Arid and Humid Phases in Southern Spain during the Last 4000 Years: The Zoñar Lake Record, Córdoba.

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Abstract

A multiproxy study of sediments cores from Zoñar Lake (37º29’00’’N, 4º41’22’’ W, 300 m a.s.l.) supported by 11 ^{14}C AMS dates provides the first high-resolution centennial-scale reconstruction of past humidity changes in southern Spain during the last 4000 years. Arid periods occurred prior to 2.9 cal. kyr BP and during 1.3-0.6 cal. kyr BP (Medieval Climate Anomaly). The most humid period occurred during 2.6-1.6 cal. kyr BP encompassing the late Iron Age-Iberian and Roman epochs. Two humid periods of lower intensity occurred between 0.8 – 0.6 cal kyr BP (1200 – 1400 AD) and about 400 cal. yr BP (around 1600 AD) coinciding with the onset of the Little Ice Age. Humid conditions are synchronous with a decline in solar output and seem to correspond to atmospheric patterns similar to negative NAO phases. Arid conditions show better correlation with northern Africa climate evolution suggesting a possible link to subtropical dynamics. The geographic location of Zoñar Lake and the robust chronology provides an opportunity to improve our understanding of the climate evolution in mid latitudes during the Late Holocene and to evaluate subtropical and high latitude factors in Mediterranean climate evolution.

Keywords: Mediterranean climate, lacustrine sediments, humid periods, NAO, Late Holocene.

(A) Introduction

The Mediterranean region is very sensitive to global climatic changes, as has been shown for short (decadal) and long (millennial) time scales (Giralt et al., 1999; Rodrigo et al., 1999; Larrasoaña, 2003; Gil García et al., 2007). Mediterranean climate is controlled by the descending branch of the Hadley circulation in summer, and by the dominance of Westerlies in winter (Rodwell and Hoskins, 1996, 2001), and consequently it responds to changes in global atmospheric patterns.

Effective moisture shifts in the Mediterranean region have had a strong impact on human societies and the environment during recent millennia (Zorita et al., 1992; Jones et al., 1997; Rodrigo et al., 2000). The paleoclimate evolution during the late Holocene has been reconstructed in northern Spain on the basis of the mercury content in a peat bog (Martínez-Cortizas et al., 1999), multiproxy studies in Sanabria Lake sediment cores (Luque and Juliá, 2002), pollen records from the Ría de Vigo (Desprat et al., 2003), studies on the Galician continental shelf (González-Alvarez et al., 2005), and multiproxy studies in Estanya Lake (Riera et al., 2004 and Morellón et al., 2007) and Las Tablas de Daimiel (Gil García et al., 2007) among others studies. In southern Spain, changes in humidity and regional vegetation during the Holocene have been described at millennial scale: Padul, Granada (Pons & Reille, 1996); Salines, Alicante (Giralt et al., 1999); Villaverde, Ciudad Real (Carrión et al., 2001); Laguna de Medina, Cádiz (Reed et al., 2001); Siles Lake, Jaén (Carrión., 2002); Doñana National Park, Huelva (Sousa and García-Murillo, 2003), and Archidona, Málaga (Luque et al., 2004). However, these studies do not attain enough temporal resolution to describe short and rapid climate events during the late Holocene. Thus, this study based on sedimentological, mineralogical, geochemical and biological proxies from a series of sediment cores from Lake Zoñar (Córdoba province, Andalucia) provides the first high-resolution palaeohydrological reconstruction for the last 4000 years B.P. in southern Spain.

(A) Site Description

Zoñar Lake (37º29'00''N, 4º41'22'' W, 300 m a.s.l.) is the deepest (15 m) and largest (37 ha) lake in the Southern Córdoba Natural Reserve (Córdoba province, Andalucía). The area is located in the Guadalquivir River Basin, characterized by a semi-humid Mediterranean climate with average annual temperature of 16.1 °C, and about 530 mm annual rainfall, although with high interannual variability during the last 50 years of records (300 – 1100 mm)(Enadinsa, 1989; Valero-Garcés et al., 2006). The bedrock consists of Triassic formations (carbonates, mudstones, evaporites and ophites), and Miocene marine formations (IGME, 1986). The origin of the lake basin is related to karstic and diapiric activity along fault structures (Moya, 1984, 1986; Sánchez et al., 1992). Three main springs (Escobar, Zoñar and Eucaliptos), connected to Miocene and Quaternary alluvial aquifers, feed the lake (Enadimsa, 1989; Valero-Garcés et al., 2006) (Fig.1) and the only output is by evapotranspiration (1760 mm/yr) (Enadimsa, 1989). Zoñar Lake is monomictic with a thermocline at 4 m depth in summer and a mixed period in winter. Waters are saline (2.4 g/l), alkaline (pH 7.1-8.4) and dominated by Cl^-, SO_4^{2-} and Na^+ (Valero-Garcés et al., 2006). Submerged vegetation is dominated by *Najas marina* and *Zannichellia palustris*, and a wide littoral area is colonized by *Phragmites australis* and *Typha domingensis* (Enadimsa, 1989). The regional vegetation is mainly characterized by sclerophyllous trees and shrubs such as *Quercus ilex*, *Olea europaea sylvestris, Pistacia lentiscus*, *Ceratonia siliqua*, Genista *sp., Rosmarinus officinalis, Myrtus communis, Rhamnus alaternus* or Cistaceae (Rivas-Martínez 1982) and by herbaceous areas and little patches of mesophytes in riparian formations (*Alnus* *glutinosa, Fraxinus angustifolia, Populus alba*, *Populus nigra*, *Ulmus minor, Salix sp.,* and *Tamarix sp.*). The landscape is strongly influenced by anthropogenic activities, and is dominated by cultivated olives.

(A) Methods

Four sediment cores were collected in 2004 with a Kullenberg piston corer in collaboration with the Limnological Research Center (University of Minnesota, USA). Before splitting the cores, magnetic susceptibility was measured by a Geotek® every 1 cm. The sediment cores were split, imaged with a DMT Core Scanner and described and correlated by sedimentary facies. Two cores were selected and sampled: ZON04-1B (600 cm long) and ZON04-2A (170 cm long) (Fig.2). The first one was sampled every 2 cm for total organic carbon (TOC), total inorganic carbon (TIC), and total sulfur (TS), every 4cm for analysis of total nitrogen (TN) and biogenic silica (BGS), every 5 cm for mineralogy and every 20 cm for biological proxies (ostracods and diatoms); ZON04-2A was sampled every 2 cm for TOC, TIC and TS, and every 5 cm for mineralogy. The sample thickness was 1cm except for ostracod sampling (2cm).

Sedimentary facies were defined by visual description and microscopic observations following LRC procedures (Schnurrenberger et al., 2003) and by mineralogical and chemical compositions. The TC, TOC and TS contents were determined by a LECO elemental analyser and TN by a VARIO MAX CN elemental analyzer. Mineralogy was characterized by X ray-powder diffraction (XRD) with a Bruker D8 advance and scanning electron microscopy and EDS analyses with a FEI-Quanta ESEM. Semi quantitative mineral composition of samples was determined by the normalized reference intensity ratio (RIR) method of Chung (1974 a, b).

Light elements were measured in cores 1B, 1A and 1C with 5 mm resolution (for massive units) and 2 mm resolution (for laminated units) by an XRF core scanner at the University of Bremen, using 30 seconds count time, 10 kV X-ray voltage and an X-ray current of 1000 µA (massive units) and 500 µA (laminated units). The iron and sulphur contents are expressed as total counts.

Pollen grains were extracted by the classic chemical method (Moore et al., 1991) and using Thoulet formula heavy liquid, modified according to Dupré (1992), for pollen concentration. The pollen sum is normally 300 but exceptionally as low as 275 terrestrial grains per sample. Ostracods were separated with the procedure described by Forester (1988), and diatoms prepared following Renberg (1990).

Fourteen samples (terrestrial and aquatic plant macrorests, charcoal, and bulk organic matter) from cores ZON04-1B and ZON04-2A were analyzed by AMS for ^{14}C dating (Table I). Varves were counted in selected intervals based on the procedure described by Brauer and Casanova (2001).

(A) Results

(B) Chronology

The age-depth model for the Zoñar record provides a robust chronology for the last 4000 years based on nine AMS ^{14}C dates from ZON04-1B core and one from ZON04-2A core, and additional dates previously published (two AMS ^{14}C dates from ZON01-1A and ^{137}Cs and ^{210}Pb chronologies from ZON01-1B core; Valero-Garcés et al., 2006). (Table I; Fig. 3). AMS ^{14}C-dates were calibrated with CALIB 5.1 software and the INTCAL04 curve (Reimer et al., 2004). The top of Unit 1 in core ZON04-1B does not correspond with the sediment-water interface because the upper sediments were disturbed during coring. However, sedimentary facies and TOC values allow a perfect match between the upper part of ZON04-1B and the ZON01-1B and ZON04-1A cores, previously dated with ^{137}Cs and ^{14}C AMS chronologies (Valero-Garcés et al., 2006). The top unit 1 was deposited during the second part of the 20th century, as indicated by the AD 1963 ^{137}Cs peak (70-71 cm depth in ZON01-1B, and 60 cm depth in ZON04-1B), and the "modern" age (104.49% modern carbon) of the sample at 60cm depth in core ZON04-1B. This modern age also indicates that there is no significant reservoir effect in Zoñar Lake. The 663 ± 23 cal. yr BP date (bulk organic matter sample) at 96 cm is not consistent with the ^{137}Cs chronology and it is rejected. Five bulk organic matter and charcoal dates show reversals not consistent with the chronological model and have also been rejected. Likely they represent reworked material transported from older lacustrine sediments during periods of increased floods in the basin, lower lake levels that exposed older lacustrine sediment or inwash of old soil carbon during periods of increased catchment erosion. Some transitions between sedimentary units are abrupt, but few erosive surfaces have been identified. Only at 170 cm core depth (transition between subunits 3B and 3A), the presence of an erosive surface suggests a hiatus at AD 1350, although it is likely of a short time span. The chronological model is based on linear interpolation between the dates. Varve counting in unit 6 also supports the AMS chronology. About 400 varves were counted between 392 cm (AMS date: 2153 ±57 cal yr BP) and 450 cm (onset of varves). Although we do not have an AMS date for the unit 6 at 450 cm, the age of 2566 ±77 cal. yr BP at 472 cm (22 cm lower) is consistent with the inferred varved age (> 2567 cal yr BP).

