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An environmental snapshot of the Bølling interstadial in Southern Iberia

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A B S T R A C T

The Bølling–Allerød interstadial is the closest warm time period to the Holocene. The study of the climate variability during this most recent warm scenario provides a natural record of potential environmental changes related with global temperature variations. Little is known about this interstadial in the Southern Iberian Peninsula. Therefore, the exceptional climatic record of the Otiñar paleo-lake (ca. 14.5–14.0 cal ka BP), provides environmental information about the first part of this interstadial (Bølling) in this key region. Although the studied high-resolution isotopic record point to almost invariant hydrological conditions in the paleo-lake, with little change in the carbon budget and important limestone dissolution, the pollen record shows an increase in forest species that can be interpreted as a warming trend and an increase in humidity during the Bølling in the area. This record is one of the few continental archives that show this climatic trend in Southern Iberia, agreeing with many other regional records from the western Mediterranean. This does not agree with higher latitude records that show an opposite trend. This opposite pattern in precipitation between the western Mediterranean and more northern latitudes could be explained by a persistent and increasing negative NAO mode during the Bølling in this area.

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Introduction

The last glacial–interglacial transition, or Termination 1 [from the Last Glacial Maximum (~22–18 cal ka BP) to the Holocene (~11 cal ka BP)] is characterised in the Northern Hemisphere by millennial-scale abrupt climate changes (McManus et al., 2004; Lowe et al., 2008; Liu et al., 2009; Denton et al., 2010). Cold conditions during Heinrich Event 1 and Oldest Dryas (GS-2) ~17 cal ka BP were followed by an abrupt warming around ~14.7 cal ka BP — the Bølling–Allerød period (GI-1) (Yu and Eicher, 1998; Broecker et al., 2010; van Raden et al., 2013). After this warm period, cold conditions were recorded again during the Younger Dryas (GS-1) between ~12.7 and 11.5 cal ka BP (Broecker et al., 2010; van Raden et al., 2013). Subsequently, the early Holocene was characterised by a warming trend (Lowe et al., 2008).

The onset of the Bølling warm period corresponds to the beginning of the Greenland Interstadial-1 (GI-1) in the GRIP chronology of Björck et al. (1998) and Lowe et al. (2001, 2008). High-resolution paleoenvironmental records from Bølling–Allerød interstadial show occasional interruptions by short climatic cold excursions, such as the Inter-Bølling Cold Period, the Older Dryas and the Inter-Allerød Cold Period, probably caused by changes in thermohaline circulation from the North Atlantic and subsequent changes in sea-surface temperatures (Björck et al., 1996; Brauer et al., 1999; Fleitmann et al., 2008; among others).

Although the Bølling–Allerød interstadial is overall a relatively warm period, opposite climatic trends can be observed from Bølling to Allerød period in the Northern Hemisphere between mid and high latitudes. At present, this kind of opposite humidity trends at inter-annual and decadal scales can be explained by the effect of the North Atlantic Oscillation (NAO), one major climate mode that naturally affects weather and climate patterns across Europe. The NAO is controlled by changes in the atmospheric circulation caused by the difference between surface sea-level pressure of the Subtropical High and the Subpolar Low (Hurrel, 1995, and references therein). These differences are expressed in the NAO index (positive or negative): in the positive mode, enhanced zonal westerlies from the North Atlantic provide warm and moist air across northern Europe, with dry conditions over southern Europe, and the negative mode, with more meridional atmospheric flow, generate opposite effects (Hurrel et al., 2003). This climatic pattern controls annual precipitation in arid southern Iberia and high-resolution records are required to investigate cyclical

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patterns in the past hydrological variations linked to decadal and multidecadal NAO changes.

Marine sediment cores of this age have been studied in the western Mediterranean area and warm and humid conditions were reconstructed (Barcena et al., 2001; Jiménez-Espejo et al., 2008; Rodrigo-Gámiz et al., 2011, 2013). However, continental records describing the latest Pleistocene/earliest Holocene climate evolution, although frequent in Northern Iberia, are very rare in the South (Moreno et al., 2010, 2011; Muñoz Sobrino et al., 2013, and references therein), which is an especially arid and very sensitive area to climate variations (García-Alix et al., 2012a,b, 2013). In this area, the Bølling–Allerød period is only well-recognized in the sequences from El Padul peat-bog (Ortiz et al., 2004) and Alicún travertines (Prado, 2012) and other less detailed records including the cave sequence from the Carihuela cave (Fernández et al., 2007), the site of Navarrés (Carrión and Dupré, 1996; Carrión and van Geel, 1999) and the montane site of Siles (Carrión, 2002).

Recently a paleo-lake sedimentary sequence deposited during the Bølling interval was discovered at Otiñar, SE Spain (García-García et al., 2011). This new sequence represents a unique record, as it is characterised by very high sedimentary rates (~11 m of fine-grained sediment during ~500 yr; García-García et al., 2011). In this study we show a sedimentological, isotopic and palynological record carried out on this sedimentary sequence. This was done to improve our knowledge on the paleoclimatic and paleoenvironmental conditions during the Bølling period in the Southern Iberian Peninsula.

Geological setting

The Otiñar paleo-lake sedimentary sequence is located near Jaén, Southern Spain, in the External Zones of the Betic Cordillera, close to the Guadalquivir Foreland Basin. A previous study shows that these materials were deposited in a small lake, ~1 km^2, after a landslide dammed the Quiebrajano River during the latest Pleistocene sometime before ca. 14.5 cal ka BP (García-García et al., 2011) (Fig. 1).

