive facies
Distal laminated facies
Substrate
1: Silts [Fine (1.1); Medium (1.2); Coarse (1.3)]
2: Sands [Fine (2.1); Medium and Coarse (2.2)]
3: Gravels
4: Fine laminated silts
5: Decalcified substrate
Cretaceous basement


Section: GLOKA-PA10-1A-3U
Length (cm): 143
Sediment length (cm): 143
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral massive facies
Distal laminated facies
Substrate
1: Silts [Fine (1.1); Medium (1.2); Coarse (1.3)]
2: Sands [Fine (2.1); Medium and Coarse (2.2)]
3: Gravels
4: Fine laminated silts
5: Decalcified substrate
Cretaceous basement


Section: GLOKA-PA10-1A-4U
Length (cm): 148
Sediment length (cm): 148
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral massive facies
Distal laminated facies
Substrate
1: Silts [Fine (1.1); Medium (1.2); Coarse (1.3)]
2: Sands [Fine (2.1); Medium and Coarse (2.2)]
3: Gravels
4: Fine laminated silts
5: Decalcified substrate
Cretaceous basement

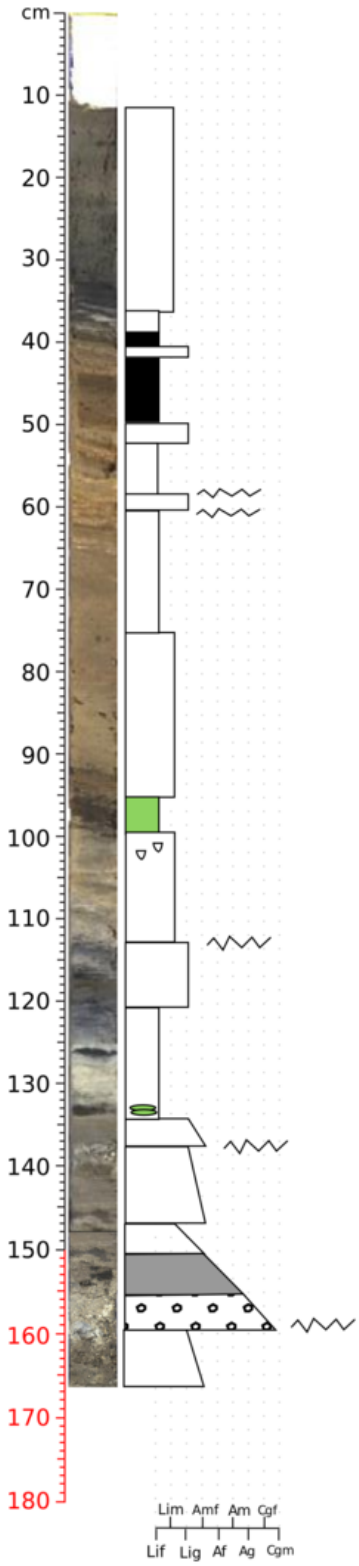

Section: GLOKA-PA10-1A-5U
Length (cm): 127
Sediment length (cm): 127
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral massive facies
Distal laminated facies
Substrate
1: Silts [Fine (1.1); Medium (1.2); Coarse (1.3)]
2: Sands [Fine (2.1); Medium and Coarse (2.2)]
3: Gravels
4: Fine laminated silts
5: Decalcified substrate
Cretaceous basement

El Tejo



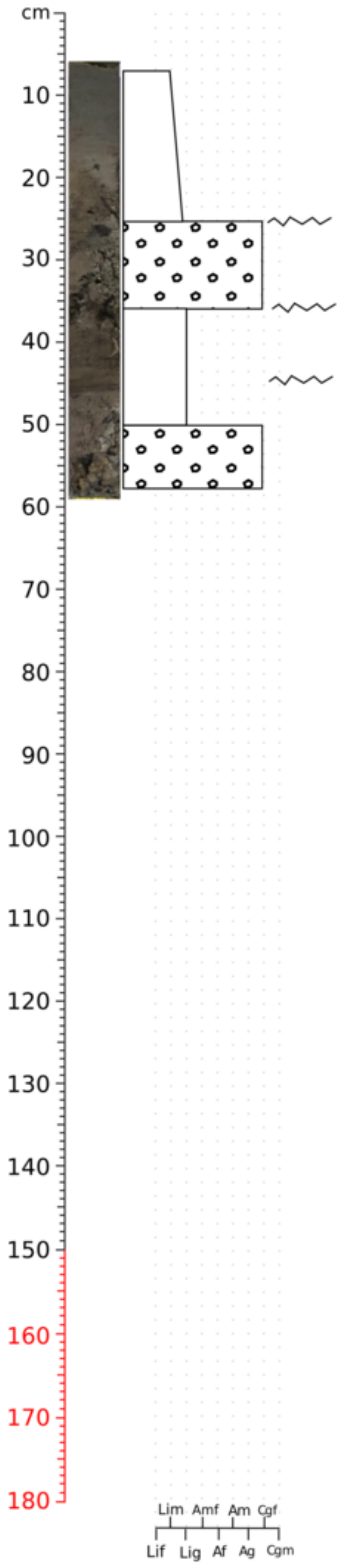
Section: GLOKA-TEJ11-1A-1U
Length (cm): 148
Sediment length (cm): 148

Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)



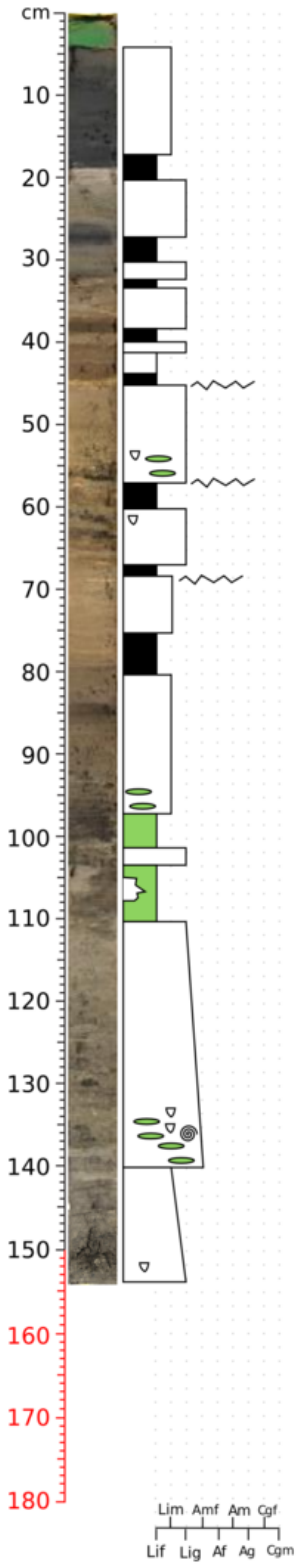
Section: GLOKA-TEJ11-1A-2U
Length (cm): 166
Sediment length (cm): 154

Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)



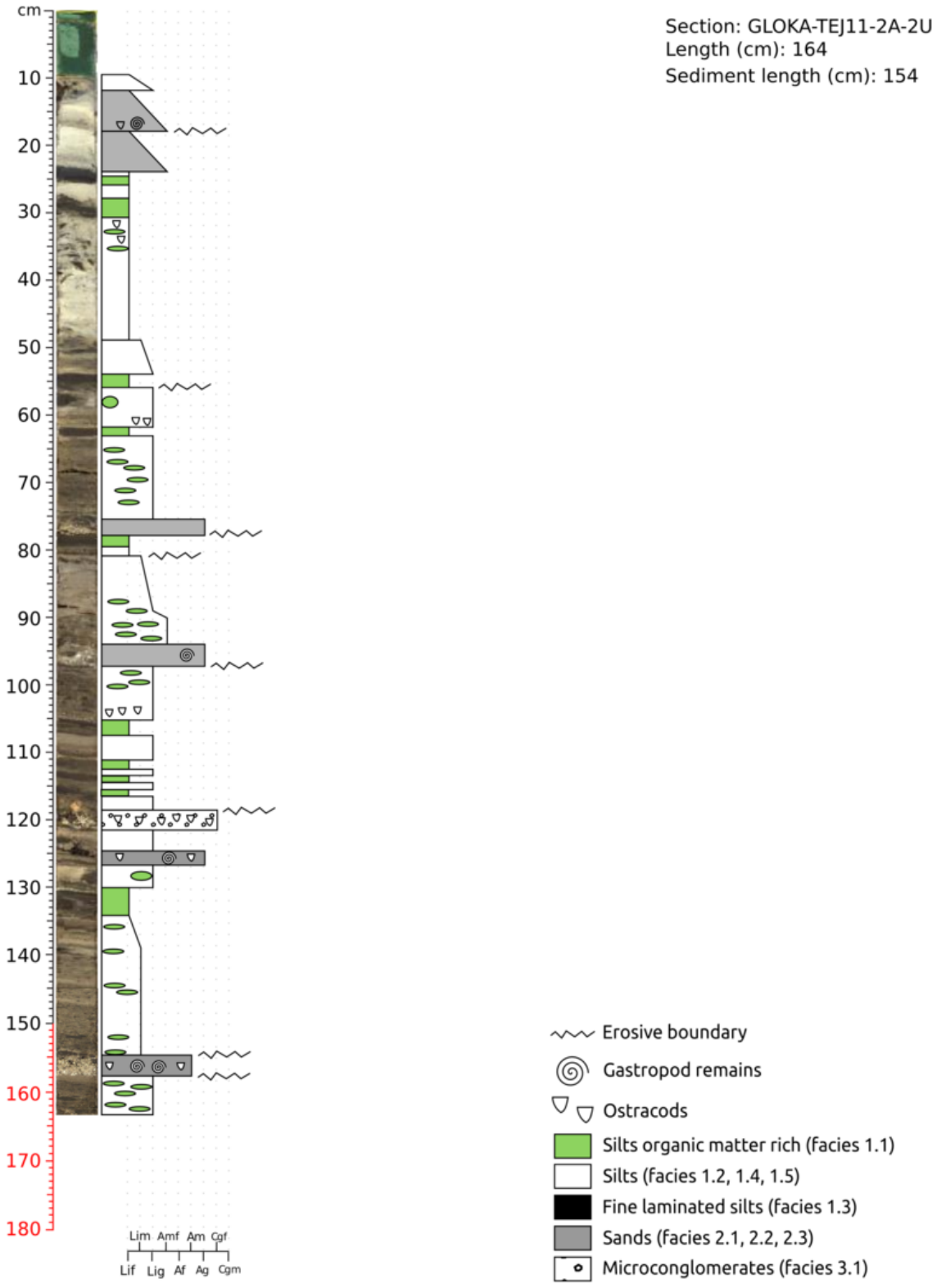
Section: GLOKA-TEJ11-1A-3U
Length (cm): 58
Sediment length (cm): 51

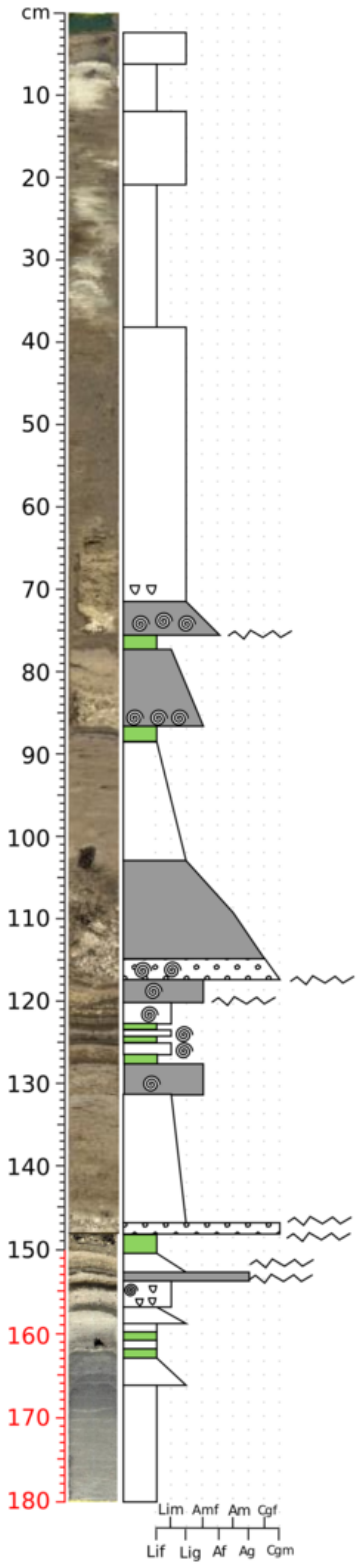
Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)



Section: GLOKA-TEJ11-2A-1U
Length (cm): 154
Sediment length (cm): 150

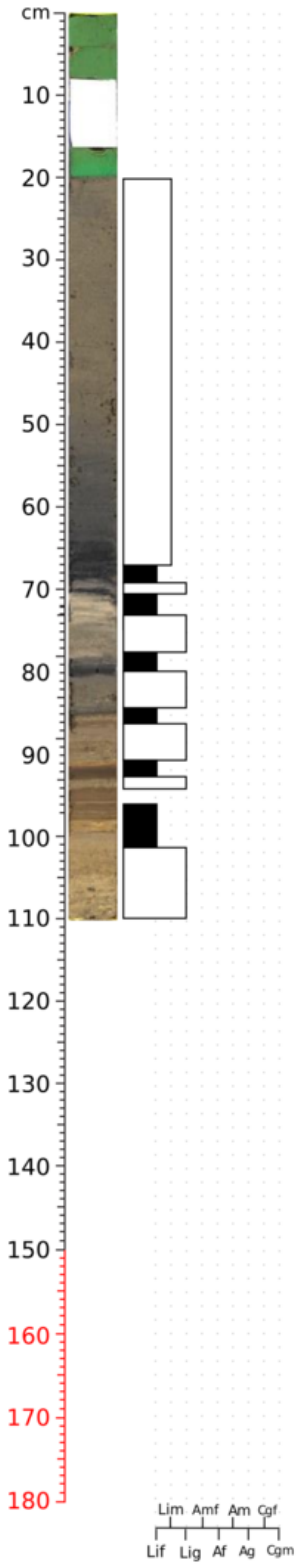
Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)