Sedimentation rate in the upper unit 1 is the highest (1.76 cm/yr) (Valero-Garcés et al., 2006). The rates are about 1-2 mm/yr for the laminated intervals and 2-3 mm/yr for the massive facies characterized by higher detrital composition.

(B) Sedimentology

The 600 cm long core from the deepest area of Zoñar Lake (14.5 m water depth) is composed of four main sediment types: i) massive, brownish and grey carbonate mud and silt layers; ii) finely laminated layers composed of mm to cm thick laminae of four types: authigenic calcite, organics (mostly diatoms and algal remains), detrital (carbonates, quartz and clay minerals) and gypsum; not all the laminae occur in one particular facies; iii) cm-thick layers of gypsum; iv) massive facies with pedogenic textures at the base of the sequence.

Nine sedimentary facies were identified after visual description, microscopic observations and sediment composition analyses (Fig.4, Table II). Facies 1-5 are similar to those described by Valero-Garcés et al., 2006 in a 170 cm long core (ZON01-1A) and have been identified and correlated in the new cores.

Massive facies (facies 1 and 2) represent deposition during periods of higher detrital input into the lake and more littoral deposition, with oxic conditions at the water sediment interface and frequent bioturbation. Brown layers, with higher organic matter, diatom and ostracod content are indicative of relatively higher organic productivity in littoral environments.

Laminated facies indicate depositional conditions with limited bottom bioturbation, usually caused by low oxygen content, and lower clastic input. Depositional conditions for laminated facies can occur in quite different lake settings: i) high lake level conducive to water stratification and dominance of an anoxic hypolimnion, as those described by Brauer (2004) in central European lakes; ii) low lake levels and saline conditions leading to development of algal/bacterial mats (Valero-Garcés et al., 2001), iii) high organic productivity leading to eutrophication and consumption of oxygen (Kalff, 2002). To ascribe some paleodepth and paleosalinity conditions to the laminated facies in the Zoñar record, we have used the following criteria: i) the presence of incipient algal/bacterial mat, dominance of benthic diatoms, and the occurrence of aragonite and gypsum laminae point to shallow depths and chemically concentrated waters; ii) the occurrence of finely laminated facies with a regular pattern of laminae, dominance of plancktonic diatoms, and absence of aragonite or gypsum suggest deeper depositional setting in less concentrated waters. Facies 3 is interpreted as incipient benthic bacterial-algal mat (Valero-Garcés et al., 2006). The occurrence of the highest abundance of benthic diatoms and the absence of ostracods (see below) suggest high salinity and anoxic bottom sediments. Facies 4 shows five different types of laminae (Table II) but the dominance of intercalated algal mat laminae and the high content in benthic diatoms also support deposition in a brackish setting. Facies 5 and 7 are interpreted as annually laminated sediments (varves) deposited in the anoxic hypolimnion during periods of higher lake level. These varves are similar to those described by Brauer (2004) in meromictic, relatively deep lakes. They contain three layers: i) calcite layer precipitated in spring, ii) organic matter deposited in summer and iii) detrital layer in winter. The AMS ^{14}C chronology (436 years) and the varve counting (433 varves) support the annual nature of this lamination. Laminated gypsum facies (facies 6) indicate higher salinity, likely a result of chemically concentrated waters and decreasing lake levels (Arenas et al., 1999; Anselmetti et al., 2006; Möller et al., 2007).

Massive facies with edaphic textures (facies 8 and 9) at the base of both littoral (ZON04-2A) and off-shore cores represent lacustrine deposition and subsequent subaerial exposure, colonization by terrestrial vegetation, and development of incipient soils. Aragonite would precipitate during periods of an ephemeral brackish lake (facies 8).

Figure 4 shows sedimentary facies and the chemical and mineralogical composition of core ZON04-1B. Higher magnetic susceptibility values and quartz and iron values occur in the more massive, clastic facies (Units 8 and 1 and several intercalated thin layers). The sulphur curve parallels that for gypsum, since sulphides are relatively low (only traces at some levels), and mark two intervals of increased water salinity. The occurrence of *Artemia salina* faecal pellets and the association of gypsum and aragonite in unit 4, underlines the saline nature of the depositional setting.

Eight stratigraphic units, described in detail in core ZON04-1B (Fig.4), are correlated across the Zoñar Lake basin (Fig.2 and 4). Sedimentary units from cores located in the deeper areas (SW) show similar thickness for the laminated units and more variability for the massive to faintly laminated ones (Fig.2). The littoral core shows evidences of subaerial exposure and soil development below unit 2 (100 cm; about 390 cal. yr BP), suggesting that the lake did not flood the NE area of the basin until 400 yr ago.

(B) Biological proxies

(C) Ostracods

Most of the samples are sterile, and those with ostracods have a low number of valves (< 10 valves per sample). The ostracod assemblage from the Zoñar record is characterized by six species: *Eucypris mareotica (E. inflata), Plesiocypridopsis newtoni, Sarcypridopsis aculeata, Heterocypris salina, Ilyocypris cf. gibba and Candona cf. neglecta*. These species suggest shallow, temporary lake environment, except *Candona cf. neglecta* which could live in deeper areas (Meisch, 2000), although there is evidence of this species in temporary water bodies (Roca et al., 2000). Ostracods are absent in unit 8. The presence of *P. newtoni, Eucypris mareotica and Sarcypridopsis aculeata* in unit 7 indicates an ephemeral lake, consistent with the sedimentological evidence for periods of subaerial exposure and soil formation. *Plesiocyprydopsis newtoni* is the dominant species in the varved unit 6, suggesting that the lake was not very deep even during this period. Relatively high abundance of *Eucypris mareotic* and low abundance of *Heterocypris salina* in unit 4 indicates higher salinity and lower lake level conditions (Reed et al., 2001) corresponding to the occurrence of gypsum layers. Better ostracod preservation indicates deeper and fresher waters after the gypsum episode in unit 3. Shallow water species *(Ilyocypris cf. gibba, Candona cf. neglecta and Plesiocypridopsis newtoni*) and the ephemeral indicator *P.newtoni* (Meisch, 2000; Reed et al., 2001*)* occur at the top and bottom of unit 2. However, unit 2 is devoid of ostracods similarly to core ZON01-1A (Valero-Garcés et al., 2006). Anoxic bottom and higher chemical concentrations would be more favourable for bacterial mats could have impeded survival of benthic ostracoda. An oligosaline-mesosaline assemblage composed of *Ilyocypris sp.* and *Plesiocypridopsis newtoni* is dominant in unit 1.

In summary, ostracod assemblages suggest relatively lower lake levels and higher chemical water concentrations in sedimentary units 7, 4 and 2, and relatively higher lake levels and less concentrated waters in units 1, 3 and 6 (Fig. 5).

(C) Diatoms

Diatom assemblages from the upper three units are described in detail in Valero-Garcés et al. (2006). Semiquantitative inspection of the diatom assemblages preserved in core ZON04-1B (Fig.5) shows that benthic diatoms constitute the dominant ecological group. Reworked marine taxa (mainly *Thalassionema* spp., among others) are also abundant in some levels, particularly in units 1 and 3 (core ZON01-1A, Valero-Garcés et al., 2006) and at the base of units 4 and 6 (core ZON04-1B, Fig. 5) marking periods of increased erosion of the Miocene marine rocks in the watershed. Diatom preservation in units 8 and 7 is poor. In Unit 6, although the majority of the diatoms are benthic, some layers are exclusively made up of planktonic taxa. This unit also shows the highest content of euplanktonic (*Cyclotella* spp.) and tychoplanktonic diatoms (*Fragilaria* spp.), with a net increase from the bottom of the unit (480 cm) to the gypsum layer (400 cm), a sharp decrease in the gypsum-rich interval, and a recovery afterwards up to Unit 5 (340 cm). The planktonic / periphytic ratio is higher at the bottom and top of unit 6 and the trend continues in Unit 5 (Fig. 5) suggesting that this interval represents the highest lake levels in Zoñar.