The catchment basin of the studied paleo-lake had a surface ~139 km^2, and its bedrock is mainly composed of Jurassic limestone, dolomite and marls (Fig. 1A), Cretacic marls and Triassic (Keuper) clay and gypsum. The maximum elevation around the site is 1860 m, with average values around 1169 m. The altitudinal gradient of this catchment basin was steep, causing high sedimentation rates in the paleo-lake of about 11.5 cm/a. The lacustrine sedimentation is mainly represented by lutites and fine sands (Figs. 1B and 2) (García-García et al., 2011).

The Otiñar paleo-lake record consists on typical facies belts in siliciclastic lakes: Gilbert-type facies in the margin, followed by shallow coastal wetlands and suboxic bottom sediments with episodic turbiditic deposits in the central zone (Fig. 1C). The sequence is about 15-m-thick and is partially eroded on the top by alluvial-fans and fluvial deposits (García-García et al., 2011) (Figs. 1A, B). These alluvial-fans from the southeastern sector of the lake developed at the latest stage of the lake sediment filling (Figs. 1B and 2). Finally, when the accommodation space was filled, an erosive phase started, and exorheic drainage developed, crossing longitudinally the basin.

Material and methods

The sequence studied is characterised by a total of ~11.5 m of lacustrine sediments (Fig. 1B), although the main lacustrine outcrops have a thickness of ~9–10 m due to erosion (Fig. 2A). The Otiñar sedimentary sequence was sampled at ~50-cm increments, recovering a total of 24 sediment samples. Samples were taken directly from the outcropping sedimentary sequence. These sediments consisted mainly on lutites, with some fine sandy levels. The sand content progressively increases to the top of the section (Fig. 2). Two recent water samples from the Quiebrajano River, close to the studied outcrop, were analysed as well for comparison.

The age model for the studied section follows García-García et al. (2011). It is based on three radiocarbon dates from leaves and other plant fragments analysed in the Leibniz Laboratory for Radiometric Dating and Isotope Research (Table 1). They were taken from the studied sequence at ca. 0, 3 and 9 m depths that were calibrated using CALIB Version 7.0 html and the calibration curve IntCal13 (Stuiver et al., 1998) (14.50 ± 0.43, 14.26 ± 0.32 and 13.97 ± 0.16 cal ka BP) (Fig. 1B; Table 1). The age model was constructed by linear interpolation using the calibrated ages. The error bars are referred to the 2-sigma error (Fig. 1b).

Carbon isotopes from bulk organic matter, oxygen and carbon isotopes from carbonate fraction, total organic carbon content (TOC), atomic C/N ratio, pollen and the bulk mineral composition were analysed from these lacustrine sediments, as well as oxygen and carbon isotopes from recent waters.

Samples for organic matter analyses were decalcified with 1:1 HCl in order to eliminate the carbonate fraction. Carbon isotopes ($\delta^{13}C_{om}$), TOC percentages, and the atomic C/N ratios were measured by means of an EA-IRMS elemental analyser connected to a XL Thermo Finnigan mass spectrometer. Isotopic results were expressed in δ notation, using the standard V-PDB (carbon). Samples were measured in duplicate. %TOC per gramme of sediment was calculated from %C yielded by the elemental analyser, and recalculated by the weight of the sample before and after decalcification.

Oxygen and carbon isotopes of the carbonate fraction ($\delta^{18}O_c$, $\delta^{13}C_c$) were analysed using the classic method from McCrea (1950) by mean of a XL Thermo Finnigan mass spectrometer with a coupled Thermo Finnigan Gas Bench II. Results were expressed in δ notation, using the standard V-PDB (carbon and oxygen). Samples were measured in triplicate. The calculated precision, after correction for mass spectrometer daily drift, using standards systematically interspersed in analytical batches, was better than ±0.1‰ for $\delta^{18}O$ (carbonates) and $\delta^{13}C$ (organic matter and carbonates).

Isotopic composition of dissolved inorganic carbon (DIC) from recent water samples was measured by reaction with pure phosphoric acid to bring all DIC to gaseous CO_2 during 48 h at 25°C constant temperature, and then measured in a Finnigan DeltaPlus XP mass spectrometer attached to a Finnigan GasBench II. Results are expressed in δ notation, using the standard V-PDB (carbon). Samples were measured in triplicate. The analytical precision is 0.05‰ and reproducibility of measurements is <0.1‰.

Pollen analysis was carried out on samples taken every metre in the section. Pollen extraction methods followed a modified Faegri and Iversen (1989) methodology. Counting was performed at 400 magnification to a minimum pollen sum of 300 terrestrial pollen grains. Fossil pollen was identified using published keys (i.e., Faegri and Iversen, 1989). The raw counts were transformed to pollen percentages based on the total pollen sum. The pollen zonation was accomplished using pollen percentages of the most significant species and through a cluster analysis (CONISS; Grimm, 1987).

X-ray diffraction was carried out on nine samples through the section (Fig. 3). Bulk mineral compositions were obtained by X-ray diffraction (XRD) following the international recommendations compiled by Kirsch (1991). Measurements were performed on a PANalytical diffractometer using a Cu anode. Diffractograms were interpreted using the Xpowder software available at http://www.xpowder.com (Martin, 2004). Peak areas have been measured in order to estimate semiquantitative mineral content. The estimated semiquantitative analysis error for bulk mineralogy absolute values is 5% and error ranges from 5% to 10% for clay mineral proportions; although semiquantitative analysis aims to show changes or gradients in mineral abundances rather than absolute values.