Section: GLOKA-TEJ11-2A-2U
Length (cm): 164
Sediment length (cm): 154
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)



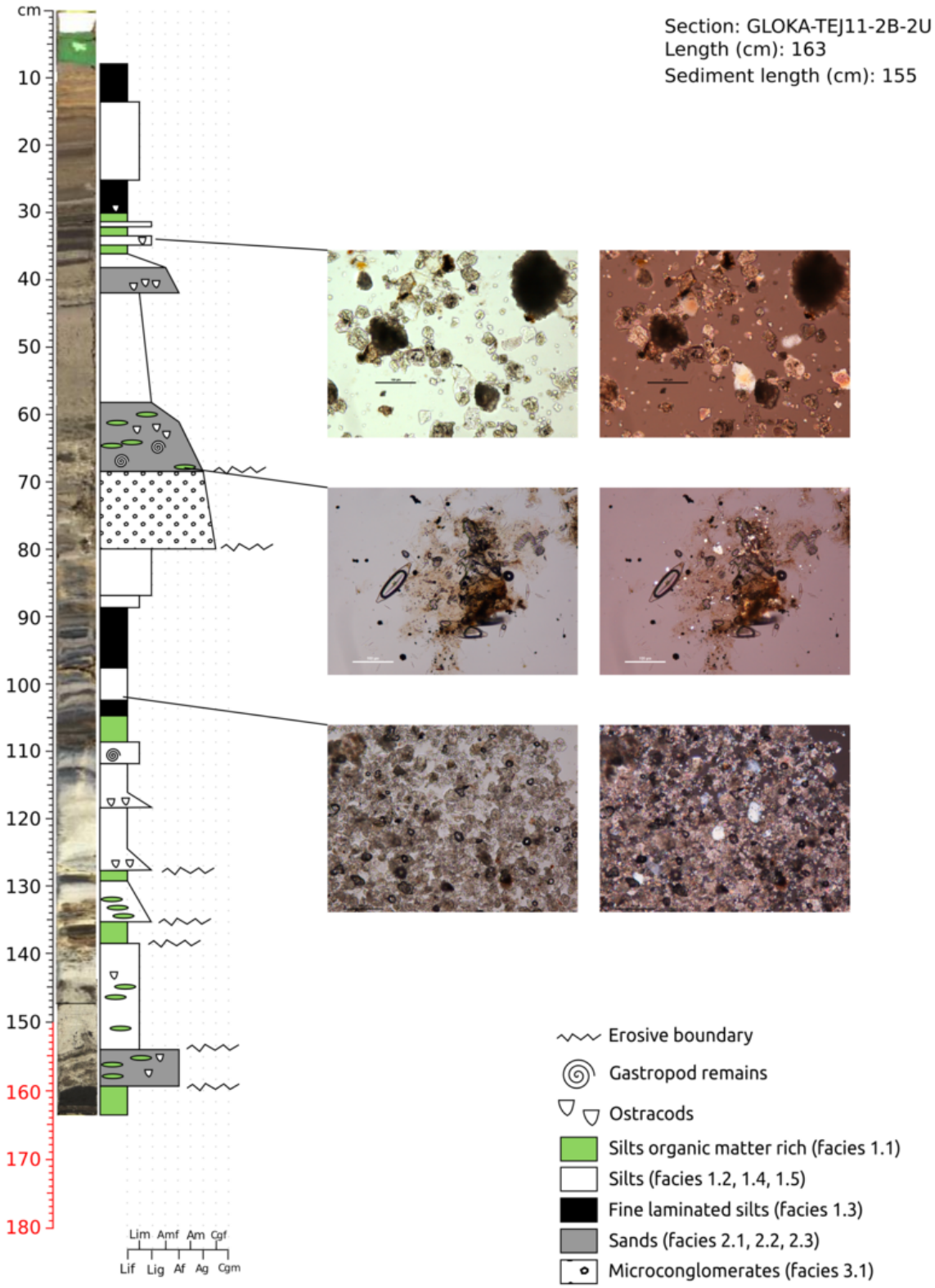
Section: GLOKA-TEJ11-2A-3U
Length (cm): 180
Sediment length (cm): 173

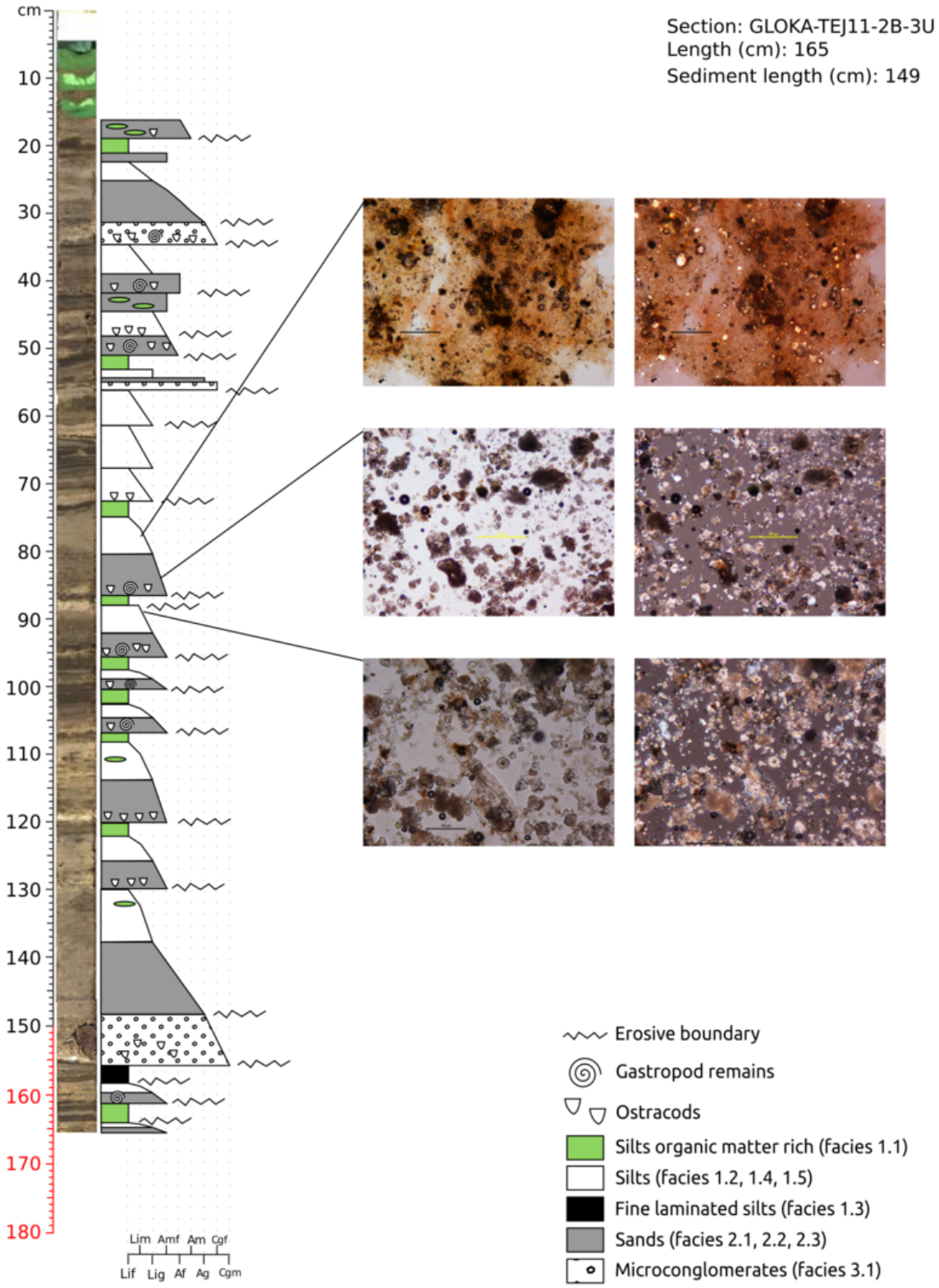
Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)

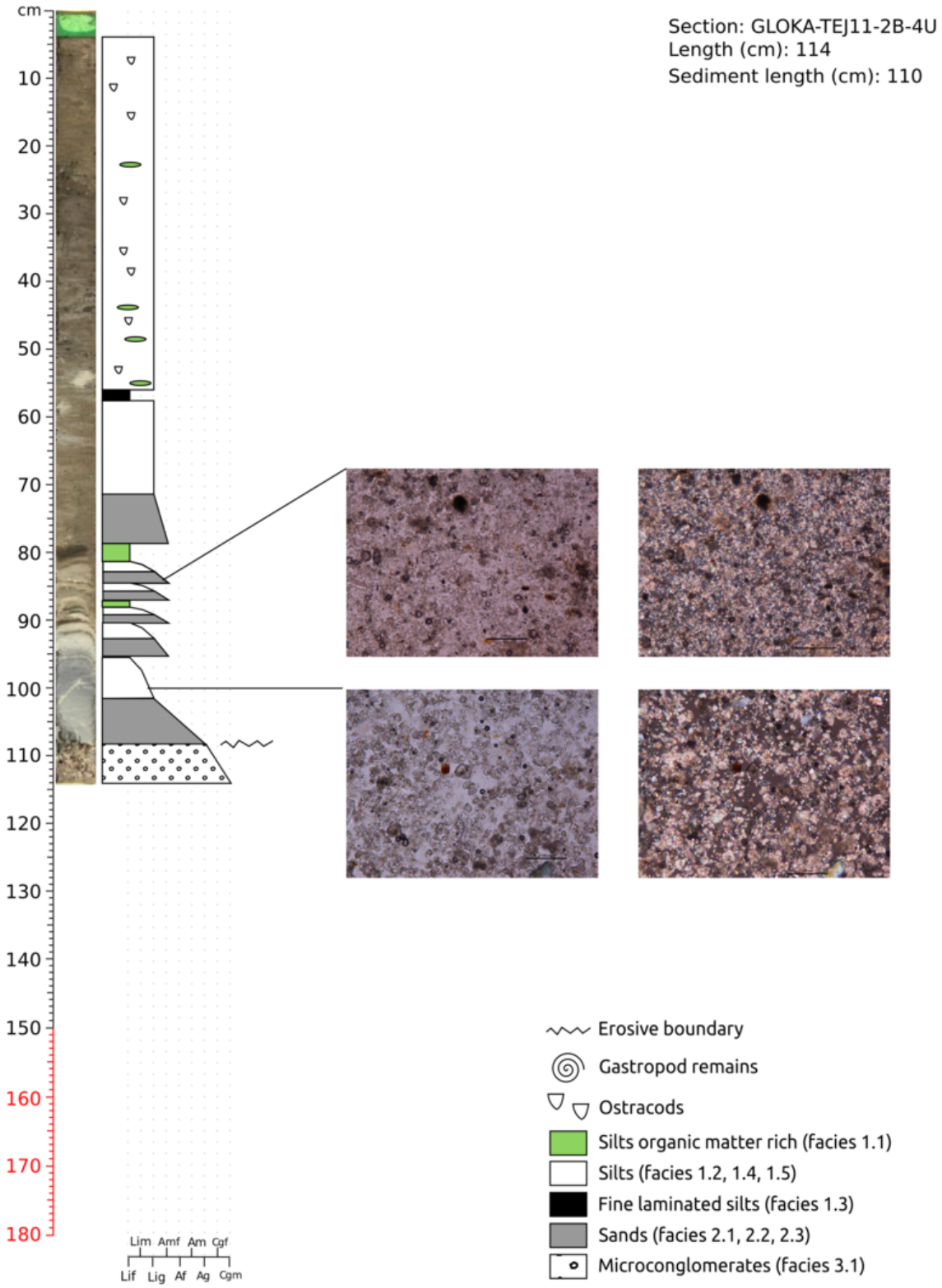


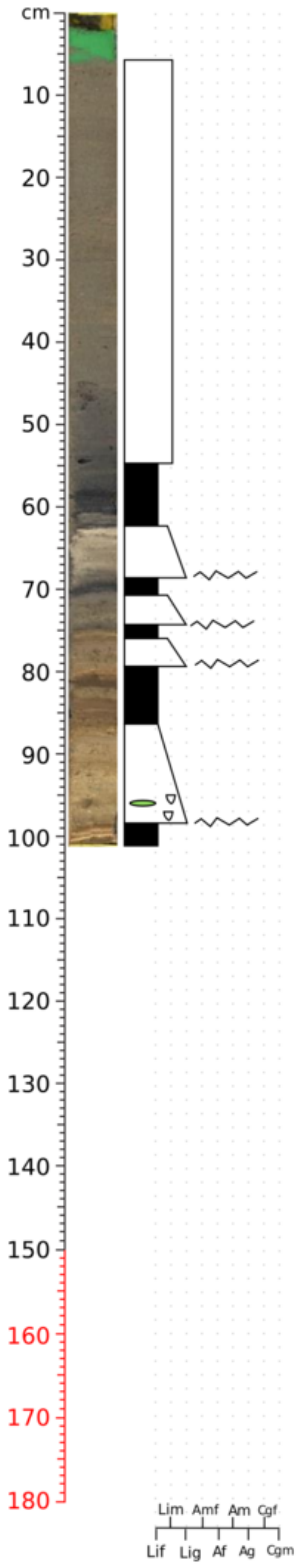
Section: GLOKA-TEJ11-2B-1U
Length (cm): 110
Sediment length (cm): 90

Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)


Section: GLOKA-TEJ11-2B-2U
Length (cm): 163
Sediment length (cm): 155
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)

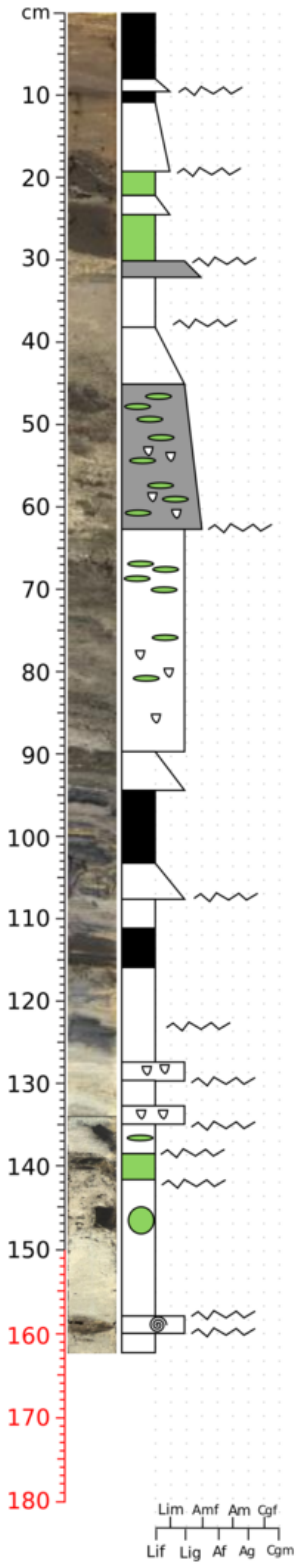

Section: GLOKA-TEJ11-2B-3U
Length (cm): 165
Sediment length (cm): 149
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)


Section: GLOKA-TEJ11-2B-4U
Length (cm): 114
Sediment length (cm): 110
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)



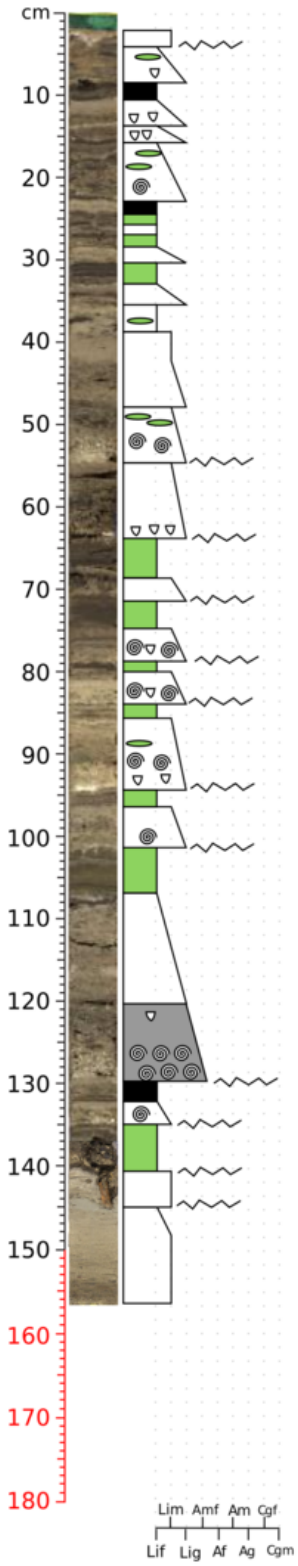
Section: GLOKA-TEJ11-2C-1U
Length (cm): 100
Sediment length (cm): 94

Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)



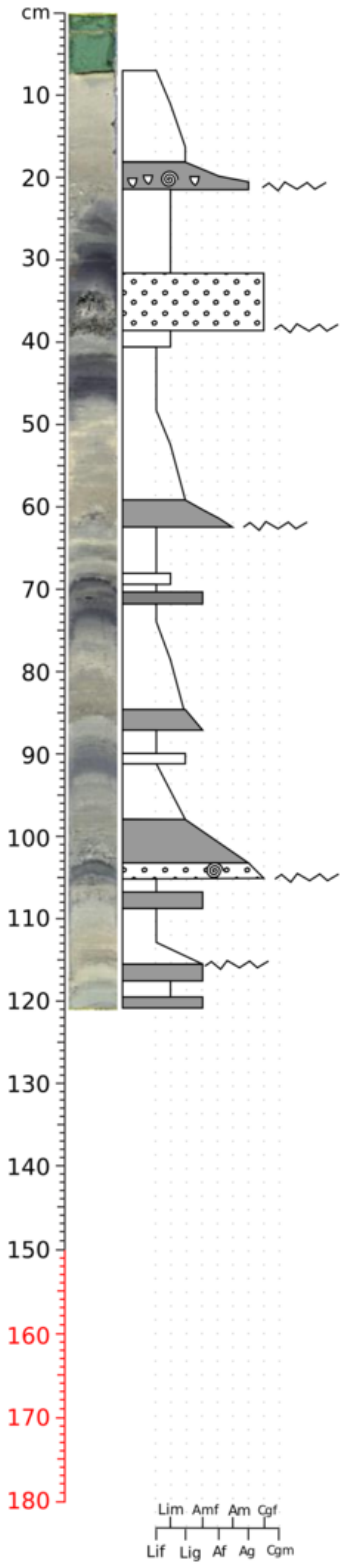
Section: GLOKA-TEJ11-2C-2U
Length (cm): 162
Sediment length (cm): 162

Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)



Section: GLOKA-TEJ11-2C-3U
Length (cm): 156
Sediment length (cm): 154

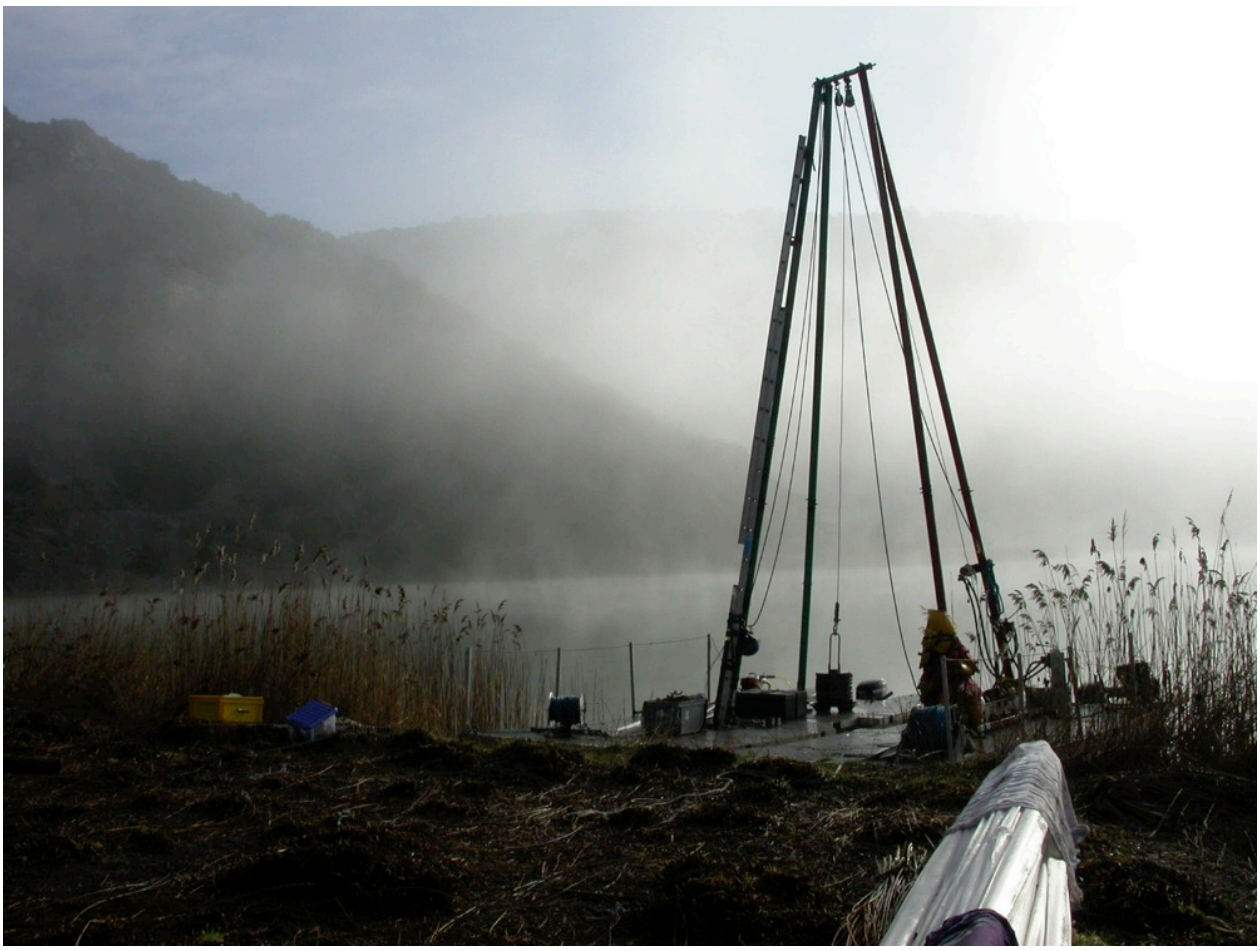
Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)

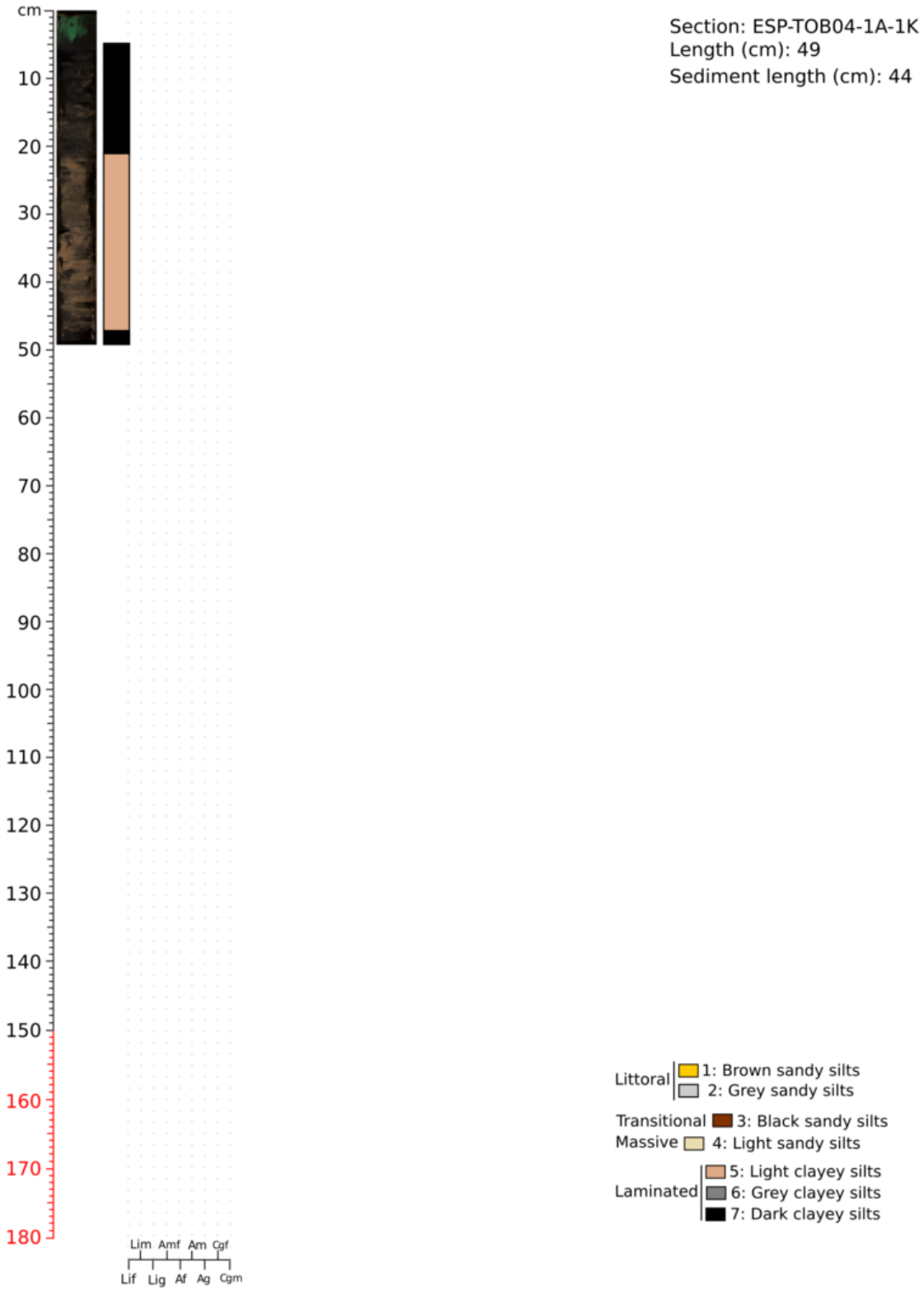


Section: GLOKA-TEJ11-2C-4U
Length (cm): 121
Sediment length (cm): 114

Erosive boundary
Gastropod remains
Ostracods
Silts organic matter rich (facies 1.1)
Silts (facies 1.2, 1.4, 1.5)
Fine laminated silts (facies 1.3)
Sands (facies 2.1, 2.2, 2.3)
Microconglomerates (facies 3.1)