The transition from Unit 5 to Unit 4 shows the dominance of benthic taxa (mainly *Cocconeis* spp., *Navicula* spp., *Amphora* spp. and *Nitzschia* spp.), underlining a shallowing trend that continues in Unit 4. Although benthic taxa with subdominant tychoplanktonic diatoms (*Fragilaria* spp.) dominate in Unit 3B, a progressive increase in the planktonic component occurs after the gypsum layers in unit 4 and continues in unit 3B. However, Subunit 3B correlates with diatom assemblage zone V (170-200cm core ZON01-1B) defined in Valero-Garcés et al. (2006) with more abundant euplanktonic *Cyclotella meneghiniana* and *Fragilaria brevistriata*. Subunit 3A groups diatom assemblage zones IV(150-170cm core ZON01-1B), III (150-110cm core ZON01-1B) and II (110-90 cm core ZON01-1B) (Valero-Garcés et al., 2006) showing: i) a slight increase in freshwater benthic diatoms (mainly *Cocconeis neodiminuta*, but also *Amphora pediculus*) (zone IV) interpreted as a decrease in lake level compared to unit 3B, ii) a dominance of oligosaline benthic *Cocconeis neothumensis* indicative of more saline conditions (zone III) and iii) an increase in the planktonic *Cyclotella meneghiniana*, suggesting an increase in lake level (zone II). After this period of relatively higher lake levels at the top of Unit 3, the transition to Unit 2 represents a substantial change in diatom assemblages, dominated by benthic forms, both freshwater and saline (zone I-70-90cm core ZON01-1B). The mixture of freshwater and saline taxa points to short term large changes in salinity during deposition of Unit 2 (Valero-Garcés et al., 2006). Unit 1 shows low preservation and a high number of fragmented *Thalassionemma* spp., indicating an increase in erosion and the input of allochthonous diatoms from the Miocene marine rocks.

Downcore variations in biogenic silica (BGS) record diatom content and past primary productivity of diatoms (Colman, 1995; Johnson, 2001). BGS content is low (between 2% and 4%) through the sediment sequence with only 2 major peaks (up to 12 %) in the laminated facies of Units 6 and 2 (ca. 400 cm and 70 cm). Lake productivity is expected to be higher at those intervals, which are also characterized by higher TOC and lower C/N ratios (Meyers, 1999 and 2003). Due to the presence of reworked, marine diatoms, BGS curve cannot be used as an accurate estimate of biogenic diatom productivity. However, some increasing (decreasing) trends are coherent with the increase (decrease) in planktonic diatoms. For example, the top of unit 4, 3B and 3A show increasing BGS and more planktonic diatoms, and the transition from Unit 5 to Unit 4 shows decreasing BGS and more benthic diatoms.

(C) Pollen

Pollen assemblages are typical of Mediterranean landscapes dominated by *Olea europaea,* evergreen *Quercus, Pistacia lentiscus* and small patches of conifers, mesophytes and shrubs, with variable contribution of herbaceous taxa and aquatic plants associated with the lake basin. In this paper we only present the major pollen taxa to correlate the past hydrological changes in the lake inferred from other proxies (Fig. 5). The frequent subaerial exposure conditions inferred for unit 8 corresponds with the minimum arboreal pollen (AP) percentages, high values of steppe herbs as Cichorioideae and Chenopodiaceae, and minimum presence of aquatic taxa. The significant increase in the AP components (*Olea europaea*, evegreen *Quercus* and the Mediterranean group) and the decrease in non-arboreal pollen (NAP), Cichorioideae and Chenopodiaceae, parallel the onset of more humid conditions in the transition from units 7 to 6. Arid conditions are suggested for deposition of unit 4 by an increase in NAP and Chenopodiaceae, and the presence of *Ruppia* as a dominant aquatic taxon, indicating brackish and shallower conditions. The increase in *Myriophyllum* up to 20% in unit 3B (230-170cm) marks the end of the arid conditions. The *Olea* curve reflects *Olea europaea sylvestris* pollen as natural component of the Mediterranean landscape and *Olea* cultivation. Several distinctive peaks are located in units 6 (up to 50 %), and 5 (around 30%) and an increasing trend since unit 3 reflecting the historical expansion of olive tree cultivation. A decrease in *Olea* representation occurs in unit 4 and during the gypsum-rich interval of unit 6, both interpreted as arid periods. The large percentage of *Olea* during pre-Roman times is unexpected and may reflect two different formations: i) the regional Mediterranean vegetation composed of evergreen *Quercus*, *Olea europaea sylvestris* and *Pistacia lentiscus* as the main arboreal taxa, and ii) an early local use of the watershed by the Iberians (deliberate planting) due to the water availability in the springs surrounding the lake.

(A) Discussion

(B) Paleohydrological reconstruction

A direct relationship between rainfall and lake level has been documented during the last decades in Zoñar Lake (Unpublished Andalusian Government data). Although lake level has been strongly affected by human use during the 19th and 20th centuries, short cores and monitoring data suggest that climate variability was a fundamental control of lake level in the past (Valero-Garcés et al., 2006). Integration of sedimentological, geochemical and biological indicators allows a paleohydrological and paleoenvironmental reconstruction of Zoñar Lake during the last 4000 years.

Dry period prior to 2900 cal. yr BP. From ~ 4000 to 2900 cal. yr B.P (unit 8) the Zoñar Lake frequently dried out and terrestrial vegetation colonized most of the basin as indicated by high percentages of NAP, steppe taxa and heliophytes (i.e. Cichorioideae and Chenopodiaceae). The onset of this dry period cannot be dated in Zoñar since the sediment core did not penetrate the compact layers of littoral sediments. There is ample evidence for an arid period of global scale between 3500 – 2500 cal yr BP (Mayewski et al, 2004). In Mediterranean areas a warm and dry period is associated with low lake levels from 4.5 to 2.8 kyr B.P. (Harrison et al., 1993 a, b; Issar, 2003; Sadori et al., 2004), and it is also documented in Lake Tigalmammine, Middle Atlas of Morocco (Lamb et al., 1995). In the Iberian Peninsula, lower frequency of river floods occurred during the same age interval (Macklin et al., 2006), and many records show an increase in aridity during this period: Sobrestany, Girona (Parra, 1994), Navarrés, Valencia (Carrión and Dupré, 1996), Gulf of Cádiz, Almeria, Alicante and Gulf of Valencia (Goy et al., 1996), Cantabrian littoral (Zazo et al., 1996), Lake Salines, Alicante (Roca and Juliá, 1997), Spanish Mediterranean coast (Jalut et al., 2000), Lake Siles, Jaén (Carrión 2002), Las Tablas de Daimiel, Ciudad Real (Gil García et al., 2007), Estanya, Huesca (Morellón et al., 2007).

From an archaeological point of view, the end of the Chalcolithic cultures in southern Spain (Salkield, 1987; Araus et al., 1997) coincides with this arid period, lasting until 2.8 cal. kyr BP in Zoñar. The collapse of the Argaric cultures in the SE region of Spain also occurred at around 3.5 kyr (Pozo et al., 2002 a,b; Carrión et al., 2007).

The onset of the humid Period (2800 cal yr BP). The deeper SW basin in Zoñar Lake was permanently flooded after 2800 cal yr BP (unit 7) when a brackish, shallow lake established, and aragonite-bearing sediments were deposited. The decrease in Cichorioideae and NAP pollen content and the increase and better preservation of diatoms (Fig. 5) also indicate the transition from drier to wetter conditions. The onset of this major event in Zoñar coincides with a wetter period between 3000 and 2000 cal. yr BP in Europe (Girandi, 1989; Leira, 2005), and in the Mediterranean area (Roca and Juliá, 1997; Harrison et al., 1999; Sadori et al., 2004). Iron Age settlements in the Mediterranean area have been dated around this period (Araus et al., 1997). At a regional scale, the Tartessos culture flourished precisely between 2.9 and 2.6 cal. yr BP, when the rate of climate and hydrological change was larger. Interestingly, the Tartessos civilization collapse occurred at 2.5 kyr BP when conditions seem to have been more stable and humid from a climatic point of view in the Middle Guadalquivir valley from a climatic point of view.

The Post Bronze – Iberian- Roman Humid Period. The occurrence of an overall more humid episode in the Gualdalquivir River Basin between 2.6 and 1.6 cal. ky B.P. encompasses the Post-Bronze, Iberian and Roman civilizations development in the area. The Zoñar record allows a precise dating of the onset of this period (2600 cal yr BP) and its structure. From 2600 to 1600 cal. yr B.P. (unit 6) two humid periods characterized by varve deposition occurred separated by one arid interval with gypsum deposition (Fig. 6). Well- preserved varves during the period 2600-2100 cal. yr B.P. correlate with high *Olea* and Mediterranean forest pollen percentages. During this period several Spanish rivers had more frequent floods (Macklin et al., 2006) and some lakes in northern Africa (Sidi Ali Lake, Lamb et al., 1999) show high lake level (Fig. 6.). Gypsum deposition, the increase in Chenopodiaceae and the herbaceous component

(NAP) in Zoñar at 2100 – 1900 cal. yr B.P. (BC 250–-50), correlate with the abrupt decrease in flooding episodes at about 2350 - 2000 cal. yr B.P. (Macklin et al., 2006) and sharp lake level decrease in African lakes (Lamb et al., 1999) (Fig.6). A second varved deposition period at 1900-1600 cal. yr BP corresponds with an increased arboreal pollen and increased flooding episodes in Iberian rivers (Macklin et al., 2006). Deposition of the second varved stage in Zoñar corresponds with increased in arboreal pollen in the Tablas de Daimiel National Park (Gil García et al., 2007) from 2100 – 1680 cal yr B.P. and climate improvement in NW Spain (Desprat et al., 2003).

A moister period during the Roman Classical Period has been interpreted from archaeological, historical and proxy records in the Mediterranean (see revision by Reale and Dirmeyer, 2000) at around 2000 cal. yr B.P. Archaeological and geomorphological data from north eastern Spain show a link between slope accumulation in smooth hillsides with more vegetation and colder and moister climates during the Post-Bronze Stage around 2600–2100 cal. yr B.P. (Sopena, 1984; Gutierrez–Elorza and Peña Monné, 1998; González-Sampériz and Sopena Vicién, 2002). It is also documented in Central and Northern Europe (van Geel et al., 1999): Sweden, Lake Igelsjön (Hammarlund et al., 2003), mid-Europe (Lake Petit Maclu, Jura Magny 2004), Spain, Poland and Great Britain (Macklin et al., 2006) and in Africa (Street-Perrott and Harrison 1984).