Images were taken with a FEI ESEM QUANTA 400 of the 'Centro Instrumentación Científica' of the University of Granada. The qualitative chemical composition of the sediments has been characterised by BSE (backscattered electrons) and EDS (energy dispersive X-ray

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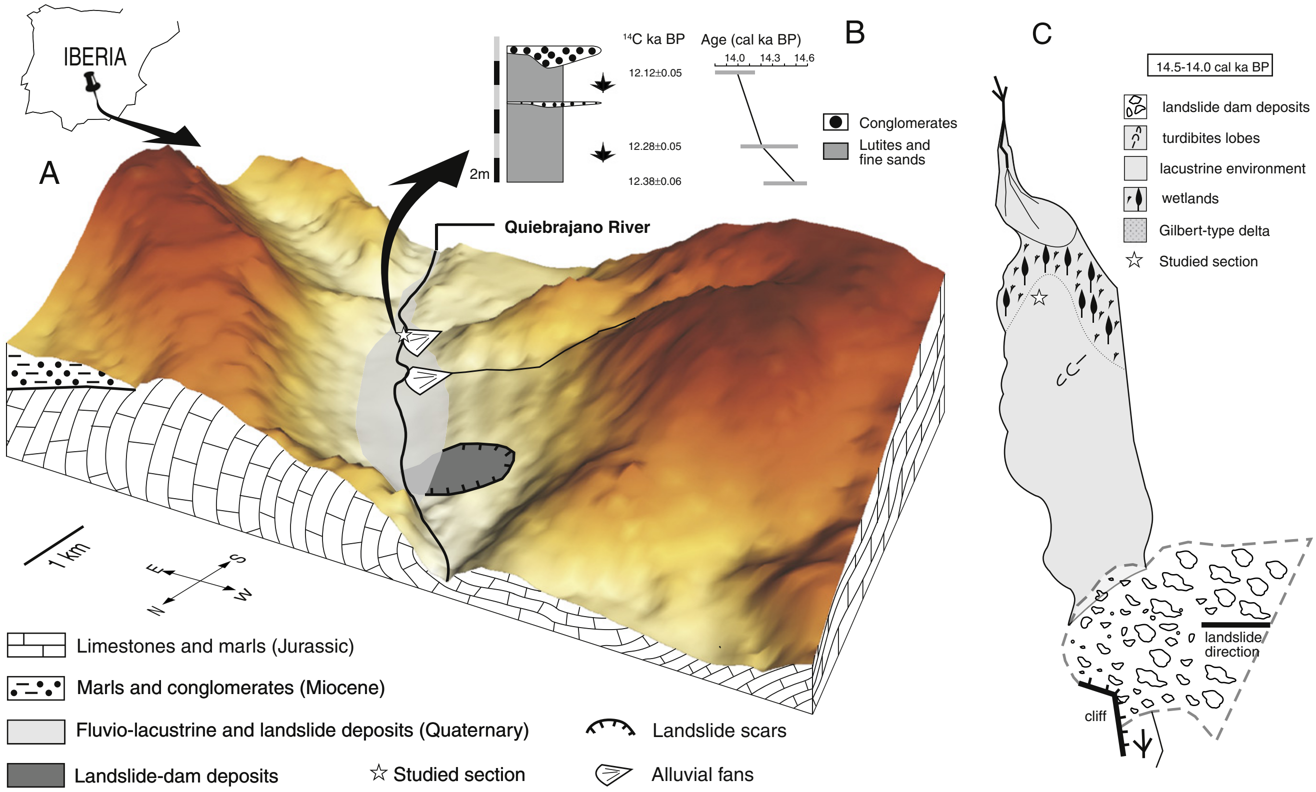

Figure 1. Geographical and geological context of the studied area. A, situation of the studied Section. B, synthetic stratigraphic column and chronological framework. The age model is constructed by linear interpolation through the calibrated age, and the grey bars represent the 2-sigma error. C, paleo-lake reconstruction from 14.45 to 14.0 cal ka BP (modified from García-García et al., 2011).

spectroscopy) using the ESEM Quanta 400. Sedimentary samples were previously coated with carbon.

Results

Sedimentology and mineralogy

The Otiñar sequence is from 15 to 9-m-thick, depending on the site, and is partially eroded on the top by alluvial-fans and fluvial deposits (Figs. 1B and 2A). The main outcrops contain ~9–11 m of lacustrine sediments due to these erosive events. The lacustrine deposits are characterised by different facies associations from the bottom to the top of the sediment succession, as well as from the centre to the lacustrine margin. The lacustrine succession (Figs. 2A, B), from the bottom to the top, consists of thin-bedded to laminated silty packestone and mudstone carbonates (lake centre association facies) (Figs. 2E, F), wavy laminated sands and silts with vertical root traces and lacustrine gastropods with normal/inverse-graded pebble beds with a sharp erosional base (lake marginal association facies) (Figs. 2G, H).

Lake centre association facies consist of a mixture of terrigenous carbonates and siliciclastics, mostly silt-sized grains and clay minerals (Fig. 2E). There is also a large amount of authigenic carbonates (mainly as micrite: Figs. 2C, D), which are covering the detrital grains (dolomite, calcite, or silicates). The EDAX analyses show the carbonate nature of this thin cover (Fig. 2C). There are also small bioclasts, such as bivalves. These sediments contain well-preserved leaves, identified as *Salix* sp., typically found within thin medium- to fine-grained sand beds 5 to 15 cm thick. The bottom of the normal-graded sand beds is typically flat, with cross-lamination. The lack of internal sedimentary structures in the mudstone facies suggests that deposition was by settling of suspended sediment in the central part of a detrital lake with a moderate biogenic component. The central part of the lake was episodically affected by distal sandy turbidite currents developing climbing ripples migrating basinwards, linked to increased sediment supply from the lake margin (Fig. 2 F). Lack of bioturbation and lamination preservation points to an anoxic or suboxic lacustrine bottom.