El Tobar




cm
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40
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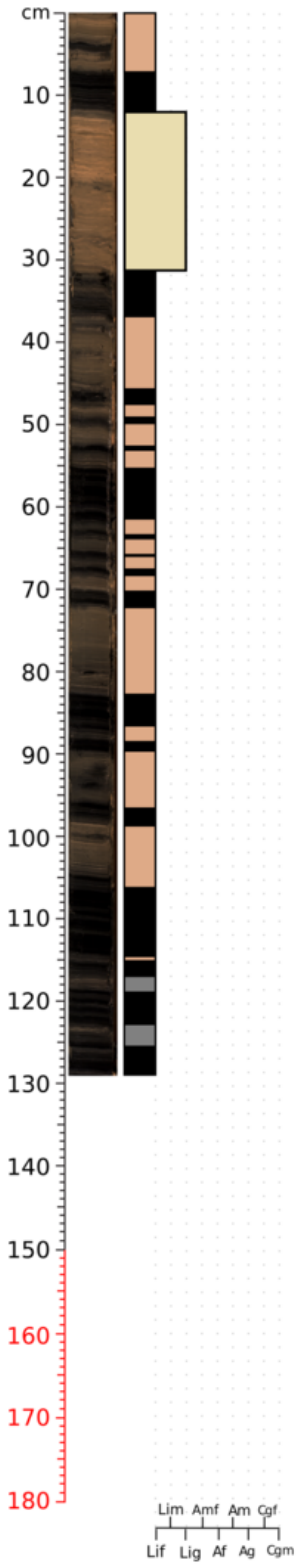
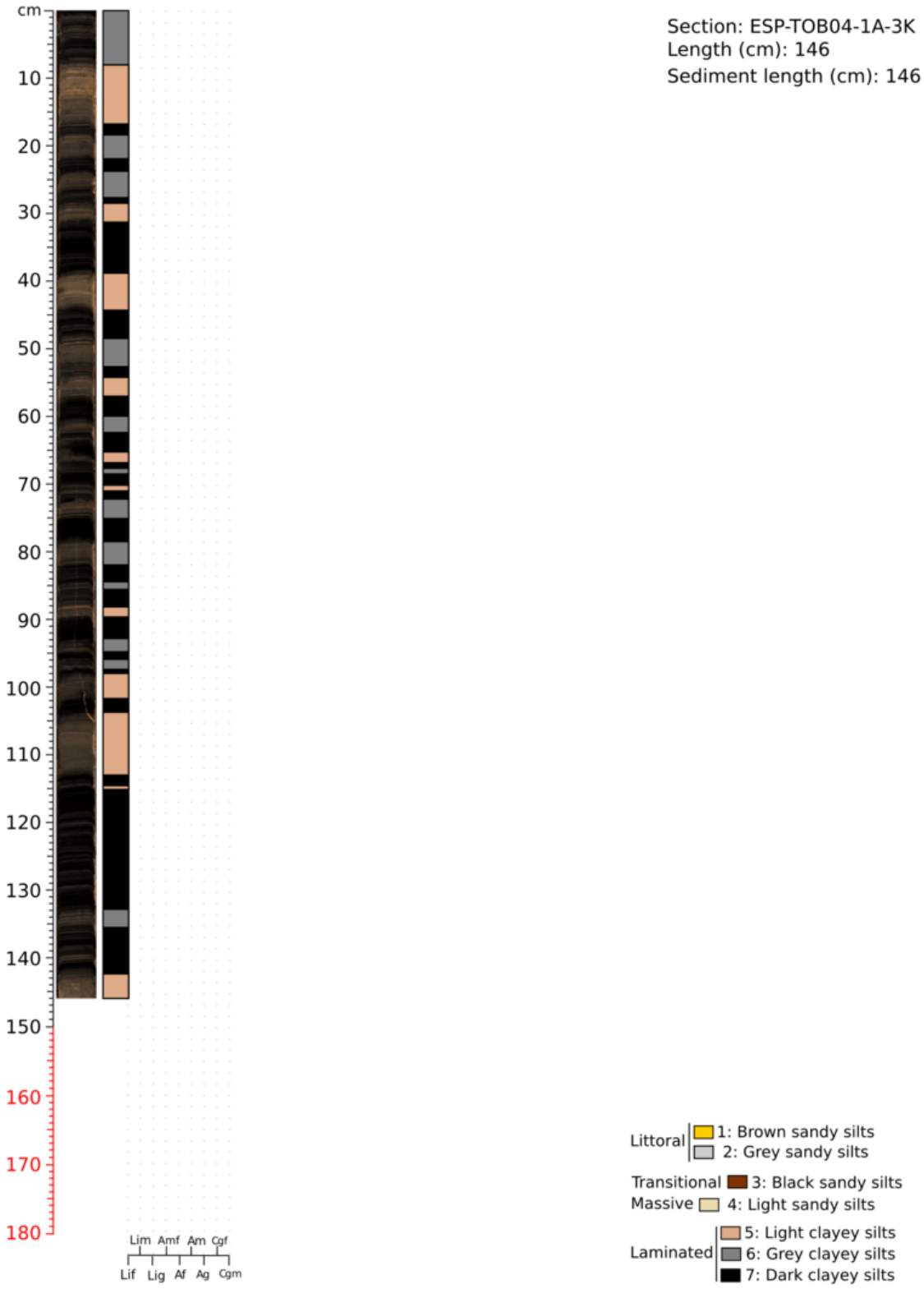
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim
Amf
Am
Cgf
Lif
Lig
Af
Ag
Cgm
Section: ESP-TOB04-1A-1K
Length (cm): 49
Sediment length (cm): 44
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts



Section: ESP-TOB04-1A-2K
Length (cm): 129
Sediment length (cm): 129

Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts


cm
10
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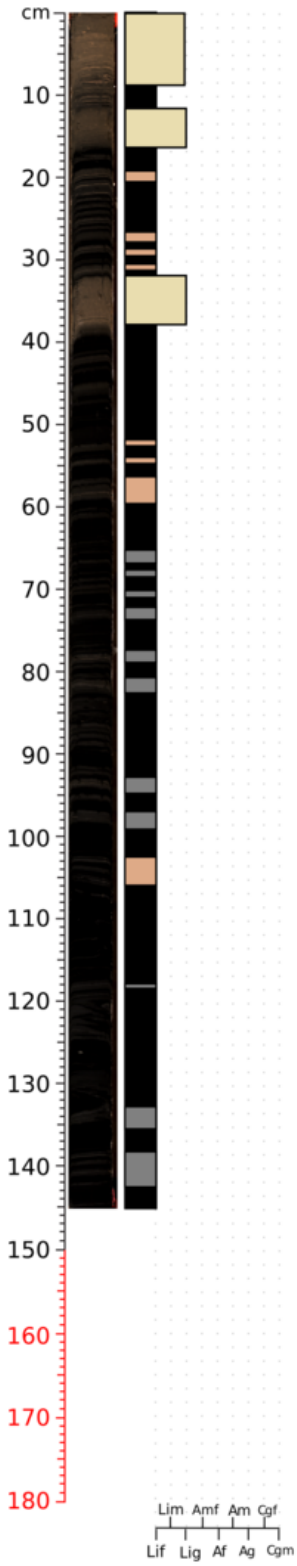
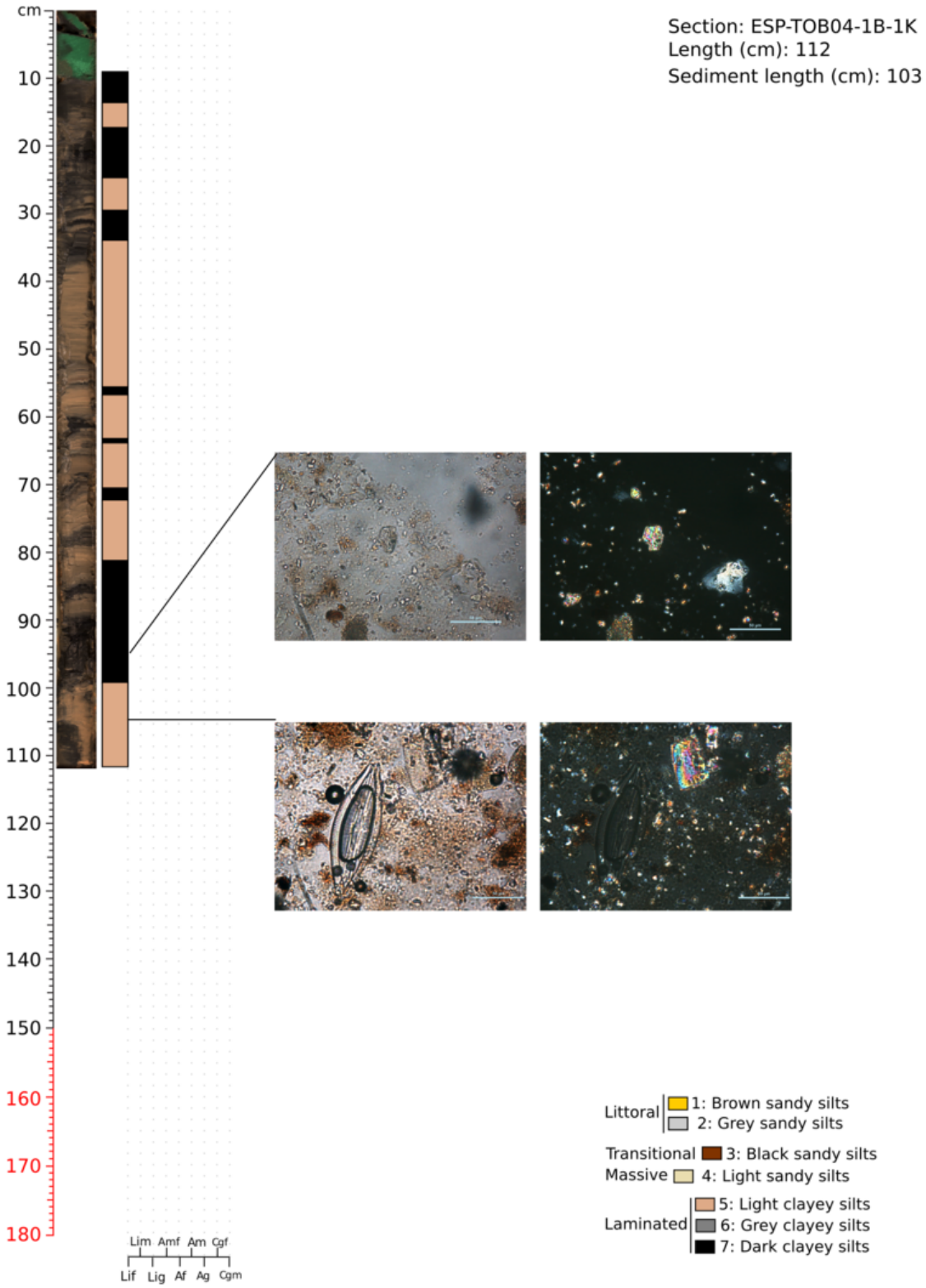
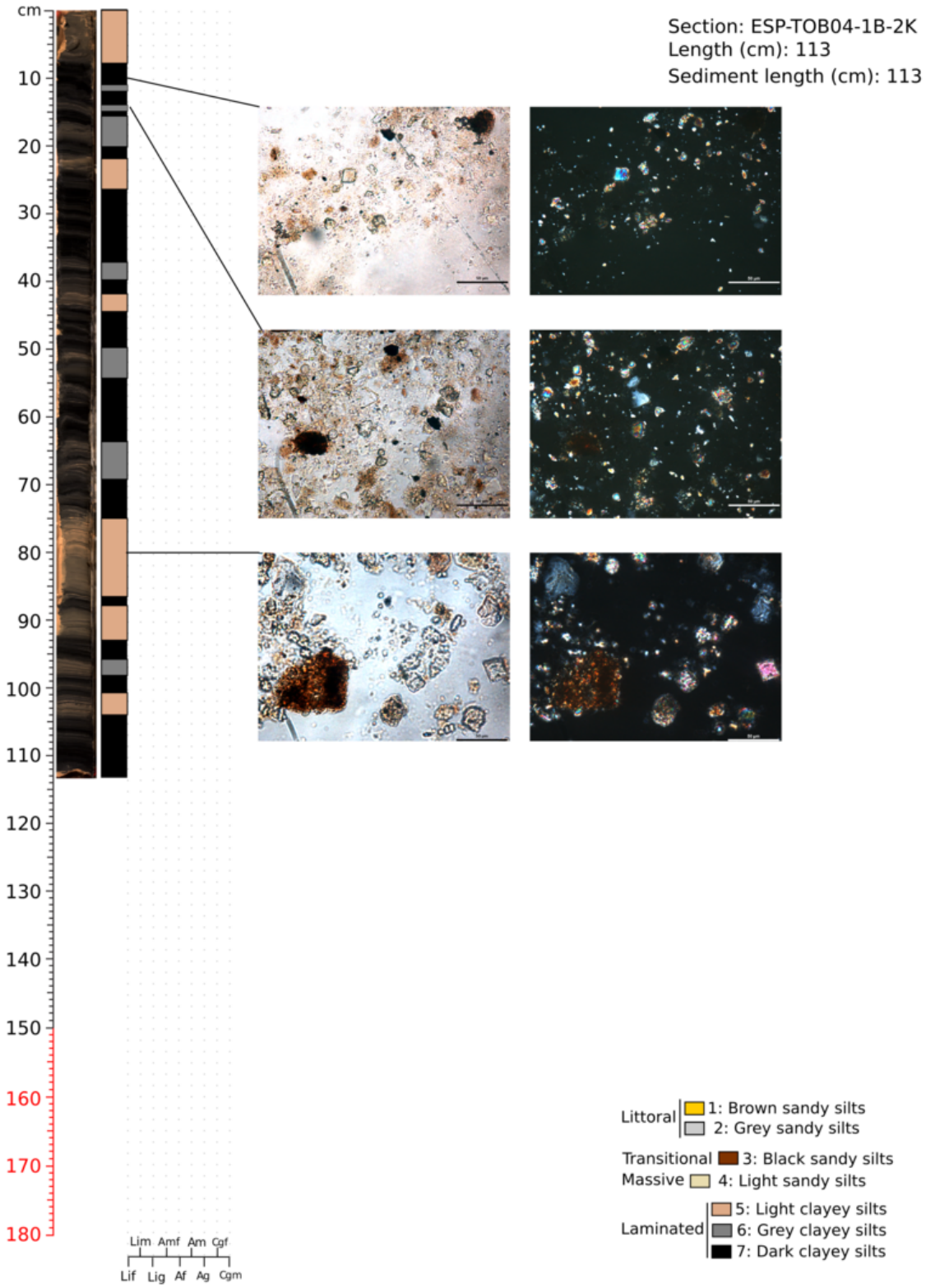
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Section: ESP-TOB04-1A-3K
Length (cm): 146
Sediment length (cm): 146
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts

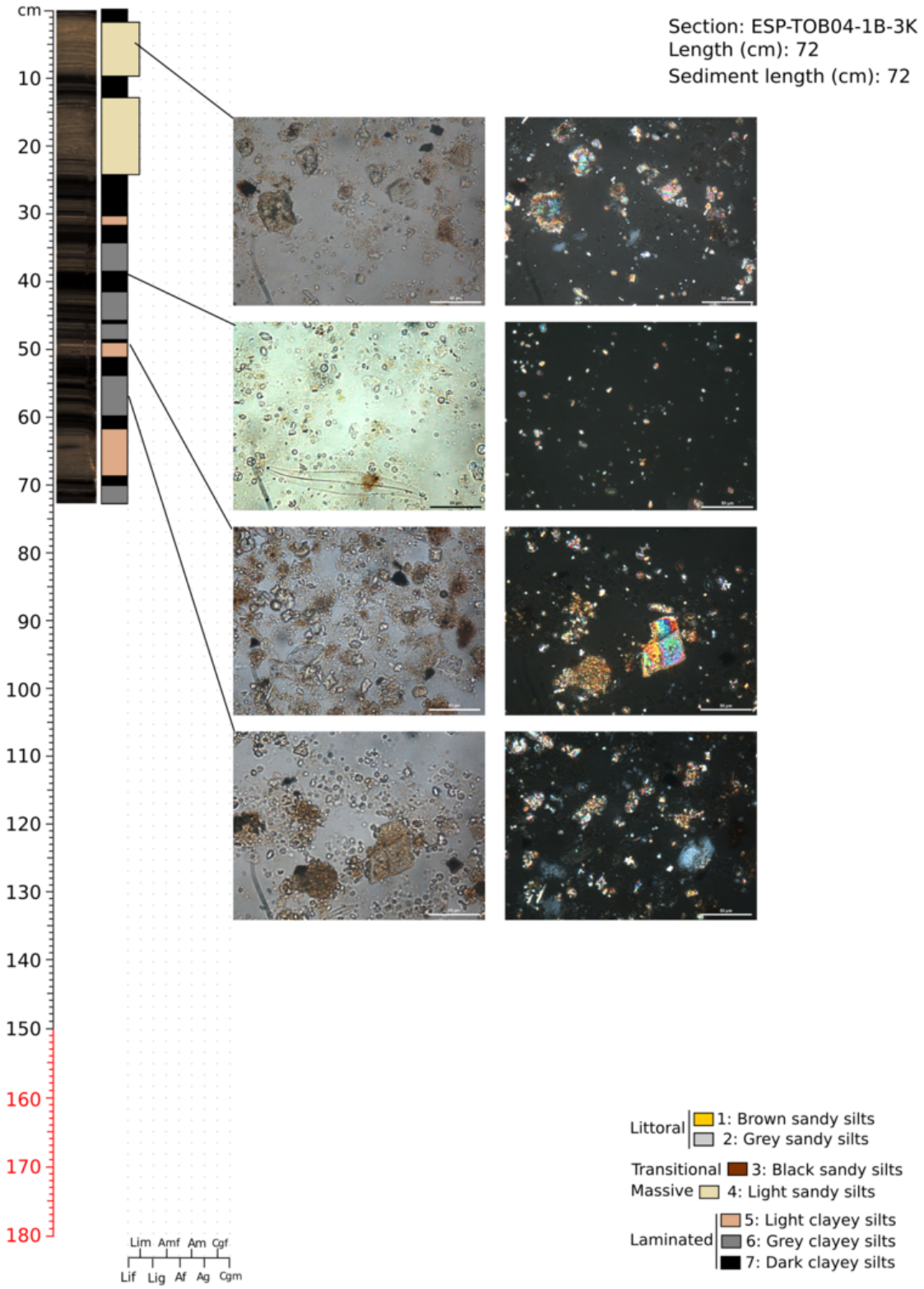


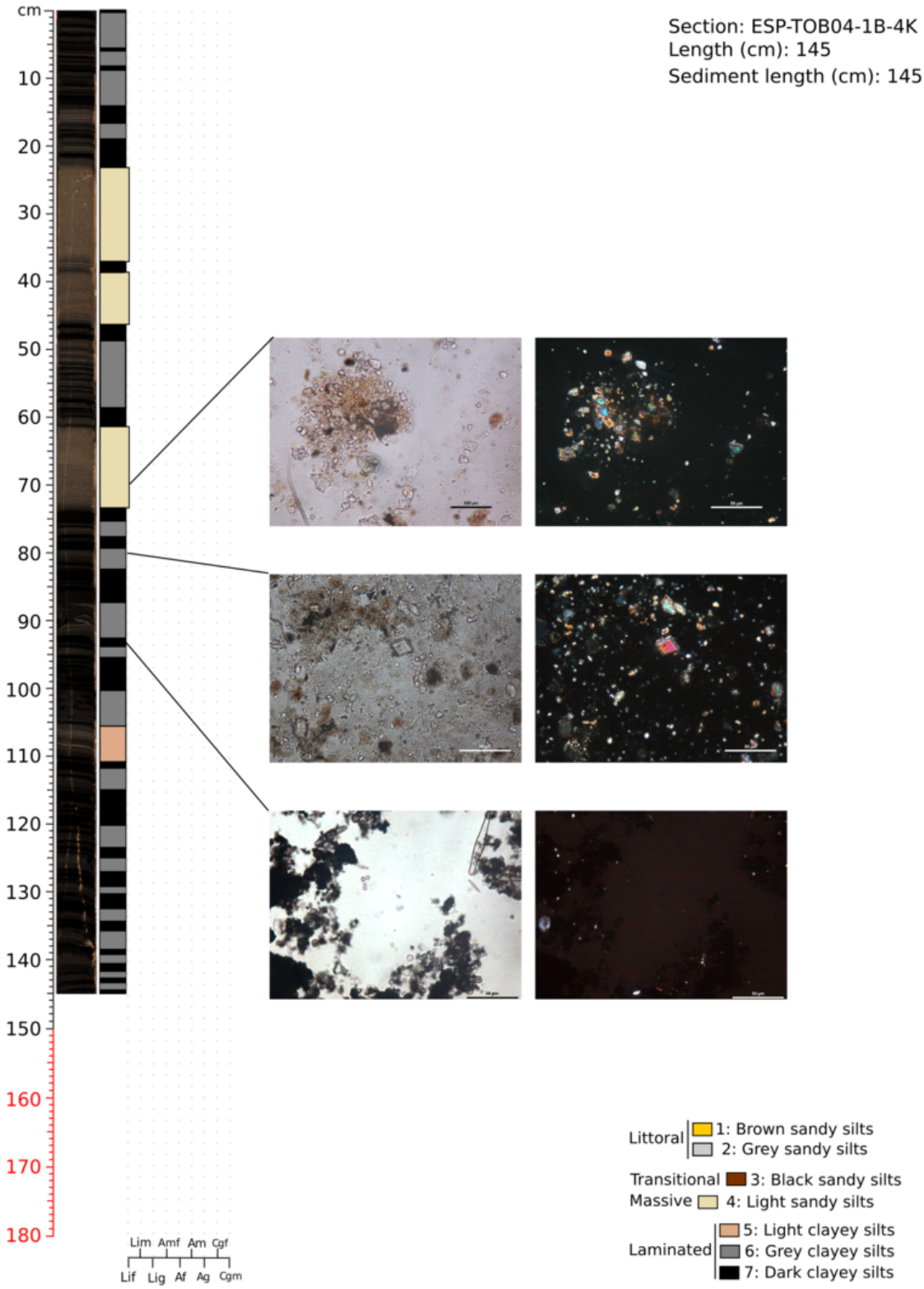
Section: ESP-TOB04-1A-4K
Length (cm): 145
Sediment length (cm): 145

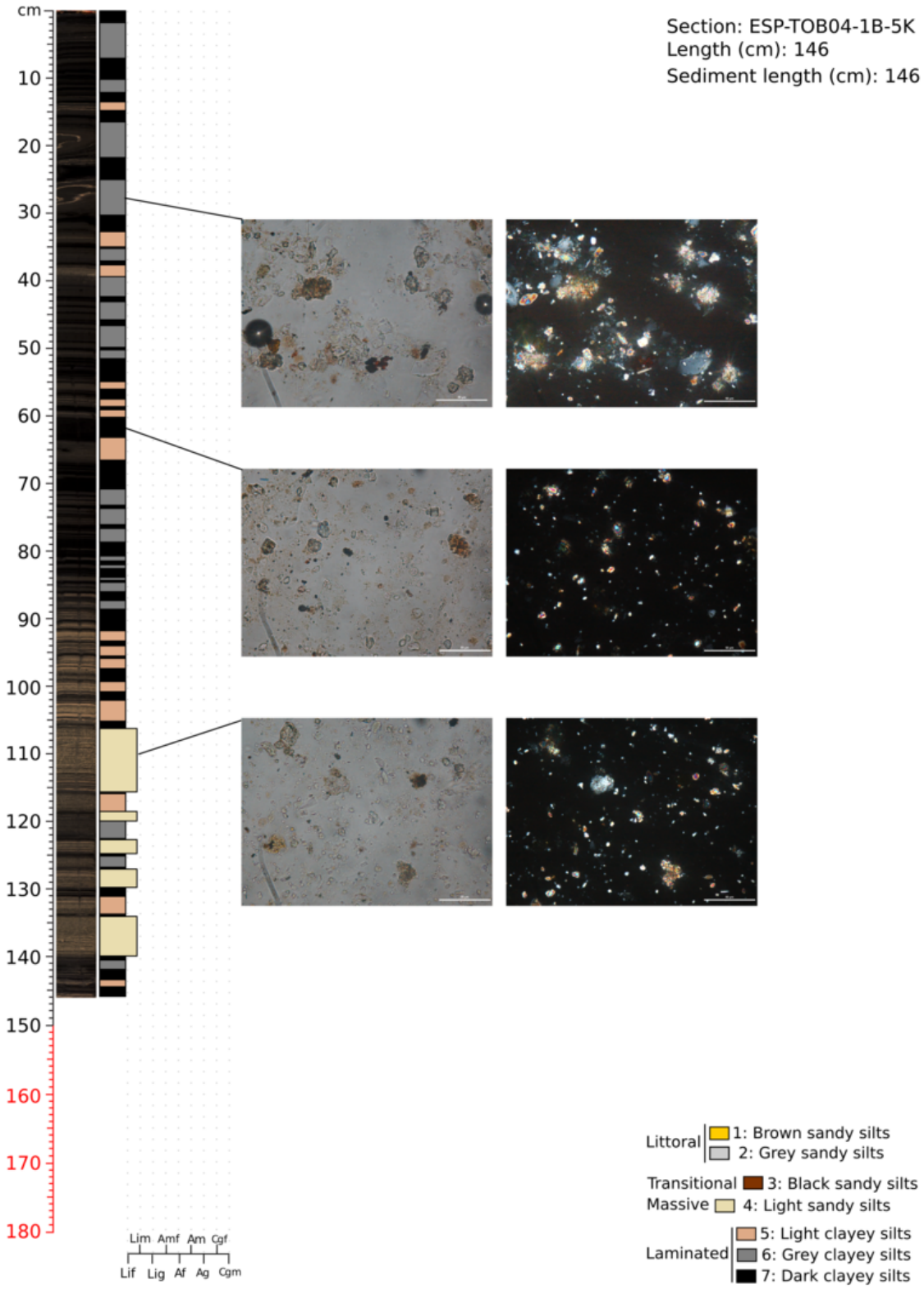
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts

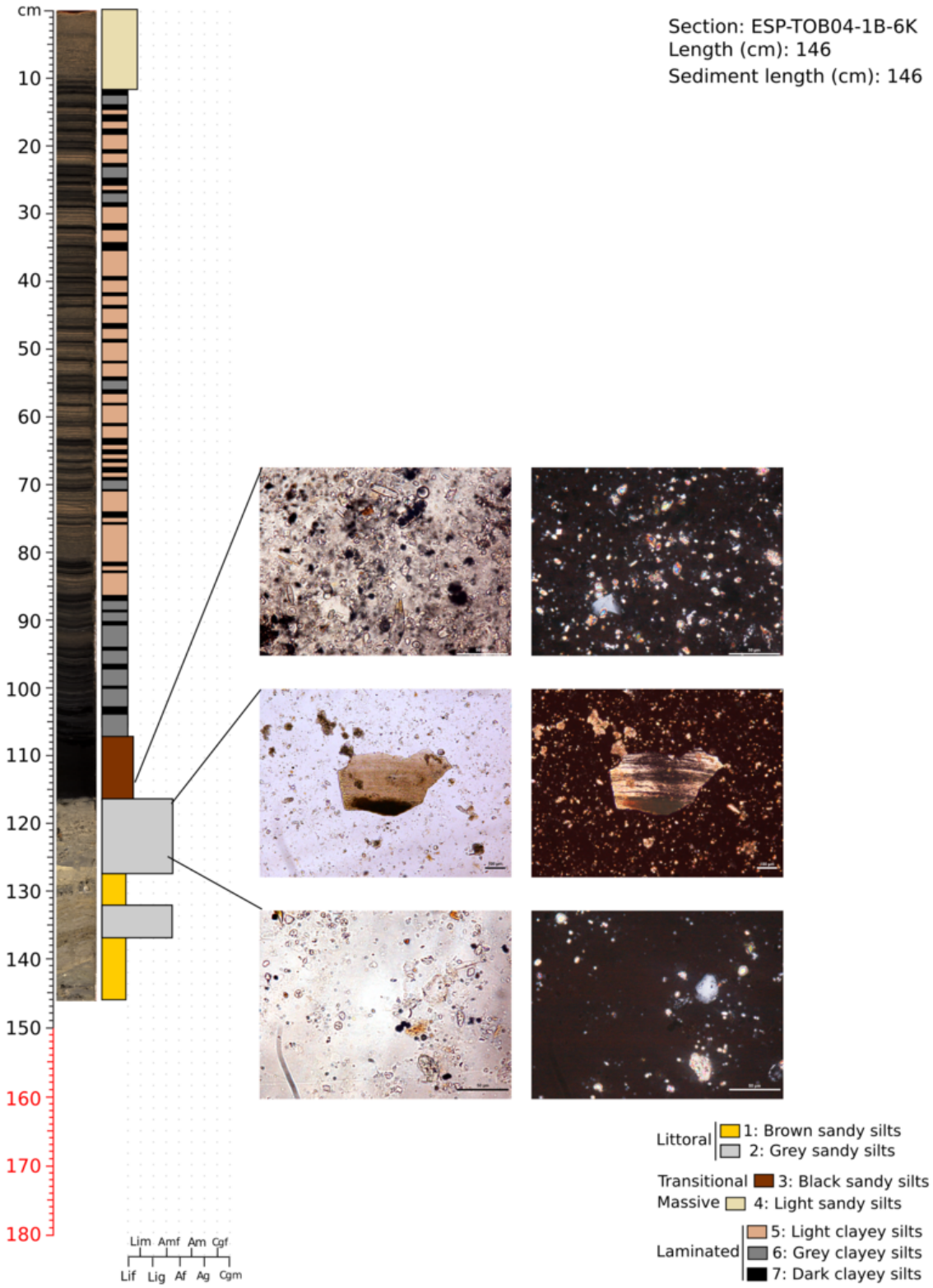

Section: ESP-TOB04-1B-1K
Length (cm): 112
Sediment length (cm): 103
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts


Section: ESP-TOB04-1B-2K
Length (cm): 113
Sediment length (cm): 113
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts


Section: ESP-TOB04-1B-3K
Length (cm): 72
Sediment length (cm): 72
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts


Section: ESP-TOB04-1B-4K
Length (cm): 145
Sediment length (cm): 145
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts


Section: ESP-TOB04-1B-5K
Length (cm): 146
Sediment length (cm): 146
cm
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts


Section: ESP-TOB04-1B-6K
Length (cm): 146
Sediment length (cm): 146
cm
10
20
30
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80
90
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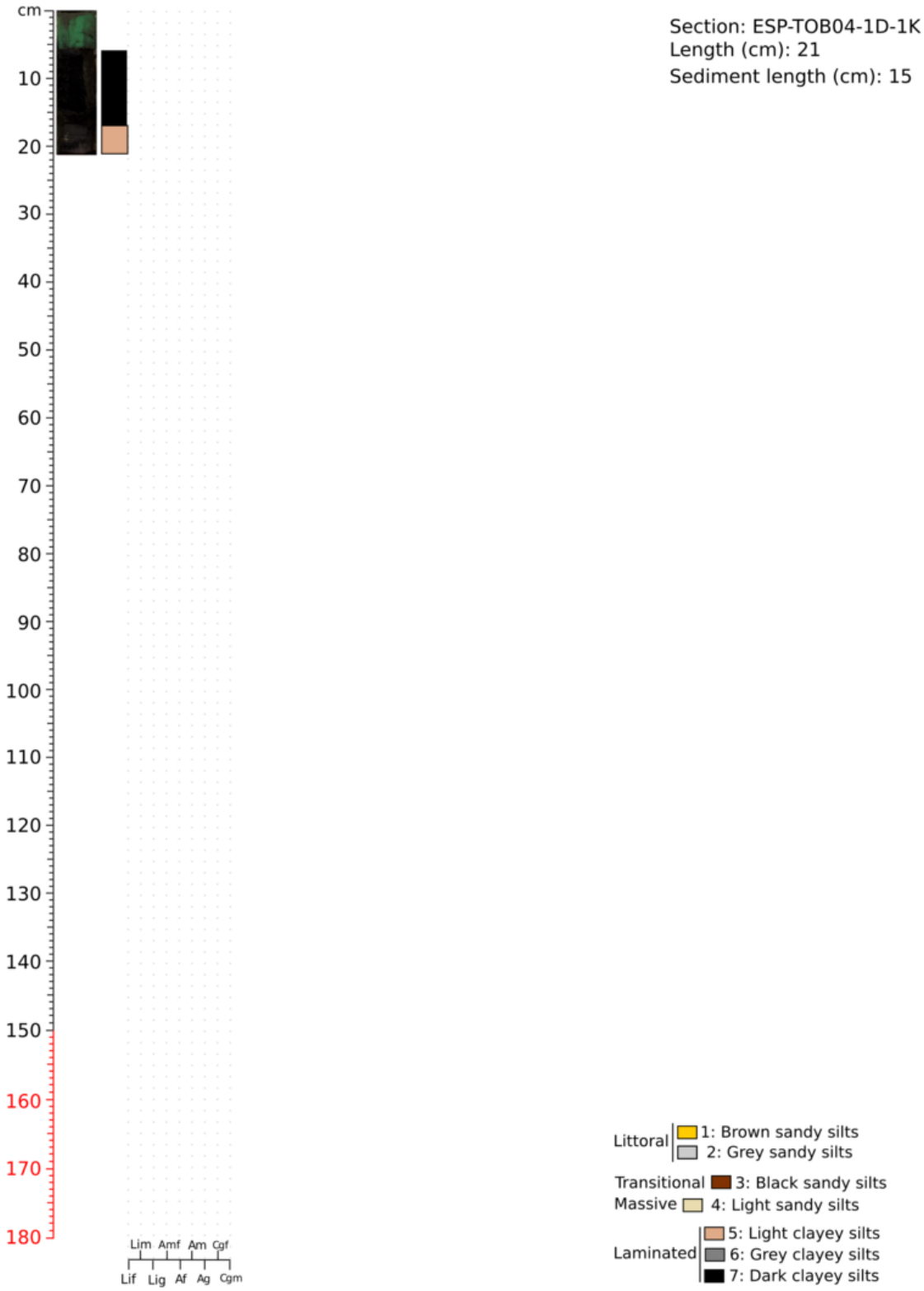
140
150
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts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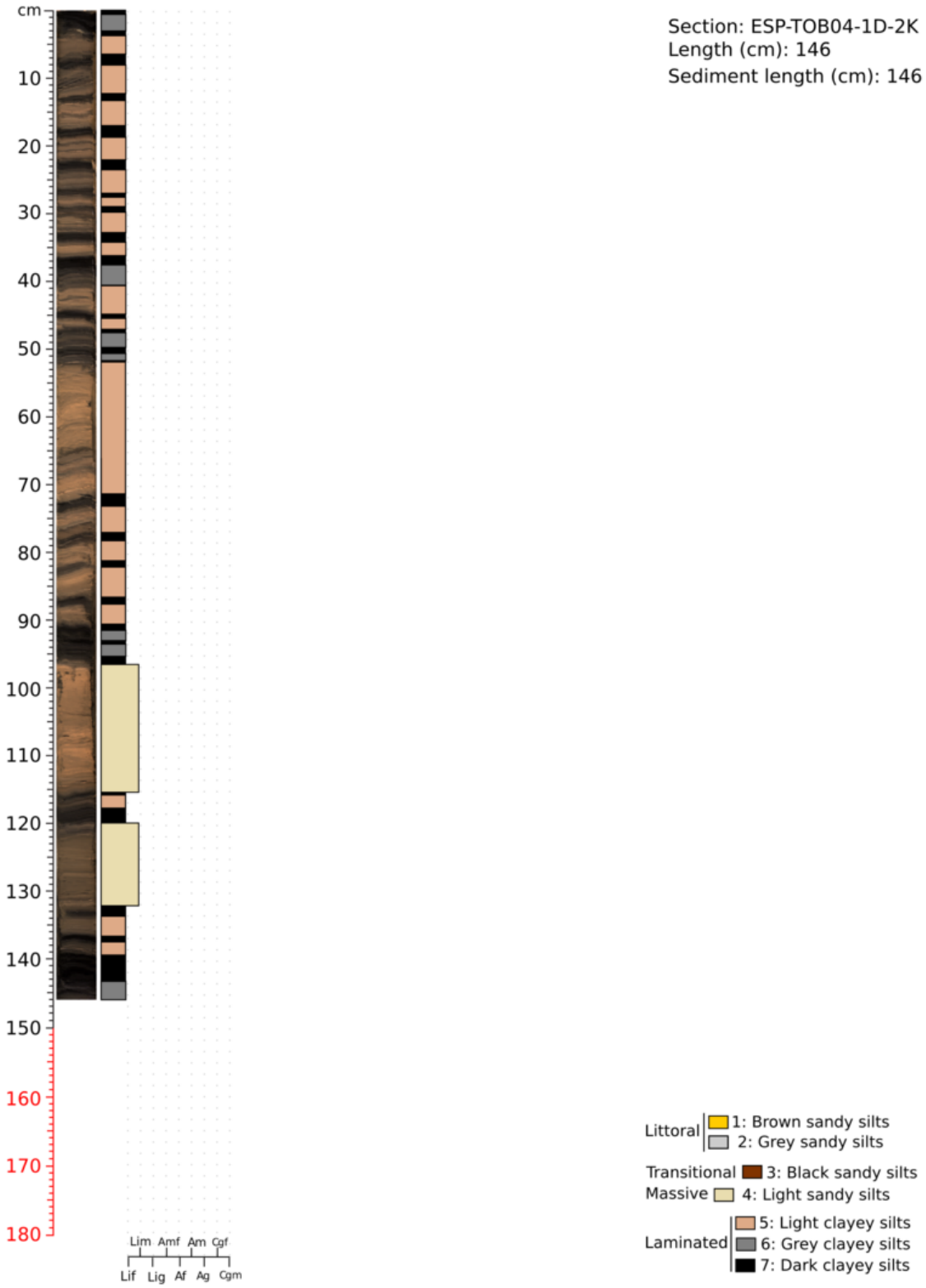
170
180
Lim
Amf
Am
Cgf
Lif
Lig
Af
Ag
Cgm
Section: ESP-TOB04-1D-1K
Length (cm): 21
Sediment length (cm): 15
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts


Section: ESP-TOB04-1D-2K
Length (cm): 146
Sediment length (cm): 146
cm
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120
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140
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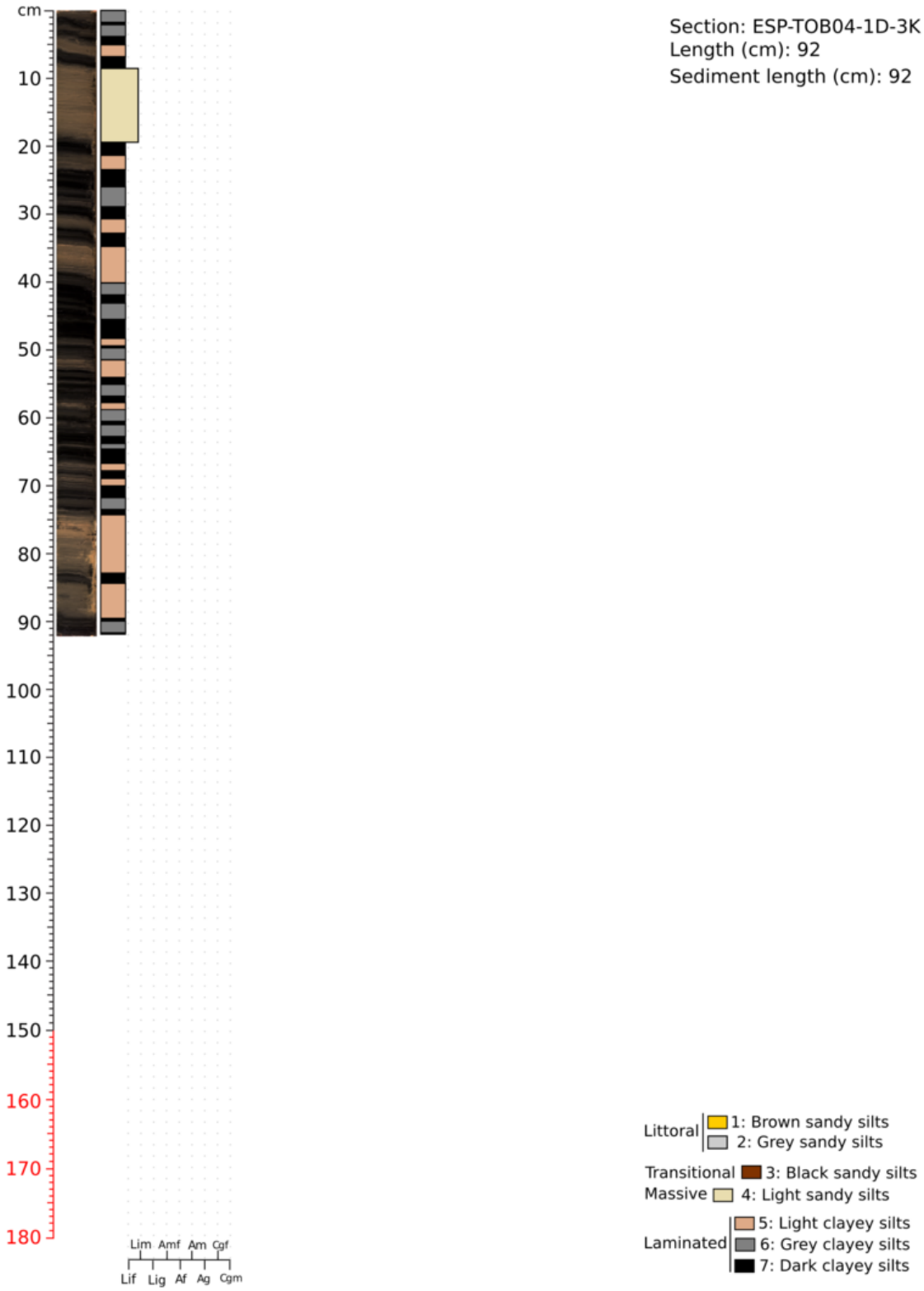
160
170
180
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts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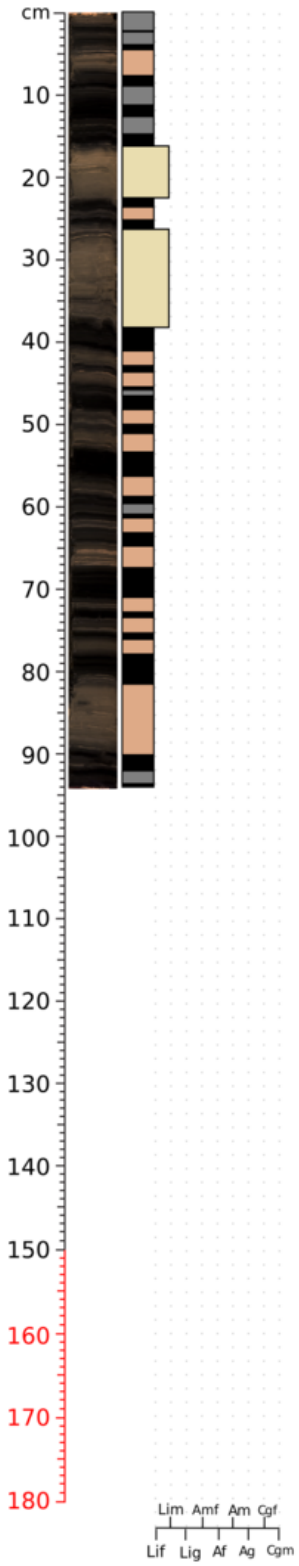
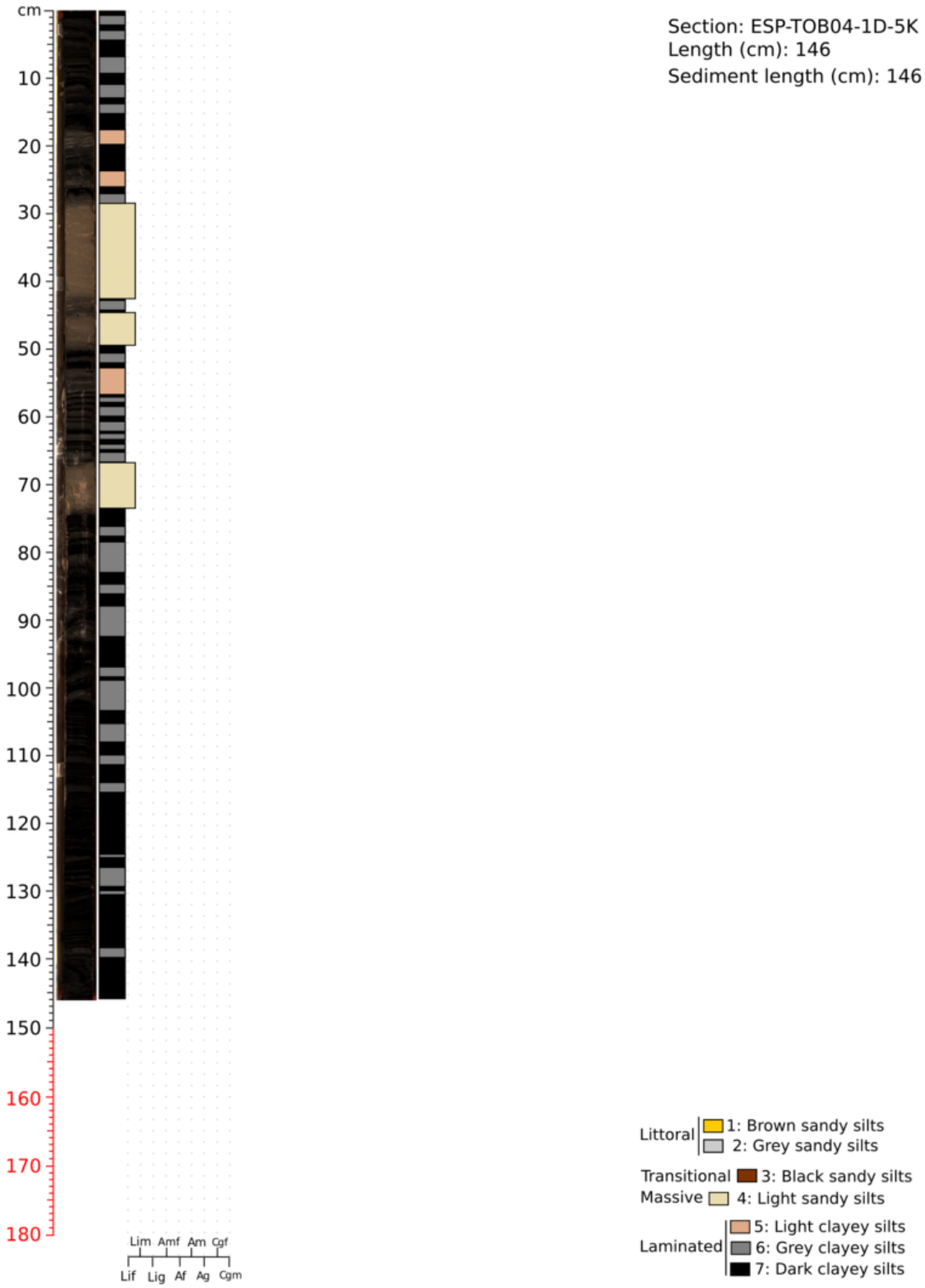
Lim
Amf
Am
Cgf
Lif
Lig
Af
Ag
Cgm
Section: ESP-TOB04-1D-3K
Length (cm): 92
Sediment length (cm): 92
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts



Section: ESP-TOB04-1D-4K
Length (cm): 94
Sediment length (cm): 94

Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts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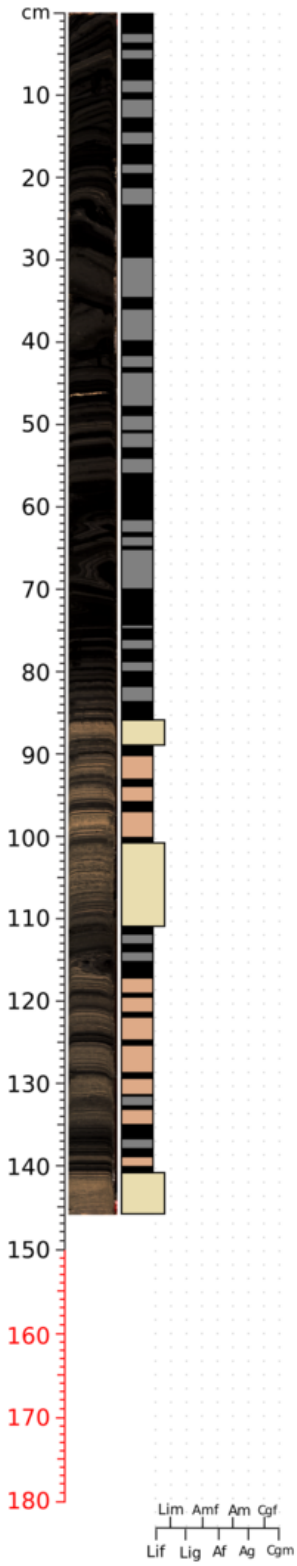
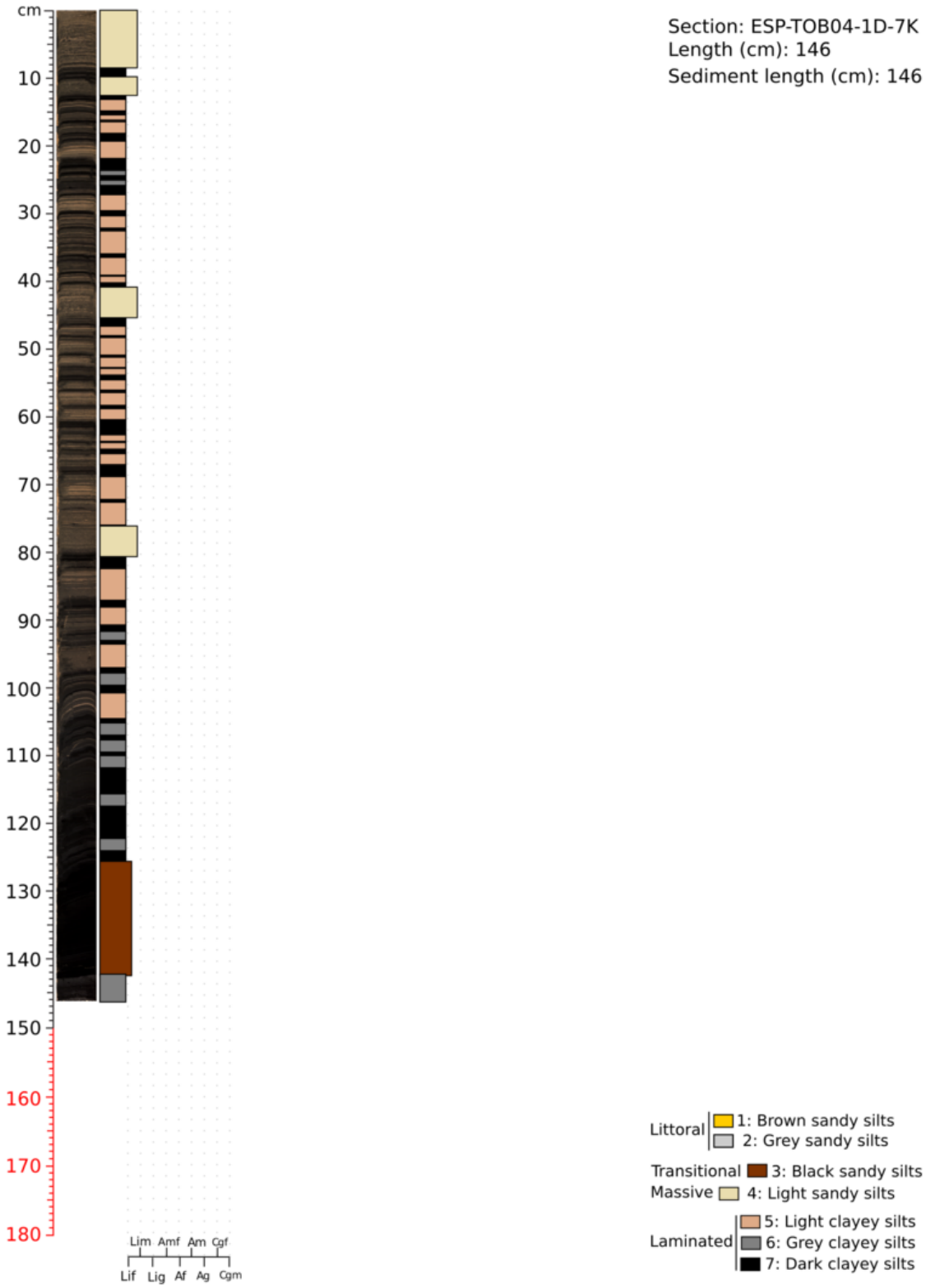
Lim Amf Am Cgf
Lif Lig Af Ag Cgm
Section: ESP-TOB04-1D-5K
Length (cm): 146
Sediment length (cm): 146
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts



Section: ESP-TOB04-1D-6K
Length (cm): 146
Sediment length (cm): 146

Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts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Lim
Amf
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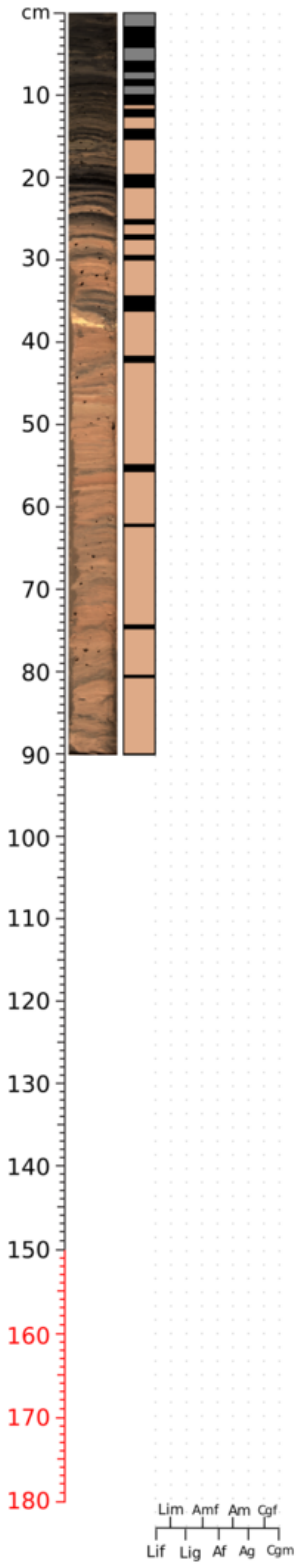
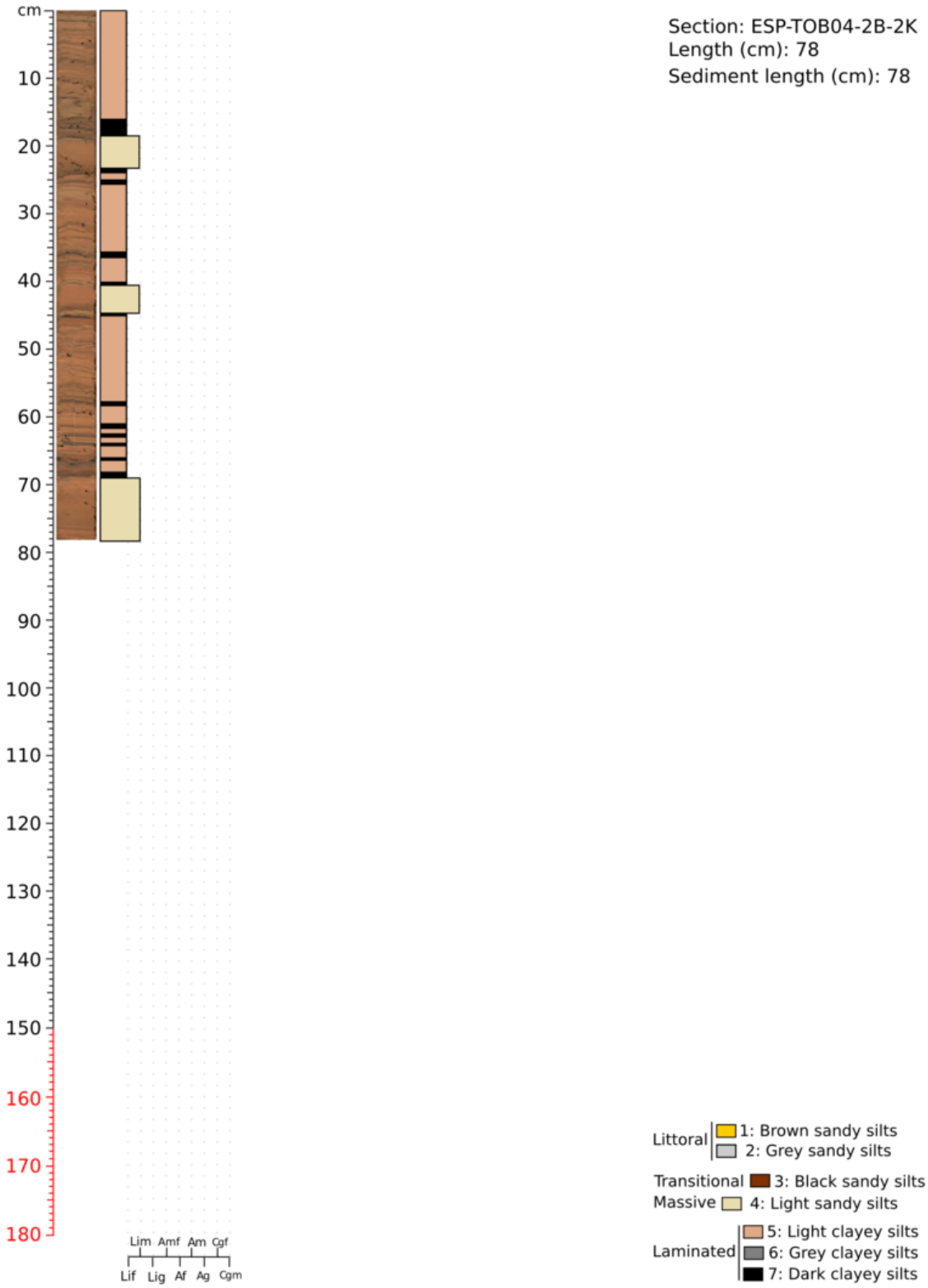
Cgf
Lif
Lig
Af
Ag
Cgm
Section: ESP-TOB04-1D-7K
Length (cm): 146
Sediment length (cm): 146
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts



Section: ESP-TOB04-2B-1K
Length (cm): 90
Sediment length (cm): 90

Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts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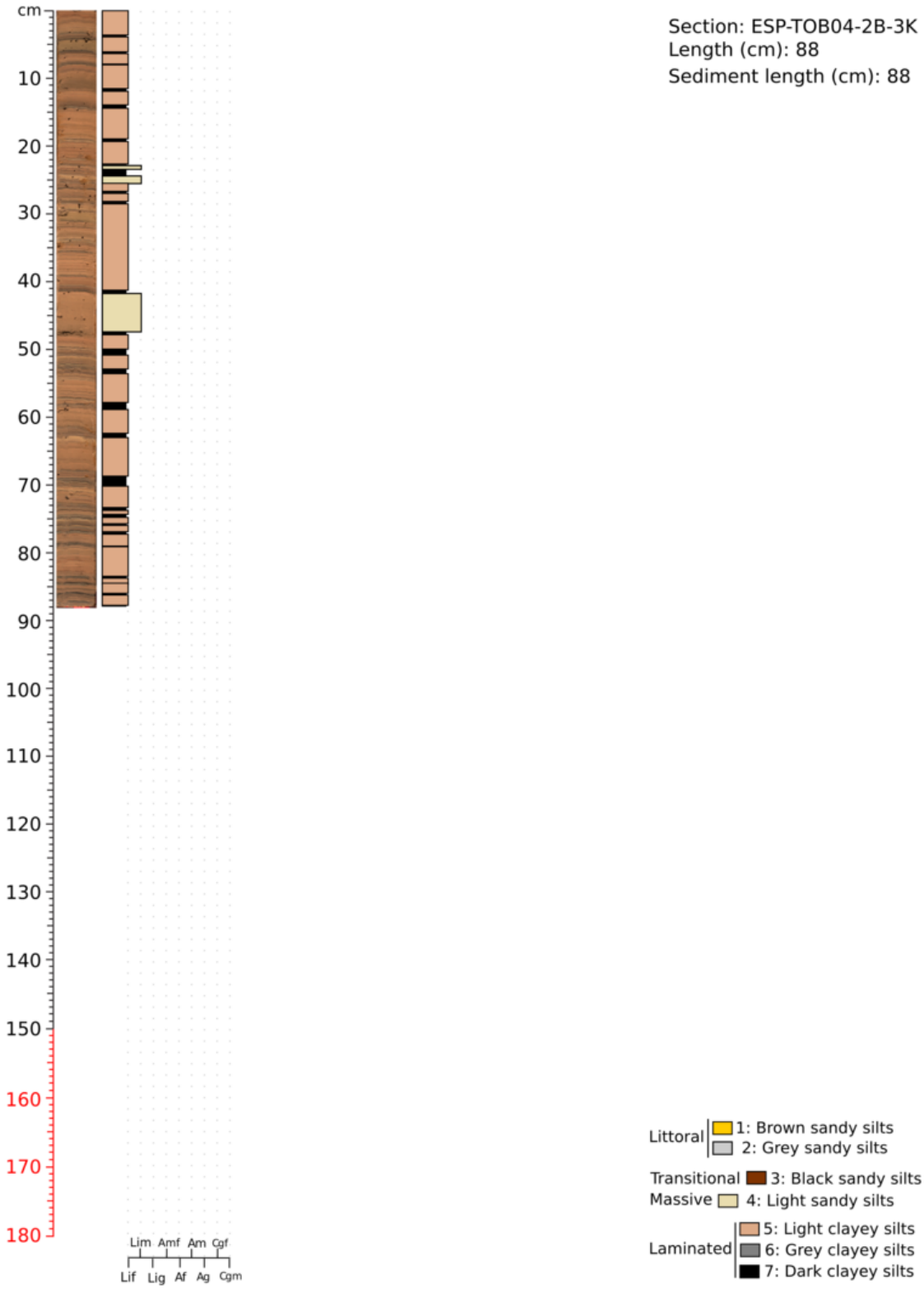
150
160
170
180
Lim
Amf
Am
Cgf
Lif
Lig
Af
Ag
Cgm
Section: ESP-TOB04-2B-2K
Length (cm): 78
Sediment length (cm): 78
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts


Section: ESP-TOB04-2B-3K
Length (cm): 88
Sediment length (cm): 88
cm
10
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90
100
110
120
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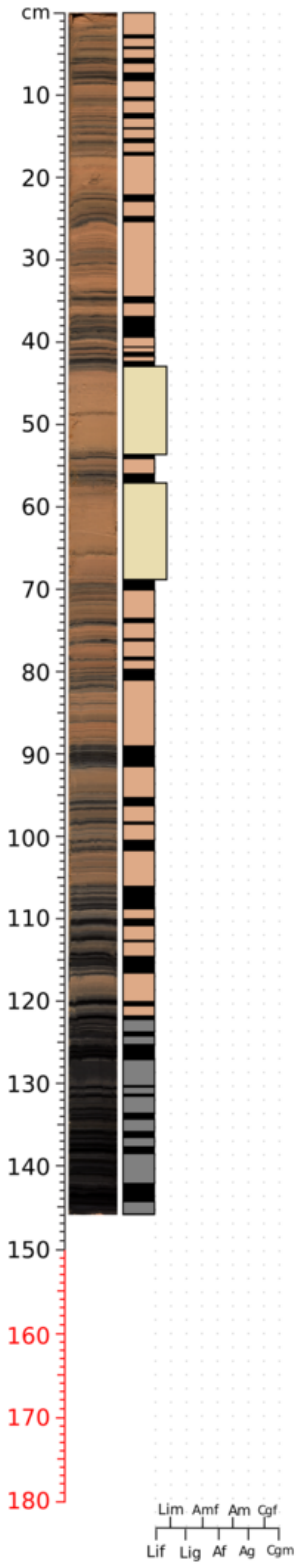
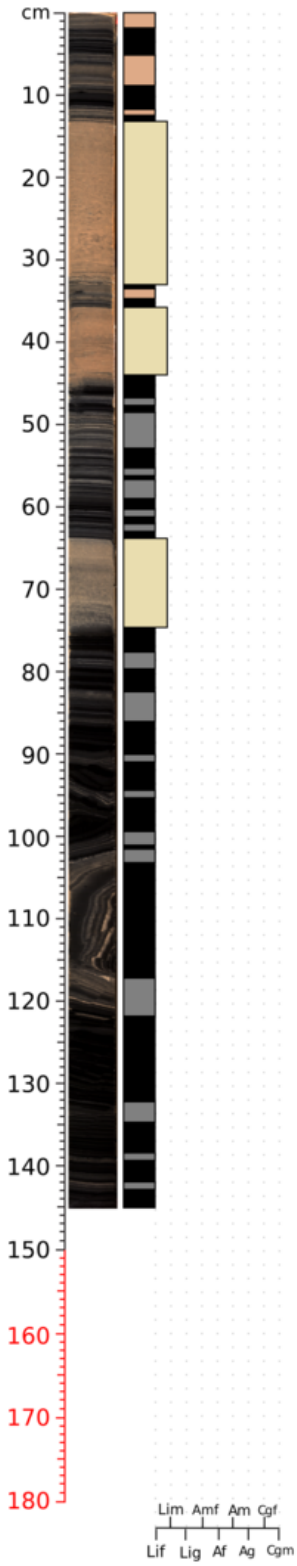
140
150
160
170
180
Lim
Amf
Am
Cgf
Lif
Lig
Af
Ag
Cgm
Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts



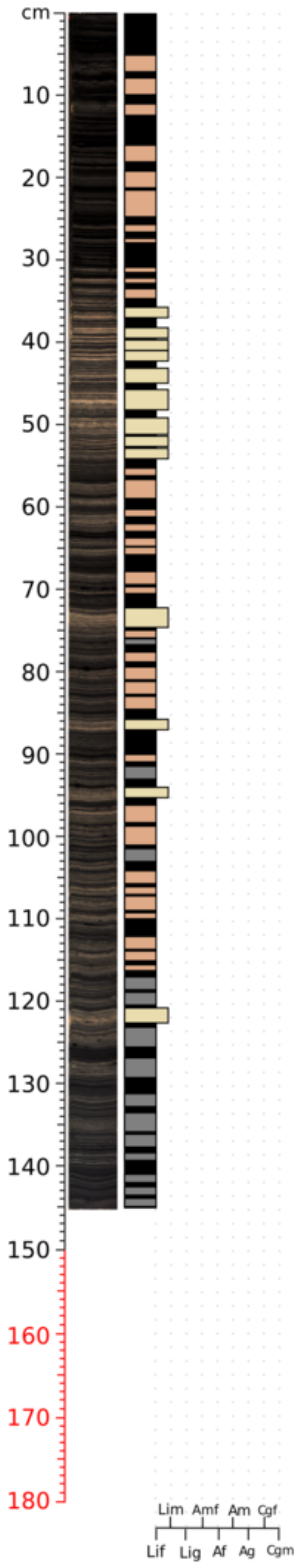
Section: ESP-TOB04-2B-4K
Length (cm): 146
Sediment length (cm): 146

Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts



Section: ESP-TOB04-2B-5K
Length (cm): 145
Sediment length (cm): 145

Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts



Section: ESP-TOB04-2B-6K
Length (cm): 145
Sediment length (cm): 145

Littoral
1: Brown sandy silts
2: Grey sandy silts
Transitional
3: Black sandy silts
Massive
4: Light sandy silts
Laminated
5: Light clayey silts
6: Grey clayey silts
7: Dark clayey silts

Quod erat demostrandum