The Medieval Climate Anomaly (1375 – 730 cal yr BP, 600 - 1200 AD). From 1600 to 1350 cal. yr BP (375 – 600 AD, unit 5), the deposition of massive sediments, with higher clastic input, and the increase of reworked marine diatoms, suggest dominance of more littoral environments in Zoñar Lake and a progressive lake level decrease. Similarly, lower lake levels occurred in Europe (Magny, 2004 and Macklin et al., 2006) and Africa (Lake Turkana, Johnson et al., 1991) after the Roman period.

From 1350 to 730 yr BP (600 – 1200 AD) (unit 4) there are several lines of evidences pointing to drought episodes, e.g. precipitation of authigenic gypsum, presence of aragonite, and faecal pellets, dominance of benthic diatoms and highest values of *Chenopodiaceae*, the presence of *Ruppia*, and a decrease in *Olea* at the same time as in increase in *Pistacia*. This period represents a large hydrological change in Zoñar at about the same time as the Medieval Climate Anomaly (MWA) in northern Europe. Lower average annual precipitation during the MWA is recorded in Soreq Cave (Bar-Matthews et al., 1998a,b) and lower lake levels are inferred in central Italy (Dragoni, 1998; Issar, 2003) and northern Africa (Lamb et al., 1999) (Fig.6). In Northern Spain, evidence for lower lake levels and decreased floods during the 9th – 11th centuries occurred in the Iberian Range (La Cruz Lake, Juliá et al., 1998; Taravilla Lake, Valero-Garcés et al., in press), and the Pre-Pyrenean Range (Riera et al., 2004; Morellón et al., 2007).

Post Medieval Climate Anomaly to the Little Ice Age: 1200 – 1650 AD.

Unit 3 marks the onset of massive sediments deposition and an increase in sedimentation rate, likely related to agricultural practices (*Olea* rise) after the Christian conquest of the Guadalquivir River valley (13th century). A transition towards a colder and more humid climate has been identified in some Mediterranean areas from 1100 cal. yr B.P. until 400 cal. yr B.P. (Issar, 2003) and to an increase in large flood frequency during the early part of the Middle Ages (1100 – 700 yr cal. B.P.) (Benito et al., 1996). However, in Zoñar, the increase in *Myriophyllum* shows that more humid conditions after the MWA started a little earlier, around 750 cal. yr B.P. (AD 1200). This fits with the overall trend across the Mediterranean basin showing maximum wetness around AD 1250–1400 (Lamb et al., 1999) overlapping with the second half of the European Medieval Warm Period (Mayewski et al, 2004; Roberts et al., 1994).

From AD 1350 to AD 1650, the disappearance of *Myriophyllum* and the diatom assemblages suggest a lower lake level and more concentrated waters (Valero-Garcés et al., 2006) and it could be associated to a low lake level period prior to 390 cal. yr BP (AD 1650) when only the deepest basin was flooded and the core ZON-04-2A site (8 m water depth, NE area) was emerged.

The 17th – 19th century: the Little Ice Age. The Little Ice Age is a period with large climate variability and a strong human impact in Zoñar Lake. The onset is noticeable in the upper part of unit 3A with the deposition of facies 1, and dominance of planktonic *Cyclotella meneghiniana* (Diatom assemblage zone II, Valero-Garcés et al., 2006), and relatively higher values of *Myriopyllum* indicating that lake levels increased at around AD 1650 (Fig. 6). The NE part of the basin would be flooded at this time. Conditions during deposition of the lower part of Unit 2 (laminated facies, subunit 2E and 2D) are still suggestive of similar, relatively high lake level. The main limnological change occurred at the base of subunit 2C with deposition of laminated sediments containing algal/bacterial mats, the disappearance of *Myriophyllum* and the dominance of benthic, more saline forms in the diatom assemblages. During the late 19th century at the beginning of the 20th century (unit 2C, 2B and 2A), Zoñar lake was characterized by low clastic input, low turbidity and a relatively lower lake level (Valero-Garcés et al., 2006), although it was higher than during the Medieval Climate Anomaly when most of the NE shallower basin was exposed. According with this interpretation, the Little Ice Age seems to have a two-fold structure: a relatively more humid period (17th – 18th centuries) and a relatively more arid period, but with high climatic variability (19th century).

The 20th century. Human impact became the main driver of limnological change in the lake during the 20th century. Increased farming activities alongside, introduction of machinery for agriculture activities caused very high soil erosion, increased turbidity and deposition of massive or faintly laminated sediments (subunit 1C) after 1950s. Faintly laminated sediments of subunit 1B could indicate lower lake levels and increased salinity during the 1960s – 1970s caused by decreased rainfall and also the use of water of the spring for human consumption. Lake level increased after 1982 when the lake was declared a natural reserve and less water was diverted for agricultural purposes and human consumption. Figure 6 shows the general trend of higher lake levels during the 20th century and not these smaller hydrological fluctuations.

(B) Paleoclimatic implications

The complex geography of the Iberian Peninsula and its location between the Atlantic and the Mediterranean, at the southern limit of the Atlantic fronts, and with influences from mid-latitude and subtropical climates explain the modern climate variability and the large temperature and precipitation gradients (Rodriguez-Puebla et al. 1998). Most of the precipitation is related to Atlantic fronts, although meso-scale convective systems produce rainfall in the Mediterranean regions (García-Herrera et al. 2005). During the Late Holocene, wetter conditions in the Iberian Peninsula may result from: i) a southward displacement of the westerlies (for example during periods of predominant negative phase of the North Atlantic Oscillation) leading to an increase in winter precipitation; ii) a local monsoon–cyclonic rainfall and storms consequence of depressions over the Mediterranean in summer (Harrison *et al.*, 1992; Kutzbach *et al.*, 1993; Harrison *et al.* 1996).

The main hydrological transitions in the Zoñar Lake record are synchronous with the major periods of Holocene rapid climate change (RCC) described by Mayewski et al. (2004). Most of these events during the Late Holocene (4200–3800, 3500–2500, 1200–1000 cal. yr B.P.) are characterized by polar cooling, tropical aridity and major changes in the atmospheric circulation, although the most recent one (600–150 cal. yr B.P.) showed increased humidity in some parts of the tropics.

In Zoñar Lake, the 3500–2500 and 600–150 cal. yr B.P. RCC intervals shows transitions to humid conditions while the 4200–3800 and 1200–1000 cal. yr B.P. RCC intervals correspond to a decrease in humidity. The 3500–2500 cal. yr B.P. RCC interval corresponds to the most significant transition in the Zoñar record when the lake basin was flooded at 2800 cal. yr B.P.. At a Northern Hemispheric scale, the onset of this humid period corresponds with a North–Atlantic iceberg-rafting event (Bond et al., 1997), glacier advances in the Alps and retreat in west central Europe (Holzhauser et al., 2005), strengthened westerlies over the North Atlantic and Siberia (Meeker and Mayewski, 2002), and cooling over the NE Mediterranean (Rohling et al., 2002). Arid conditions predominated in tropical Africa during this interval. Wetter conditions occurred later in northern Africa (around 2500 yr B.P.) than in Europe, but the highest lake levels coincides with the maximum lake level in Zoñar (Lamb et al., 1995; Lamb et al., 1999) (Fig.6).

The 600–150 cal. yr B.P. RCC period coincides with glaciers advance in the Alps, westerlies strengthened over North Atlantic and Siberia, the Greenland's Norse colonies collapse and humid conditions over Equatorial Africa (Verschuren et al., 2000) and in Eastern Mediterranean (Soreq Cave, Bar-Mattews et al., 1999).

The Zoñar Lake response to both RCCs is similar (increased humidity). A maximum ^{14}C and ^{10}Be records during the 3500 – 2500 cal. yr BP and the 600 cal yr BP suggest that a decline in solar output is a plausible forcing for these periods of rapid climate change (Mayewski et al., 2004). On the other hand two of the three main arid periods in Zoñar Lake coincide with "cool poles, dry tropics" RCCs. The Roman "warm" period identified in Zoñar and in other Mediterranean areas did not have a global signal as an RCC.

The Zoñar and the Azores records (Björck et al., 2006) (Fig.6) show similar hydrological response for the Late Holocene. In the Azores island records, main cooler/drier periods occur at 600, 1400-1500, 2600-3000 and 3300 cal yr BP, while more humid phases occur 300-400, 900-1000, 2000-2400, 3100-3200, 3800-4000 and 4700-5000 cal yr BP (Björck et al., 2006). The humid Post Bronze- Iberian – Roman Period in Zoñar is one of the most humid periods in Azores, followed by a period of generally lower precipitation that includes the post Roman till the Medieval Climate Anomaly in Zoñar. The humid phase at 300-400 cal yr BP (AD 1540 – 1700) in Azores corresponds to the flooding of the Zoñar Basin in the 16th century.

On the other hand, comparison with an eastern Mediterranean high-resolution record for the last 1700 years (Jones et al., 2006) shows similarities in the timing of the main abrupt changes (AD 530 and AD 1400) but a different response: the transition at AD 530 in Turkey towards a wetter climate corresponds with the transition in unit 5 towards more arid conditions in Zoñar, and the period after AD 1400 is more humid in Turkey and generally more arid in Zoñar. This antiphase pattern between eastern and western Mediterranean records has been explained by atmospheric teleconnections between the North Sea and the Caspian Sea (Jones et al., 2006).