Lake marginal facies association consists of wavy laminated sands and silts, with vertical root traces (Fig. 2H) and lacustrine gastropods, with 1 to 2 m in width and 15 to 50 cm in thickness normal to inverse-graded pebble beds with a sharp erosional base (Fig. 2 G). These facies are interpreted as deposited in a very shallow lake margin close to the lake level (shallow coastal wetlands) with marginal vegetation and small gravel channels.

Bulk mineralogy is mainly composed of clay minerals (40–90%), calcite (5–25%), dolomite (1–40%) and quartz (1–5%). Along the sequences we can observe a progressive decrease in clay minerals followed by a progressive increase in the detrital dolomite/calcite ratio, suggesting an increase in detrital calcite and dolomite (Fig. 3).

Isotope analyses

Isotopic values from organic matter and carbonates are almost invariant through the section, with low standard deviations (Fig. 3). Carbon and oxygen isotopic values of the sediment carbonate fraction ($\delta^{13}C_c$ and $\delta^{18}O_c$) range from 1.0‰ to 1.5‰, with a mean value of 1.2 ± 0.1‰ (V-PDB), and from −3.3‰ to −2.3‰, with a mean

Figure 2. A, stratigraphic log of the lacustrine deposits; B, field picture showing the lacustrine deposits; C, ESEM pictures and EDAX analyses of a sediment sample ~160 cm; D, ESEM picture of a sediment sample ~250 cm; E, alternation of clays (grey and white levels) and orange fine-grained sands from the central lake (coin to scale); F, 25 cm-thick sand bed into fine-grained deposits (lens cap to scale); G, 15 cm-thick inverse-graded bed from the middle-top of the succession (hammer to scale), H. Root marks (vertical yellow motting) into sandy deposits. Column scale in cm.

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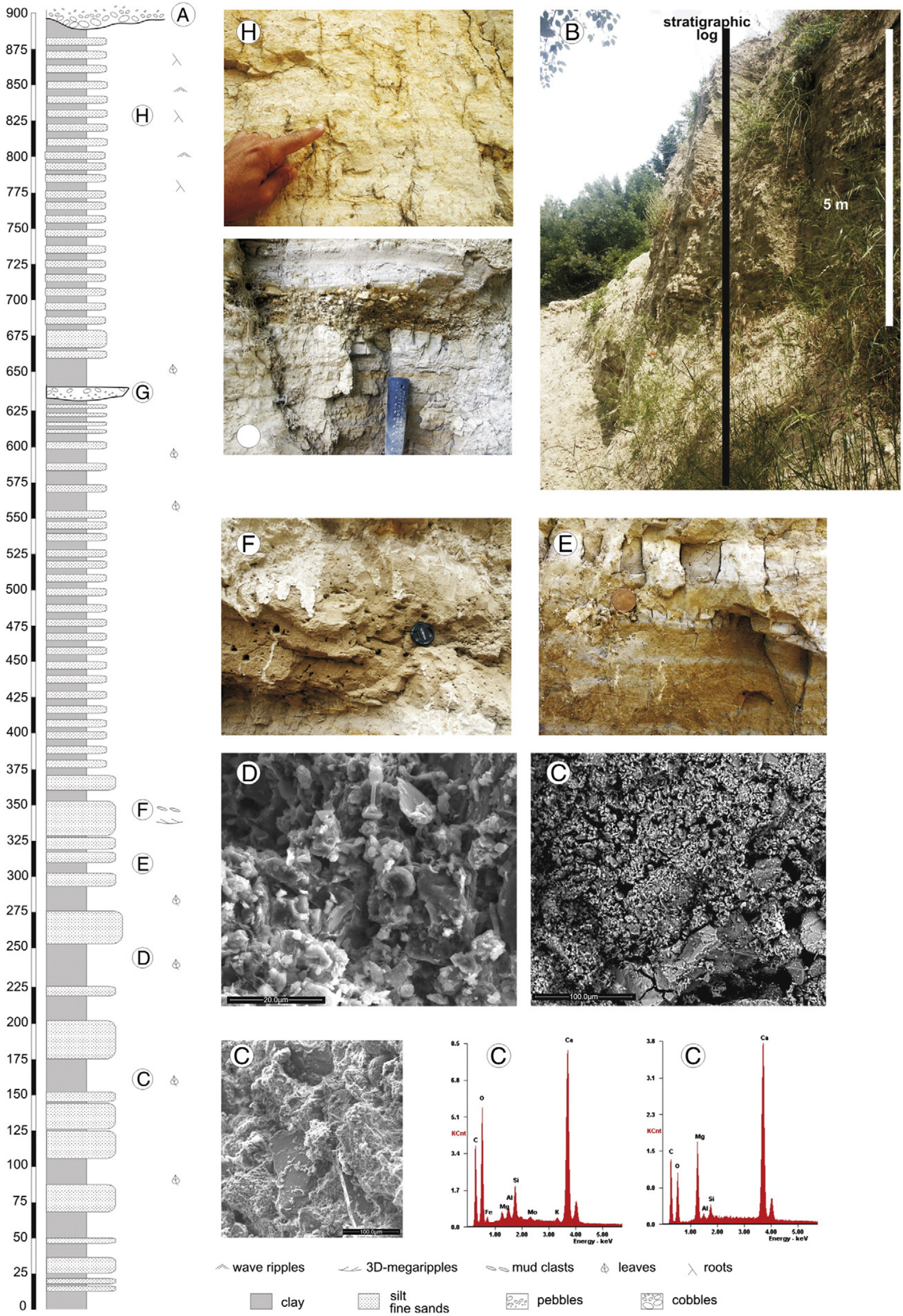
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value of −2.8 ± 0.3‰ (V-PDB), respectively. Values of $\delta^{13}C_{mo}$ from the sediment organic fraction range from −26.8‰ to −25.9‰, with a mean value of −26.3 ± 0.2‰ (V-PDB). $\delta^{13}C$ values from fossil plant remains (leaves) are −27.8‰, −28.9‰, and −29.9‰ (V-PDB), at the base, middle and top of the section. TOC values range from 0.8% to 2.1%, with a mean value of 1.5 ± 0.4%. Atomic C/N ratio ranges from 9.6 to 19.7, with a mean value of 14.1 ± 2.5. Isotopic composition of DIC from recent waters range from −10.3 to −9.5 (V-PDB).

A matrix of Pearson correlations between the $\delta^{13}C_{mo}$, TOC, atomic C/N ratio, $\delta^{18}O_c$, and $\delta^{13}C_c$ was developed (Table 2), showing a negative correlation ($r = -0.61$; $p < 0.005$) between $\delta^{13}C_{om}$ and atomic C/N ratio, a weak negative correlation between $\delta^{13}C_{mo}$ and TOC ($r = -0.396$; $p = 0.056$), a weak positive one between TOC and C/N ($r = 0.474$; $p = 0.019$), and an absence of correlation in the rest of the pairs.

Pollen

Twelve samples were analysed for pollen. Results come from 0 to 950 cm. The top of the section (more sandy) was barren of pollen grains. Tree pollen species are mostly made up of *Pinus* sp., evergreen and deciduous *Quercus*, *Olea* and *Juniperus* (Fig. 4). Arboreal pollen percentages (%AP) vary around 45%. Herbs and shrubs are mostly characterised by *Artemisia*, Lactucaceae, other *Asteraceae*, *Poaceae*, *Amaranthaceae* and *Ephedra*. Aquatics, mostly *Cyperaceae* and *Salix*, are also frequent in the pollen spectra.

We used variations in pollen species and cluster analysis using the programme CONISS (Grimm, 1987) to objectively zone the pollen data, producing three pollen zones for the Otiñar record (Fig. 4). Pollen zone 1 shows the maximum percentages in herbs (around 65%) in the Otiñar record. The early part of zone 1 depicts maximum percentages of *Poaceae* (reaching up to 20%) and high percentages of *Artemisia* (around 20%). Minimum values of *Olea* (close to 0%) and *Pinus* (around 15%) are reached in this zone. However, *Quercus* (both evergreen and deciduous) is relatively abundant in this zone. The late part of pollen zone 1 shows maximum values in *Artemisia* (reaching up to 35%). *Pinus* and *Quercus* (total) are relatively low during this part of the zone (around 25 and 10% respectively) and *Olea* increases by the end of the zone.

Pollen zone 2 shows increasing values in arboreal pollen (Fig. 4). *Quercus* (mostly deciduous) and *Pinus* peak in the early and late part of the zone respectively. A maximum in *Olea* (almost 20%) is shown in this later part of the pollen zone. Herbs generally decrease in this zone and the minimum values in *Artemisia* (around 6%) are also reached.

Pollen zone 3 is mostly characterised by decreasing values in arboreal pollen (in *Pinus*, *Olea* and *Juniperus*) and by an increase in *Cyperaceae*, *Salix* and *Tamarix*.

The Otiñar paleo-lake

Paleohydrology and paleoenvironment

The lacustrine record of $\delta^{18}O_c$ and $\delta^{13}C_c$ from authigenic carbonates can be interpreted as past variations in the isotopic composition of lake water (Benson et al., 1996; Li and Ku, 1997; McKenzie, 1985), which is mainly a function of the hydrological balance, temperature and atmospheric exchange. Isotope carbon values also depend on other factors related to the DIC pool, such as metabolic processes, or the lithology of the catchment basin (Benson et al., 1996; Bischoff et al., 1997; Talbot, 1990). Annual-average values of hydroclimatic variables from lakes usually remain unchanged on a decadal time scale, such as in this study, and the isotopic composition of lake water tends towards a steady state value (Griffiths et al., 2002). Otiñar $\delta^{13}C_c$ and $\delta^{18}O_c$ isotopic values show lack of covariance ($r = 0.067$). This could be interpreted as the absence of significant variations in the lake level (input/output + evaporation balance) (Li and Ku, 1997). In hydrologically closed lakes, $\delta^{13}C_c$ and $\delta^{18}O_c$ values usually show a covariant trend ($r > 0.7$), reacting similarly to increases/decreases in lake volume, but in open lakes, covariance is absent or weak (Talbot, 1990). However, the presence of detrital limestone can also contribute to this lack of correlation.

Table 1
Radiometric ages from Otiñar Paleo-lake, calibrated ages and 1–2 σ errors.