Mediterranean climate reconstruction from sedimentary record and historical documents (Rodrigo et al., 1999, 2000; Grove, 2001; Sousa and García-Murillo, 2003), and climate reconstructions for the last millennium in northern Europe (Visbeck et al., 2001; Björck et al., 2006; Gourirand et al. 2007) and in the Iberian Peninsula (Zorita.et al 1992; Muñoz-Díaz and Rodrigo, 2003, Trigo et al 2004) demonstrate that the North Atlantic Oscillation (NAO) has a strong influence in winter precipitation over the

Iberian Peninsula. During positive NAO phases, warmer than normal temperatures occur in central and northern Europe (Wibig and Glowicki, 2002), wet conditions dominate over western Scandinavia and Scotland (Knippertz et al., 2003), and drier conditions in southwestern Europe (Iberian Peninsula) and northwestern Africa (Marshall et al., 2001); opposite scenarios occur for negative NAO phases.

Comparison between Mediterranean and northern European records show an opposite response during some intervals of RCCs, particularly the LIA and the MCA suggesting a link to the North Atlantic Oscillation. Annually laminated records from Lake Nautajärvi (Ojala and Alenius, 2005) (Fig.6) and Lake Korttajärvi (Tiljander et al., 2003) in Finland show low catchment erosion caused by milder and wetter winter (+NAO phases) during the MCA, which is characterized by drier climate in Zoñar. From about 1440 AD, Nautajärvi record indicates a strong human impact, although more severe winters conditions (-NAO phases) conducive to increased detrital input dominate (Ojala and Alenius, 2005). Conversely, although climate variability is large in southern Spain during the LIA, there is an increase in rainfall after AD 1600 and several wet phases during the LIA (19th century) that could correspond to periods of more frequent –NAO phases over southern Europe. The most humid period in Zoñar (2600 – 1600 cal yr BP) corresponds to another period of increased mineral matter in the Finland lakes between BC 1500 to AD 500 (Ojala and Alenius, 2005). The long term changes in precipitation in Mediterranean and Azores latitudes may be related to changes in NAO phasing and comparable to millennial trends generated by the AO/NAO (Rimbu et al., 2004).

The Zoñar record supports the hypothesis that the timing of the main humid periods during the Holocene follows solar insolation, however, the occurrence of the arid periods does not follow the same pattern. Possible causes may be the northward migration of the associated winter rain belt, the strengthening of the Azores high during dominant NAO phases and/or decreased SST and evaporation due to disturbances in the thermohaline circulation of the North Atlantic (Björck et al., 2006).

(A) Conclusions

Paleoclimate reconstruction for Zoñar Lake shows the rapid responsiveness of this lake system to the Mediterranean climate evolution during the last 4000 years. Hydrological reconstruction, based on sedimentological, geochemical and biological proxies, from Zoñar Lake record allow to define four main paleohydrological episodes during the Late Holocene: i) an arid period prior to 2.8 cal. kyr BP, ii) a humid period from 2.6-1.6 cal. kyr BP that corresponds to the Late Iron–Iberian and Roman culture development in the region and includes a 300 yr arid stage (2.1 -1.8 cal kyr BP), iii) an arid period 1.3-0.6 cal. ky BP synchronous to the Medieval Climate Anomaly and iv) a humid period around 400 cal. yr BP- AD 1550 coinciding with the onset of the Little Ice Age. In addition, the Zoñar record also supports a connection between humidity changes in the lake, rapid climate changes (RCCs) during the Holocene and NAO dynamics.

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Table I. AMS data for cores ZON-04-1B, ZON-04-2A and ZON-01-1A. Dates marked with * were not included in the age model.

Depth (cm)	Dated material	Lab. number	^{14}C age yr BP	Calibrated age yr BP
Core ZON04-1B				
60	bulk organic matter	Poz-18438	modern	modern
96	bulk organic matter	Poz-16053	695±30*	665±23*
175	bulk organic matter	Poz-16013	1025±30*	945±39*
229	bulk organic matter	Poz-18459	845±30	740±54
242	Aquatic seeds	GRA-28167	825±40	735±61
280	bulk organic matter	Poz- 16014	1350±30	1275±38
342	Aquatic seeds	Poz-15969	2245±30*	2210±57*
364	bulk organic matter	Poz-18507	1865±30	1795±76
394	bulk organic matter	Poz-18460	2165±30	2155±56
452	bulk organic matter	Poz-16015	2560±30*	2725±28*
472	bulk organic matter	Poz-18508	2525±30	2565±77
532	Aquatic seeds	GRA-28166	2595±40	2740±43
565	bulk organic matter	GRA-30025	3145±40	3385±65
Core ZON-04-2A				
103,5	Littoral plant (reed)	Poz-15971	330±30	390±82
Core ZON01-1A				
125 correlated with core ZON04-1B, 168 cm)	Aquatic macrophyte	AA47855	593±38	595±58
165 correlated with core ZON04-1B, 208 cm	Pollen concentrate	AA60921	1771±38*	1705±113*

Table II. Sedimentary Facies in Zoñar core (ZON-04-1B).

Facies	**Description**	**Occurrence**	**Depositional subenvironment**
Massive facies			
Facies 1. Massive to faintly laminated, brownish calcite mud.	Cm-thick and dm-thick layers with gradational boundaries. Relatively low MS (4-8), low organic matter content (TOC 1-3%, TN <0.5%) and low Fe (200 cps); C/N: 10-15.	Units 1, 3 and 5	Littoral lacustrine
Facies 2. Massive to faintly laminated gray calcite silty mud.	Cm- to dm-thick layers (gray and brown). Relatively high MS (8-12), high organic matter content (TOC 3-6%, TN 1-1,5%) and high Fe (600 cps); C/N: 15-30	Units 1, 3 and 5.	Littoral lacustrine with high alluvial influence.
Laminated Facies			
Facies 3. Cm-thick, massive, dark brown organic ooze.	Cm-thick layers of greenish-brownish, amorphous organic matter. Very low MS (0-2) and the highest organic matter content (TOC: 18%, TN: 2,5%) and BGS (15-20 %). C/N: 10-15	Unit 2	Benthic bacterial/algal mat
Facies 4. Organic-rich, finely laminated variegated	Mm-thick laminae composed of i) greenish algal organic matter and diatoms, ii) benthic diatoms; iii) authigenic calcite; iv) brown, massive layer (algal mats) v) detrital carbonate mud. Organic laminae dominate.	Unit 2	Freshwater to brackish lake with development of bacterial/algal mat
Facies 5. Irregularly laminated (>2 mm thick) variegated	Mm-thick irregular laminae composed of i) greenish algal organic matter and benthic diatoms, ii) authigenic calcite and iii) detrital carbonate mud. Aragonite and faecal pellet are common.	Unit 4	Brackish to saline lake
Facies 6. Gypsum laminae	Laminae (3-5mm thick, unit 4) and cm-thick layers (unit 6). Both, diagenetic (nodules and intrasedimentary 100 µ long crystals) and primary (prismatic, 20 µm long crystals) occur.	Units 4 and 6	Saline lake
Facies 7: Varves, annually-laminated.	Mm-thick laminae arranged in 2-5 mm thick triplets (varves) composed of i) authigenic calcite,ii) organic ooze and iii) calcite mud.	Unit 6	Offshore lacustrine, relatively deep, with anoxic bottom conditions.
Massive facies with edaphic textures			
Facies 8. Massive, aragonite-bearing mud with edaphic textures	Massive, brownish carbonate mud. Relatively high MS (6-10) and upcore increasing TOC values (up to 4%); Aragonite 5-8%; C/N: 10-15, Presence of subaerial cracks and soil textures.	Unit 7	Ephemeral, freshwater to brackish lake
Facies 9. Massive, quartz and clay – rich carbonate mud with edaphic textures.	Massive and greyish – brownish mud. High MS (16); Low TOC (< 1%); high quartz content; C/N up to 25. Presence of gastropods, subaerial cracks and soil textures (clay cutans and mottling).	Unit 8	Ephemeral lake, frequently dried out and with incipient soil formation

Figure captions

Figure 1. (a) Geographic location of Zoñar Lake in the Iberian Peninsula. (b) The Zoñar Lake catchment and a bathymetic map over the aerial photograph.

Figure 2. Age-depth model for the last 4000 years of Zoñar Lake based on AMS ^{14}C and ^{137}Cs dates.

Figure 3. Stratigraphic correlation of the Zoñar cores, including the Kullenberg cores from the 2004 expedition (deep SW basin cores ZON04-1B, 1A, 1C and shallow NE basin ZON04-2A core) and the Livinsgtone cores from the 2001 expedition (ZON01-1A and1B from Valero-Garcés et al., 2006). The location of the cores is shown in a NE-SE longitudinal section of the lake. The correlation horizon is the boundary between units 2 and 1.

Figure 4. Sedimentary facies and units, magnetic susceptibility and sedimentological and geochemical proxies for core ZON04-1B. S and Fe intensities are expressed in count per second (cps), magnetic susceptibility in SI units, and mineralogical and compositional data en percentages. Valid AMS data are also indicated.

Figure 5. Selected pollen taxa compared with some sedimentological, mineralogical, geochemical, and biological indicators. The Mediterranean component curve includes *Rhamnus, Thymelaea, Phillyrea, Ligustrum, Ceratonia, Lycium, Cistus,* Ericaceae, *Ephedra*, Genisteae and Lamiaceae, but excludes the main arboreal elements of this group (*Olea europaea*, evergreen *Quercus* and *Pistacia*), plotted individually. Only some selected herb taxa (Cichorioideae and Chenopodiaceae) and hydrohygrophytes (*Ruppia* and *Myriophyllum*) are shown. Ostracod curve is based on semiquantitative data. Planktonic/Periphytic diatom ratio and percentages of marine diatoms are based on semiquantitative date from core ZON-04-1B. Diatom species percentages are from core ZON-01-1B (Valero-Garcés et al., 2006).