Depth (m)	^{14}C age (^{14}C ka BP)	+/− (ka)	Calibrated age (cal ka BP)				
			σ	Relative probability	Ranges (cal ka BP)		Probable age (cal ka BP)
					Lower	Upper	
0	12.38	0.06	1	1.000	14.22	14.60	14.45
			2	1.000	14.12	14.80	14.45
3	12.28	0.05	1	1.000	14.09	14.28	14.20
			2	1.000	14.02	14.52	14.20
9	12.12	0.05	1	0.910	13.92	14.09	13.99
			2	1.000	13.80	14.14	13.99

The XRD analyses show that the studied sediments are mainly composed of calcite, quartz, dolomite and clay minerals corresponding to the rock composition of the surrounding reliefs: Mesozoic clay, dolomite, limestone, and marls. Mineralogical data indicate that detrital input sources did not change much through the record. Calcite has two different sources, authigenic and detrital, which affect the isotopic interpretation. Authigenic carbonates are mainly composed of micritic sediment covering the detrital grains (Figs. 2C, D), and some bioclasts, such as gastropod or bivalve remains. Rock features and the depositional setting indicate that detrital dolomite can only originate from the Mesozoic formations in the catchment area. Therefore, dolomite can be a useful proxy tracking the detrital carbonate input to the lake. The relationship between detrital dolomite and detrital calcite should be considered almost constant through the section due to: (1) the short distance between the lake and the source (Fig. 1), preventing physical detrital carbonate fractionation and (2) the short time recorded in the lake (~500 yr), preventing major changes in the source area. The calcite/dolomite ratio is always higher than 1, except in the youngest samples (from 900 cm to the top). From 0 to 800 cm this ratio is close to 2, except for the oldest sample (ratio = 3.7), in which the detrital input is scarce. This trend suggests an increase in detrital input towards the top of the sequence, agreeing with an increase in particle size that can be interpreted as an overall shallowing upward trend sequence. However, standard deviation of the isotopic values from the carbonates is very low through the sequence, suggesting that the relative oscillations in the isotopic values from carbonates are little affected by variations in detrital limestone. The short paleo-lake history (~500 yr), the constant carbon isotopic composition of the organic matter, and the constant mineralogical composition of sediments, suggest neither important changes in the external supply nor in the water DIC composition. Therefore, the isotopic composition of the input from detrital carbonates was likely almost constant in these 500 yr, and the relative variations of the isotopic values were probably caused by factors that control the isotopic composition of authigenic carbonates listed above.

Although the DIC isotopic composition of the Otiñar paleo-lake during the Bølling period was unknown, the main contributors to the DIC pool can be specified. They should have been (1) the dissolution of limestones from the surrounding reliefs (External Zones range of the Betic Cordillera), whose carbon isotopic composition ranges from 1.2 to 3.4‰, with a mean value of 2.4 ± 0.4 (V-PDB) (O'Doherty et al., 2006), (2) respiration of vegetal covers/the soil CO_2 from C3 plants detritus, and (3) the pre-industrial atmospheric CO_2. The theoretical $\delta^{13}C_c$ values of calcite precipitated in waters, whose DIC sources were exclusively soil CO_2 from C3 plants detritus or pre-industrial atmospheric CO_2 (according to the calcite–CO_2 equation from Romanek et al., 1992), would range from ~ −17 to −8‰ (V-PDB) and from ~1 to 6‰ (V-PDB), respectively (Reyes et al., 1998). The lack of depleted values in $\delta^{13}C_c$ (1.2 ± 0.1‰) shows that the influence of

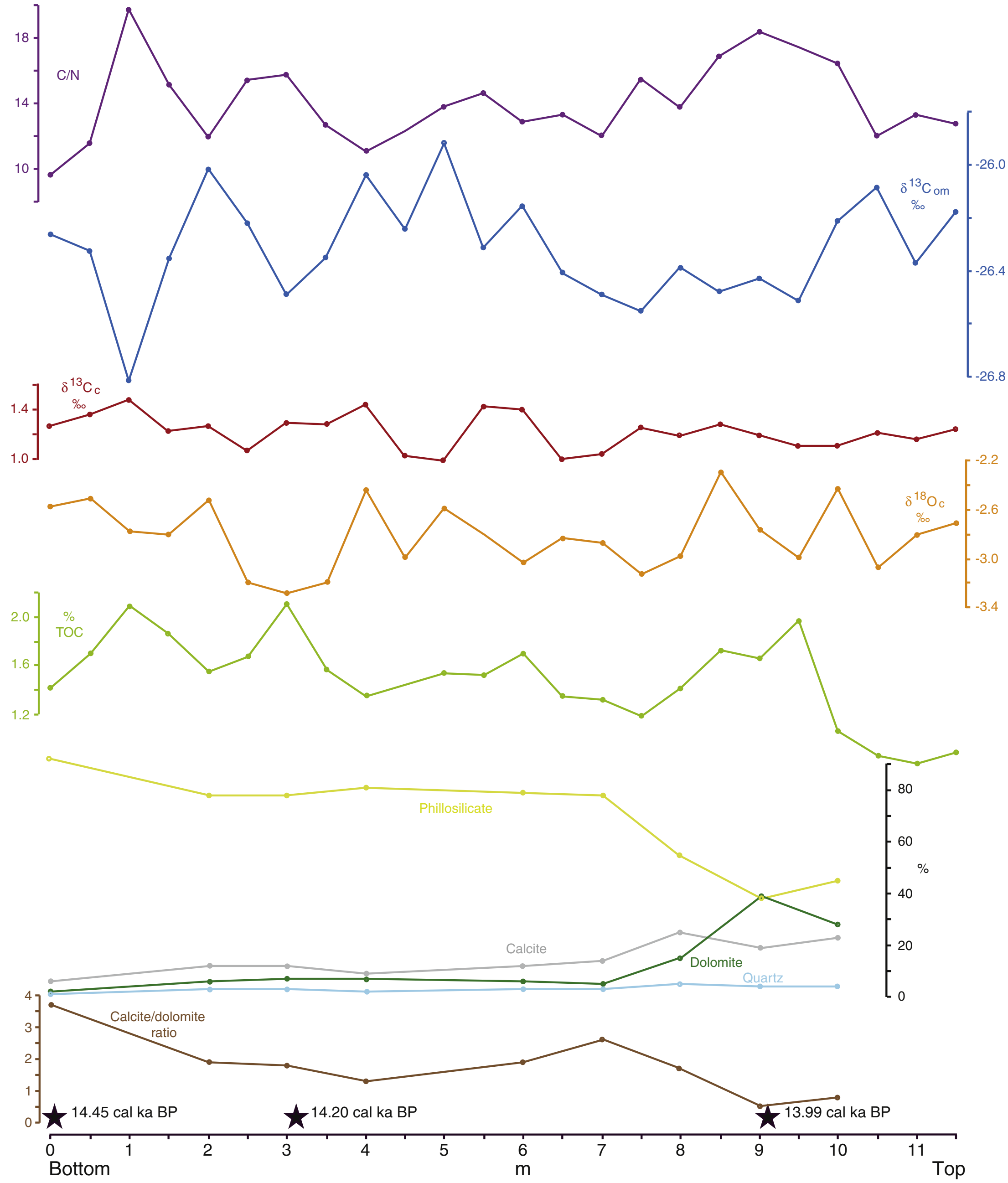

Figure 3. Comparison of values of (from bottom to top) calcite/dolomite ratio, bulk mineral semi-quantitative composition (obtained XRD), %TOC, $\delta^{18}O_c$, $\delta^{13}C_c$, $\delta^{13}C_{om}$, and atomic C/N ratio, from the Otiñar section.

C3 plants detritus from soils in the DIC pool of the paleo-lake is very little. Water DIC should be mainly affected by the dissolved carbonate ions from the catchment basin; consequently photosynthesis would not alter so much the variation in $\delta^{13}C$ DIC values, as can be shown by the very low-amplitude oscillations of $\delta^{13}C_c$ values (little change in the paleo-lake's carbon budget during these ~500 yr), and by the lack of correlation ($r = -0.034$ and $r = -0.222$) between $\delta^{13}C_{mo}$ vs. $\delta^{13}C_c$ and C/N vs. $\delta^{13}C_c$, respectively.

The current DIC isotopic values of the Quiebrajano River, one of the main inputs of the paleo-lake (Fig. 1), is −9.1 ± 0.6‰ (V-PDB), pointing to a source of soil CO_2 from C3 plants detritus (subaerial). These data would suggest a change in the DIC source during the last 14 cal ka BP, which could be related with a current reduction in water availability (recent damp upstream), and/or a major influence of surface water.

The organic proxies studied show that the carbon cycle in the lake remained relatively stable during the studied period. The obtained atomic C/N ratio of the organic matter ranged from ~10 to ~20, suggesting a mixed source of organic matter (algae and vascular plants) in the

Table 2
Pearson correlations between $\delta^{13}C_{mo}$, $\delta^{13}C_c$, $\delta^{18}O_c$, TOC and atomic C/N ratio. Bonferroni correction for multiple pairwise comparisons lowered the α value to 0.005 (α = 0.05 / 10 = 0.005). Pair-wise relationship (n = 10).

Pearson r\p-value	$\delta^{13}C_{mo}$	TOC	C/N	$\delta^{13}C_c$	$\delta^{18}O_c$
$\delta^{13}C_{mo}$	0	0.055644	0.0013658	0.87491	0.21818
TOC	−0.39566	0	0.019223	0.56309	0.54109
C/N	−0.61554	0.47422	0	0.29709	0.63503
$\delta^{13}C_c$	−0.033937	0.12421	−0.22202	0	0.75408
$\delta^{18}O_c$	0.2609	−0.13122	−0.10208	0.067474	0

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sediments (Meyers, 1994; Meyers and Teranes, 2001). Carbon isotopic values from organic matter and plant remain through the section point to C3 vegetation growing around the lake. A carbon limitation scenario in the studied paleo-lake is unlikely because the $\delta^{13}C_{om}$ values do not show important increases associated to primary productivity consumption (large aquatic blooms) (O'Leary, 1988; Street-Perrott et al., 1997; Hodell and Schelske, 1998; Talbot and Laerdal, 2000; Wolfe et al., 2001; among others). However, the organic proxies suggest that algae productivity played an important role in generating the organic matter from the sediments. $\delta^{13}C_{om}$ values are almost invariant ~ −26.3 ± 0.2‰, even during those times of increasing productivity. This could be due to an almost permanent water supply that could dilute the occasional increases from the DIC isotopic composition preventing enrichment in the heavy carbon isotope in algae. There is a negative correlation ($r = -0.61$; $p < 0.005$) between $\delta^{13}C_{om}$ and atomic C/N ratio (Table 2). This inverse correlation can be explained by a reduction in the C/N ratio together with an increase in $\delta^{13}C_{om}$ values that may be interpreted as occasional increases in productivity, probably related with slight changes in water input, lake level and temperature. There is a weak covariance between $\delta^{13}C_{mo}$ and TOC ($r = -0.396$; $p = 0.056$) and between TOC and atomic C/N ratio ($r = -0.474$; $p = 0.019$). The highest TOC values usually occur during the highest atomic C/N ratios, and the lowest $\delta^{13}C_{mo}$ values. This means that the highest TOC values correspond to the highest external input of organic matter (vascular plants) to the paleo-lake.