Figure 6. Lake level reconstruction for Zoñar Lake for the last 4000 yr BP compared with other paleoclimatic and paleohydrological records. Humid and arid periods in Zoñar lake are indicated with different shades: BIRP, Post Bronze – Iberian – Roman Humid Period; MCA, Medieval Climate Anomaly; LIA, Litte Ice Age. From left to right: lake level reconstruction from the Jura Mountains (Pre-Alps) (Magny, 2004); aridity index from Caveiro Lake (Azores Islands) (Björk et al., 2006); lake level reconstruction inferred from magnetic susceptibility from Sidi Ali Lake (Morocco) (Lamb et al., 1999); lake level reconstruction from Tigalmamine Lake (North of Africa) (Lamb et al., 1995); paleoprecipitation inferred from $\delta^{18}O$ in Nar Gölü Lake (Turkey) (Lamb et al., 1999) and Spanish flooding episodes (Macklin et al., 2006).

Figure 1

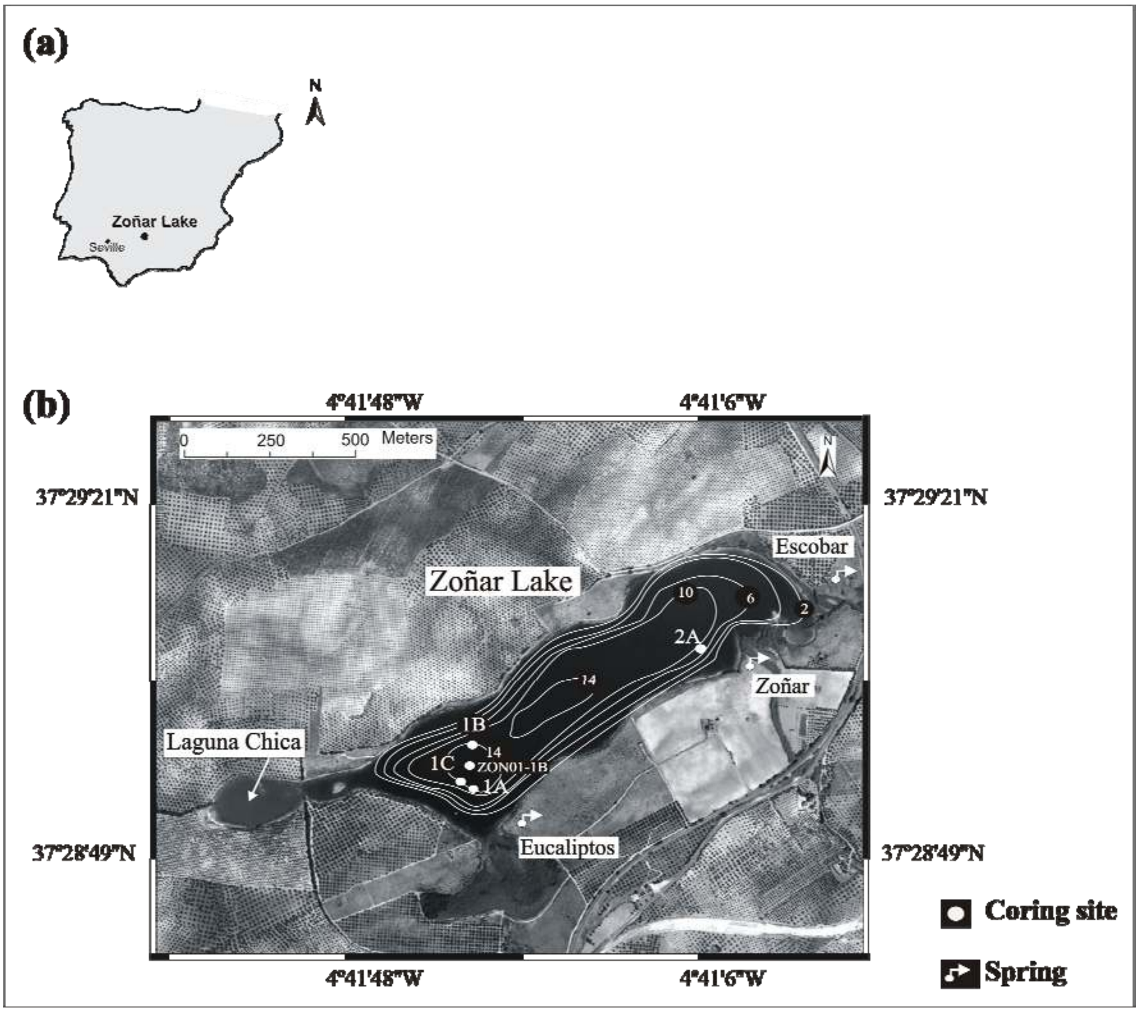

(a)
N
Zoñar Lake
Seville
(b)
4°41'48"W
4°41'6"W
0
250
500
Meters
N
37°29'21"N
37°29'21"N
Escobar
Zoñar Lake
10
6
2
2A
14
Zoñar
1B
Laguna Chica
14
1C
ZON01-1B
1A
Eucaliptos
37°28'49"N
37°28'49"N
4°41'48"W
4°41'6"W
Coring site
Spring

Figure 2.

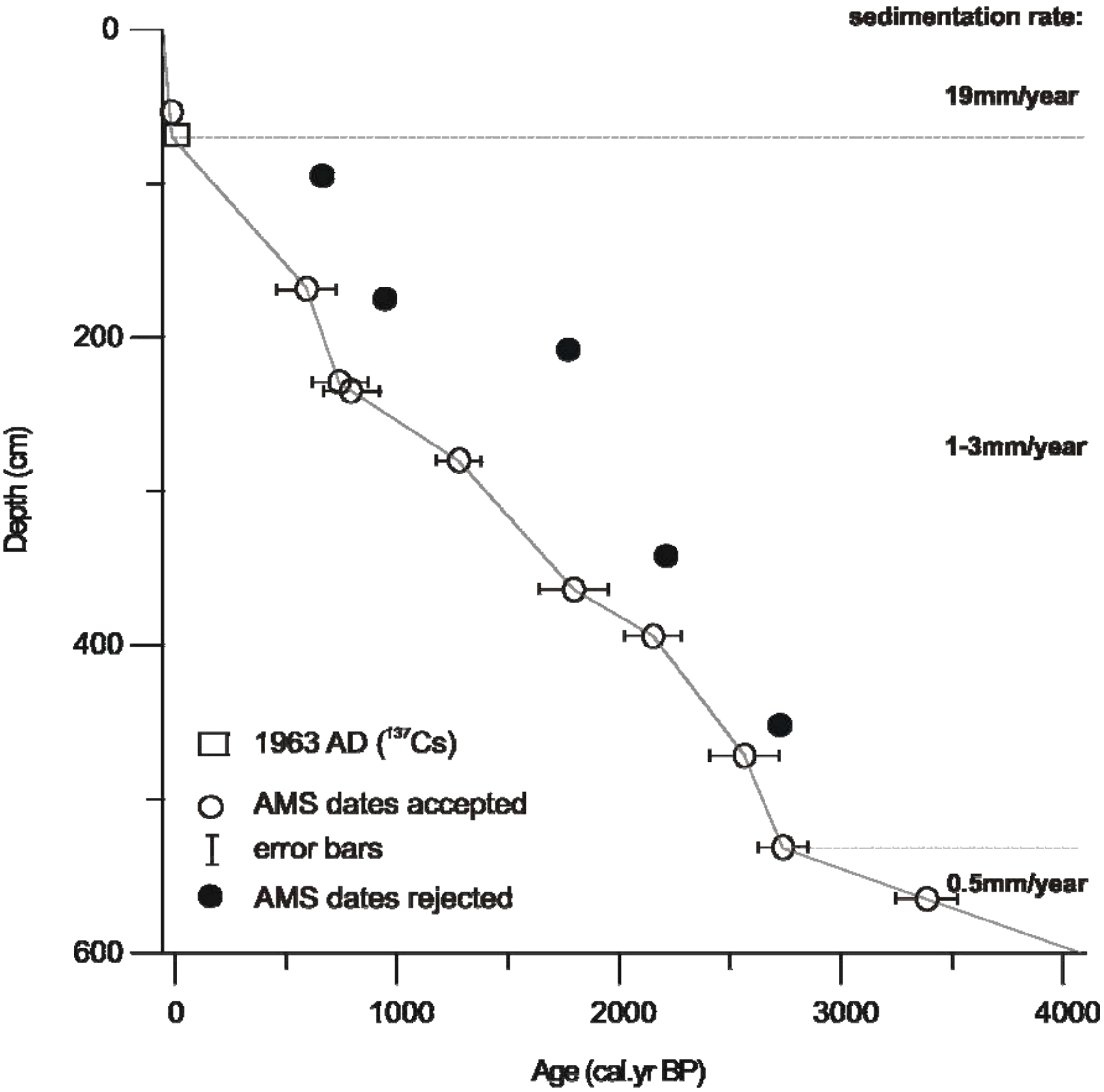

sedimentation rate:
19mm/year
1-3mm/year
0.5mm/year
0
200
400
600
Depth (cm)
0
1000
2000
3000
4000
Age (cal.yr BP)
1963 AD (^{137}Cs)
AMS dates accepted
error bars
AMS dates rejected

Figure 3.

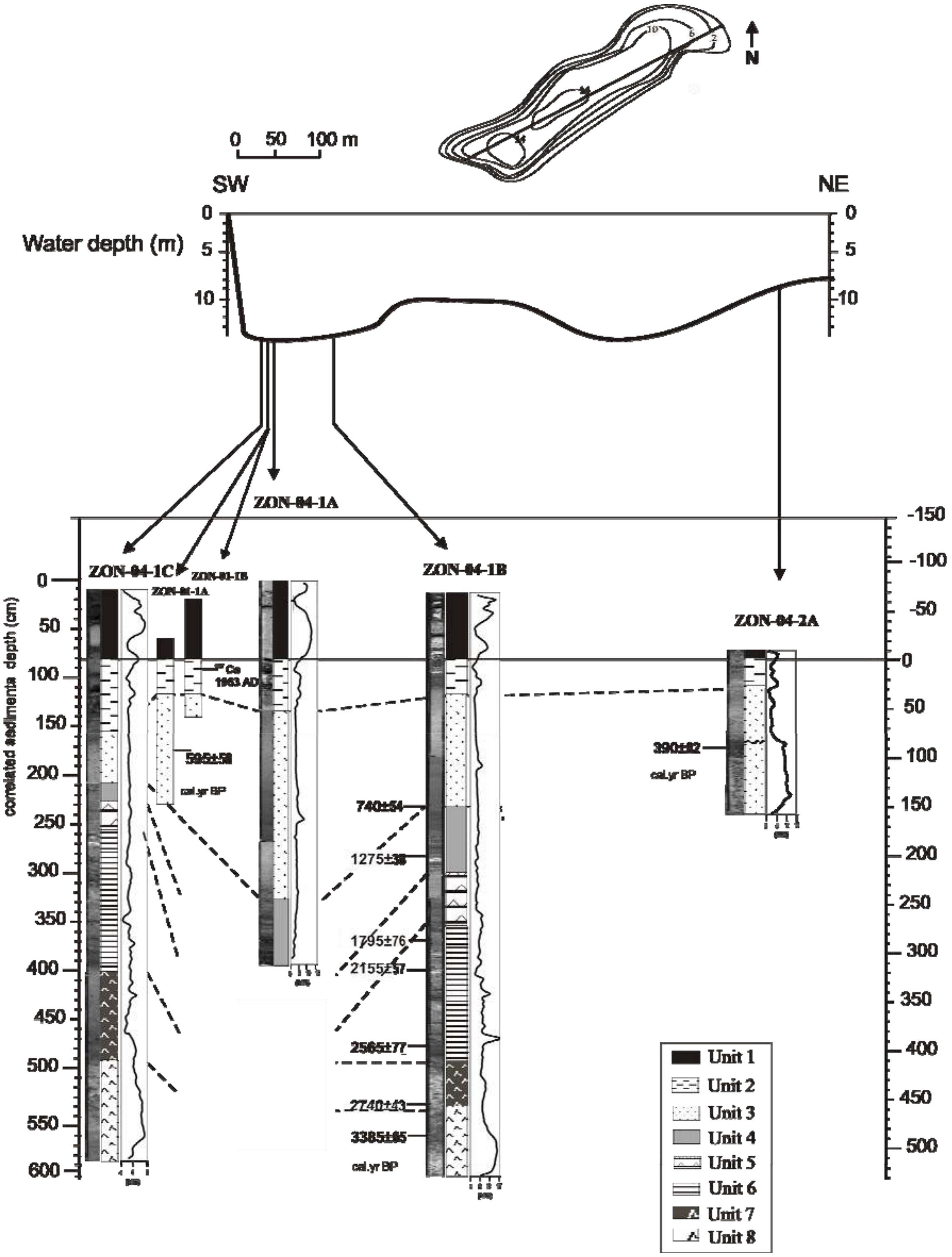

10
6
2
N
0
50
100 m
SW
NE
Water depth (m)
0
5
10
ZON-04-1A
ZON-04-1C
ZON-04-1B
ZON-04-1A
ZON-04-1B
ZON-04-2A
correlated sediments depth (cm)
0
50
100
150
200
250
300
350
400
450
500
550
600
-150
-100
-50
0
50
100
150
200
250
300
350
400
450
500
^{137}Cs
1963 AD
595±58
cal.yr BP
740±54
1275±38
1795±76
2155±37
2565±77
2740±43
3385±65
cal.yr BP
390±82
cal.yr BP
Unit 1
Unit 2
Unit 3
Unit 4
Unit 5
Unit 6
Unit 7
Unit 8

Figure 4

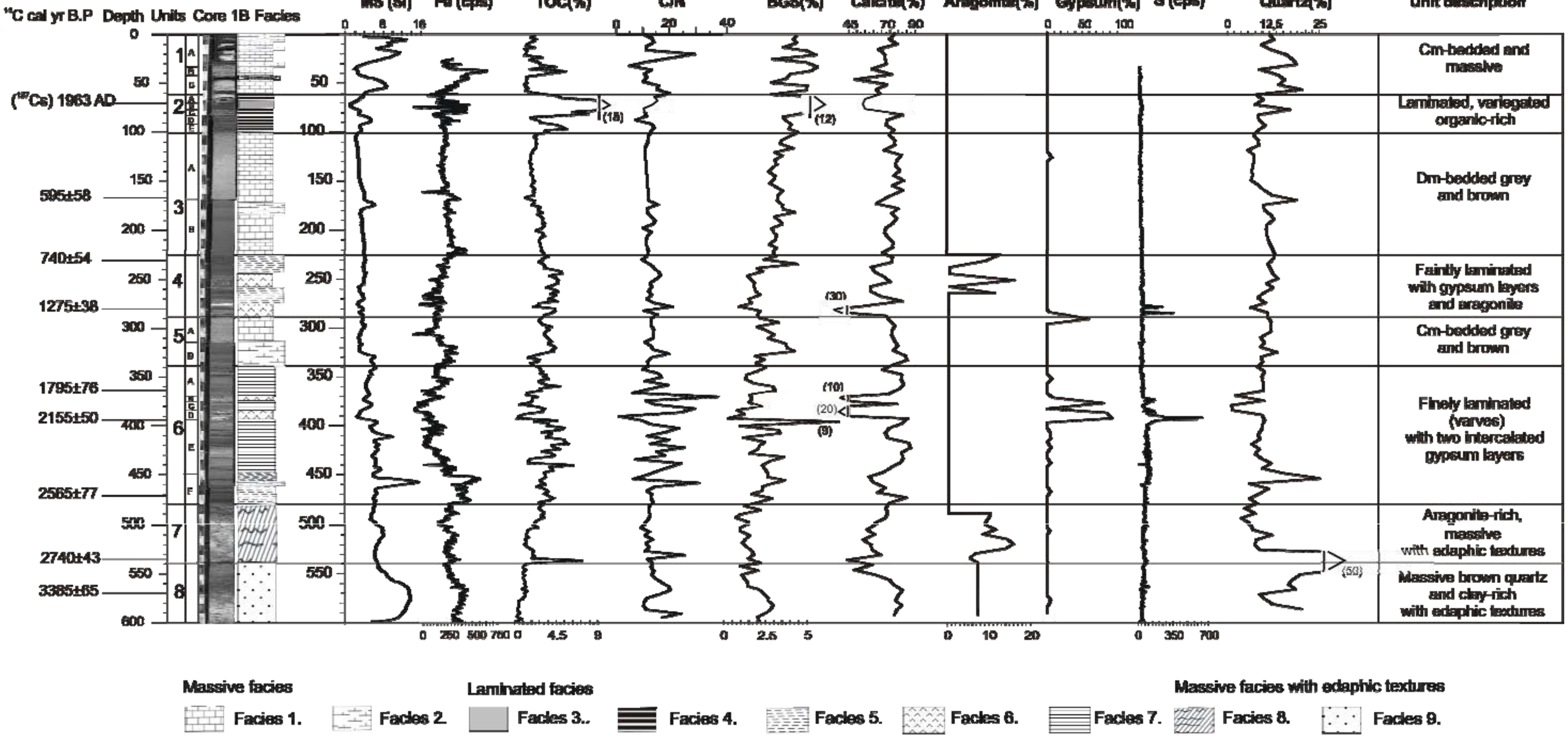

^{14}C cal yr B.P
Depth
Units
Core 1B
Facies
MS (SI)
Fe (cps)
TOC(%)
C/N
BGS(%)
Calcite(%)
Aragonite(%)
Gypsum(%)
S (cps)
Quartz(%)
Unit description
0 8 16
0 20 40
45 70 90
0 50 100
0 12.5 25
0 250 500 750
0 4.5 9
0 2.5 5
0 10 20
0 350 700
0
50
100
150
200
250
300
350
400
450
500
550
600
(^{137}Cs) 1963 AD
595±58
740±54
1275±38
1795±76
2155±50
2565±77
2740±43
3385±65
1
2
3
4
5
6
7
8
A
B
C
D
E
F
(18)
(12)
(30)
(10)
(20)
(9)
(50)
Cm-bedded and massive
Laminated, variegated organic-rich
Dm-bedded grey and brown
Faintly laminated with gypsum layers and aragonite
Cm-bedded grey and brown
Finely laminated (varves) with two intercalated gypsum layers
Aragonite-rich, massive with edaphic textures
Massive brown quartz and clay-rich with edaphic textures
Massive facies
Laminated facies
Massive facies with edaphic textures
Facies 1.
Facies 2.
Facies 3..
Facies 4.
Facies 5.
Facies 6.
Facies 7.
Facies 8.
Facies 9.

Figure 5.

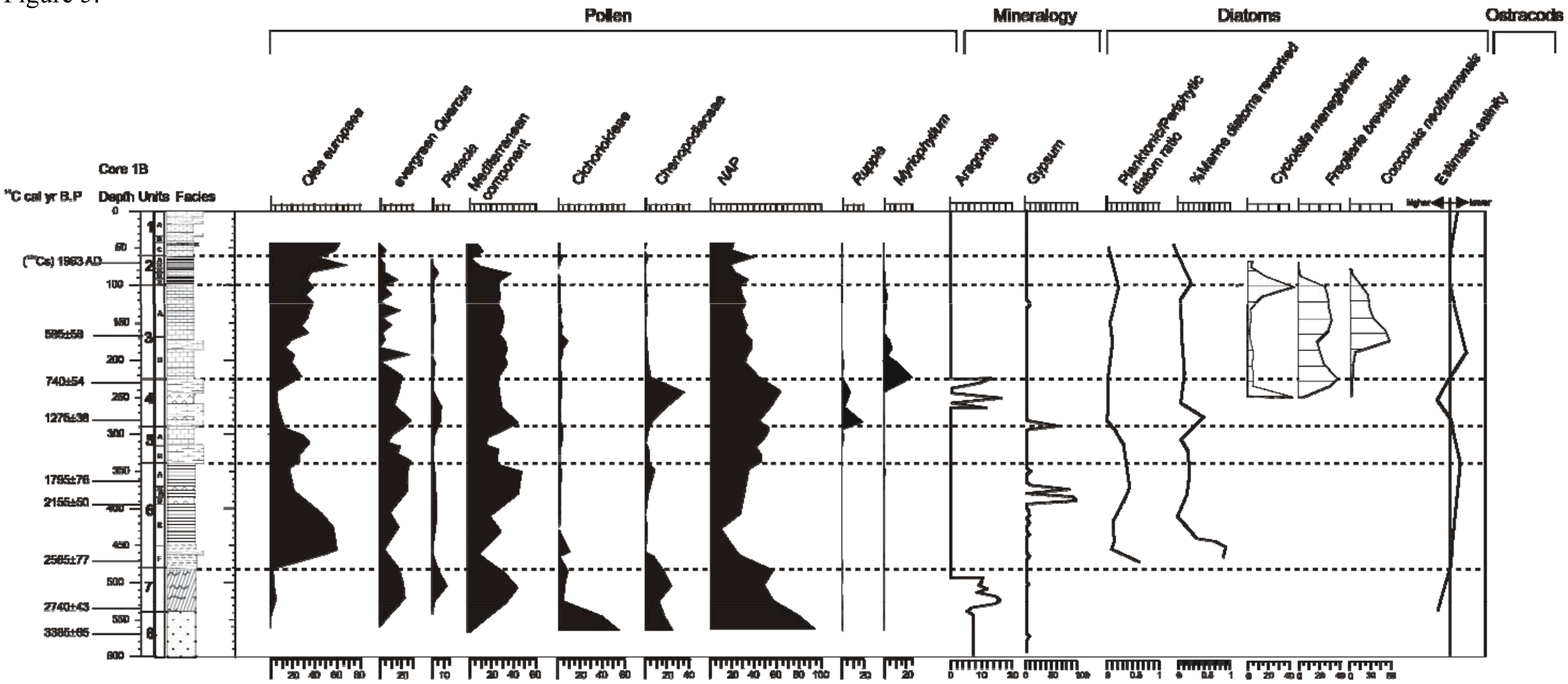
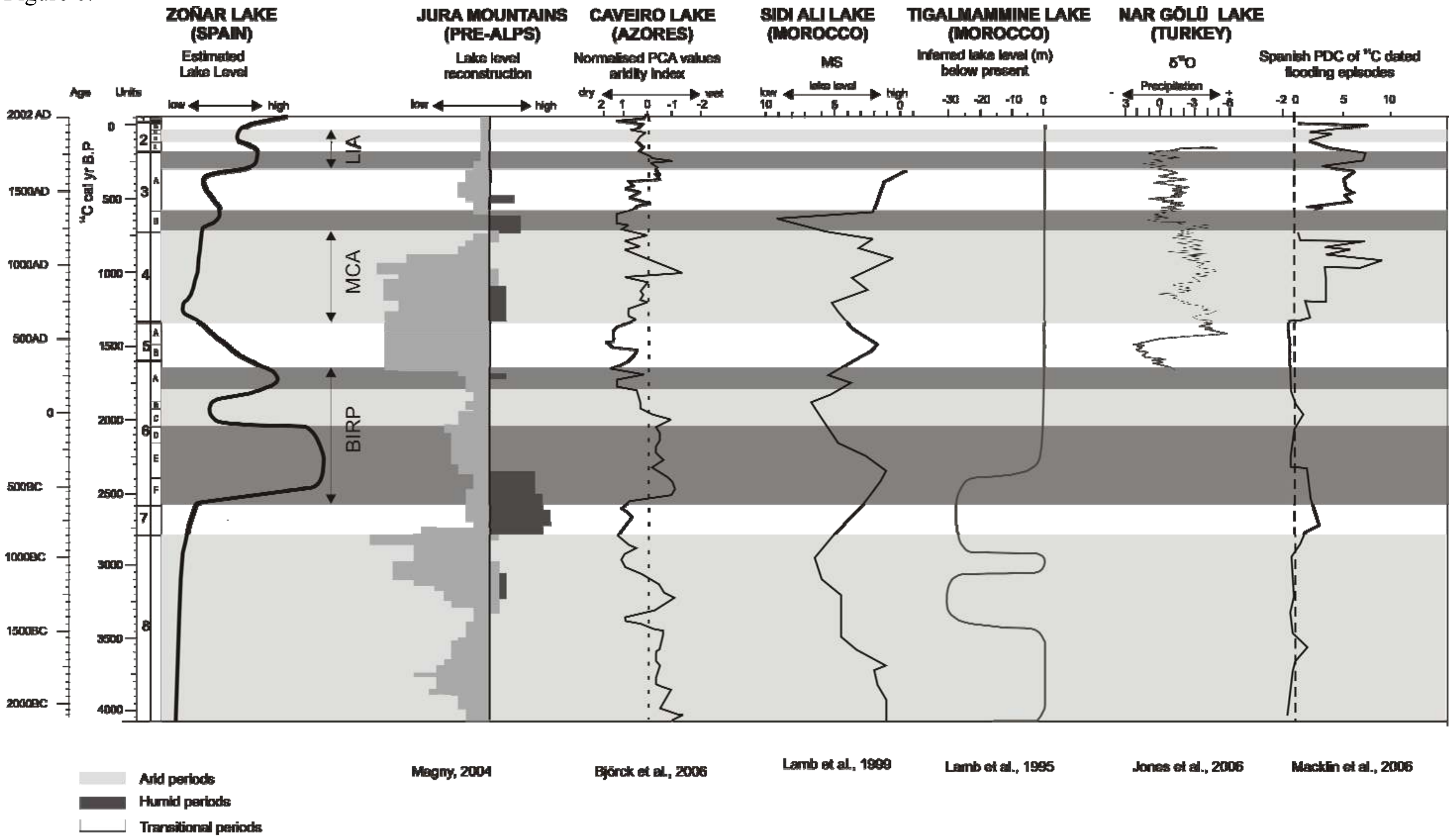

Pollen
Mineralogy
Diatoms
Ostracods
Core 1B
^{14}C cal yr B.P
Depth
Units
Facies
Olea europaea
evergreen Quercus
Pistacia
Mediterranean component
Cichorioideae
Chenopodiaceae
NAP
Ruppia
Myriophyllum
Aragonite
Gypsum
Planktonic/Periphytic diatom ratio
%Marine diatoms reworked
Cyclotella meneghiniana
Fragilaria brevistriata
Cocconeis neothumensis
Estimated salinity
higher
lower
(^{137}Cs) 1963 AD
595±58
740±54
1275±38
1795±76
2155±50
2585±77
2740±43
3385±65
0
50
100
150
200
250
300
350
400
450
500
550
600
1
2
3
4
5
6
7
8
A
B
C
D
E
F
20 40 60 80
20
10
20 40 60
20 40 60
20 40
20 40 60 80 100
20
20
0 10 20
0 50 100
0 0.5 1
0 0.5 1
0 20 40
0 20 40
0 30 60

Figure 6.


ZOÑAR LAKE (SPAIN)
Estimated Lake Level
JURA MOUNTAINS (PRE-ALPS)
Lake level reconstruction
CAVEIRO LAKE (AZORES)
Normalised PCA values aridity index
SIDI ALI LAKE (MOROCCO)
MS
TIGALMAMMINE LAKE (MOROCCO)
Inferred lake level (m) below present
NAR GÖLÜ LAKE (TURKEY)
δ18O
Spanish PDC of 14C dated flooding episodes
Age
Units
low
high
dry
wet
lake level
Precipitation
2 1 0 -1 -2
10 5 0
-30 -20 -10 0
3 0 -3 -6
-2 0 5 10
2002 AD
1500AD
1000AD
500AD
0
500BC
1000BC
1500BC
2000BC
14C cal yr B.P
0
500
1000
1500
2000
2500
3000
3500
4000
2
3
4
5
6
7
8
A
B
C
D
E
F
LIA
MCA
BIRP
Magny, 2004
Björck et al., 2006
Lamb et al., 1999
Lamb et al., 1995
Jones et al., 2006
Macklin et al., 2006
Arid periods
Humid periods
Transitional periods