The paleohydrology during the Bølling interstadial in the Otiñar paleo-lake was likely influenced by groundwater, where scarce C3-plant detritus and important limestone dissolution would affect the DIC. This interpretation agrees with the presence of groundwater aquifers upstream of the paleo-lake deposits (Benavente, 1978), which during this humid period should represent a continuous water supply. Taking into account the Mediterranean seasonality (recognised at least, since the late Pleistocene; Combourieu Nebout et al., 2009; Fletcher et al., 2010), which implies that precipitation mostly occurs during the winter (wet season), the paleo-lake would have had a continuous water input in the winter, probably from meteoric waters and groundwater (as deduced previously by DIC evidence). During the dry season, the inputs would be reduced almost exclusively to groundwater, highly influenced by limestone dissolution. Calcite precipitation would have mainly occurred during spring and summer, when evaporation would have slightly increased the isotopic values of DIC in the lake waters. As the water sources and the hydrological conditions did not change much during the Bølling, the geochemical parameters remained almost constant.

Vegetation in the Otiñar paleo-lake area

The pollen analysis from the Otiñar record shows a relatively forested environment in Southern Spain during the Bølling period (around 45% AP; Fig. 4). Forest species mostly included *Pinus*, evergreen and deciduous *Quercus*, *Olea* and *Juniperus*. Pollen data show that herbs (mostly *Poaceae* and *Artemisia*) were more abundant during the deposition of the bottom sediments (zone 1) pointing to a more open landscape. A subsequent increase in forest species, including typically Mediterranean evergreen *Quercus* and *Olea*, occurred, reaching a peak during pollen zone 2. A maximum in forest development occurred at that time. Herbs, aquatics (*Cyperaceae* and *Salix*) and *Tamarix* increased at the top of the section (zone 3). The increase in shallow aquatics and halophyte species, as well as in sand particles at the top of the section (Fig. 3) points to a shallowing upwards sequence — the small lake probably transitioned to a marsh during this time.

Carbon isotopic composition from plant remains, ranging from −27.8‰, to −29.9‰, indicates a mild-wet environment in the drainage basin, with a trend towards slightly wetter conditions throughout the record.

Paleoenvironments during the Bølling period in the Western Mediterranean

Pollen analysis has been shown to be a great tool for regional vegetation and climate reconstructions (Faegri and Iversen, 1989). Climatic reconstructions for the western Mediterranean during the Bølling–Allerød based on pollen data show temperature and precipitation values comparable to those of the Holocene (Fletcher et al., 2010). However, sea surface temperature estimations in the Atlantic Iberian Margin and in the Western Mediterranean for the Bølling interstadial

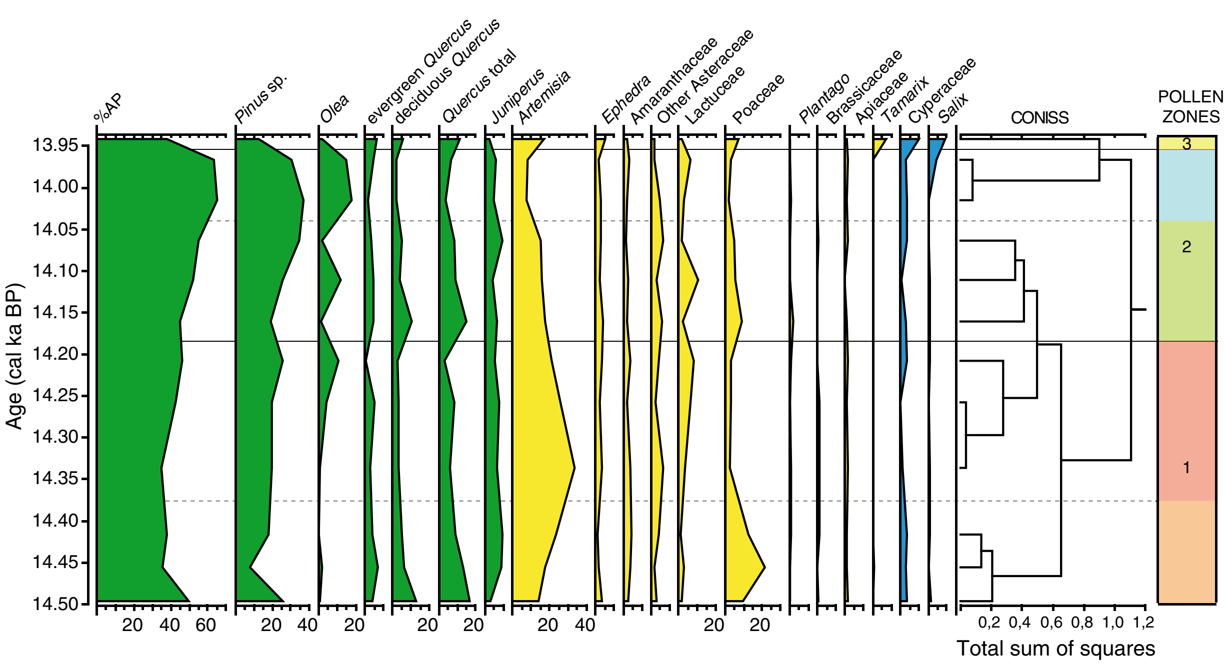

Figure 4. Pollen diagram of the Otiñar record showing percentages of selected taxa. The zonation, on the right, was made using cluster analysis provided by CONISS (Grimm, 1987).

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show temperatures ~2–3°C lower than those of the early Holocene (Martrat et al., 2004, 2007; Rodrigo-Gámiz et al., 2013).

The Otiñar pollen record shows relatively forested environments in this area during the Bølling period. Forest species were very abundant during the entire Bølling–Allerød in the western Mediterranean region (Carrión and Dupré, 1996; Carrión and Van Geel, 1999; Carrión, 2002; Fernández et al., 2007; Combourieu Nebout et al., 2009; Fletcher et al., 2010; Fig. 5), agreeing with the increase in humidity in northern

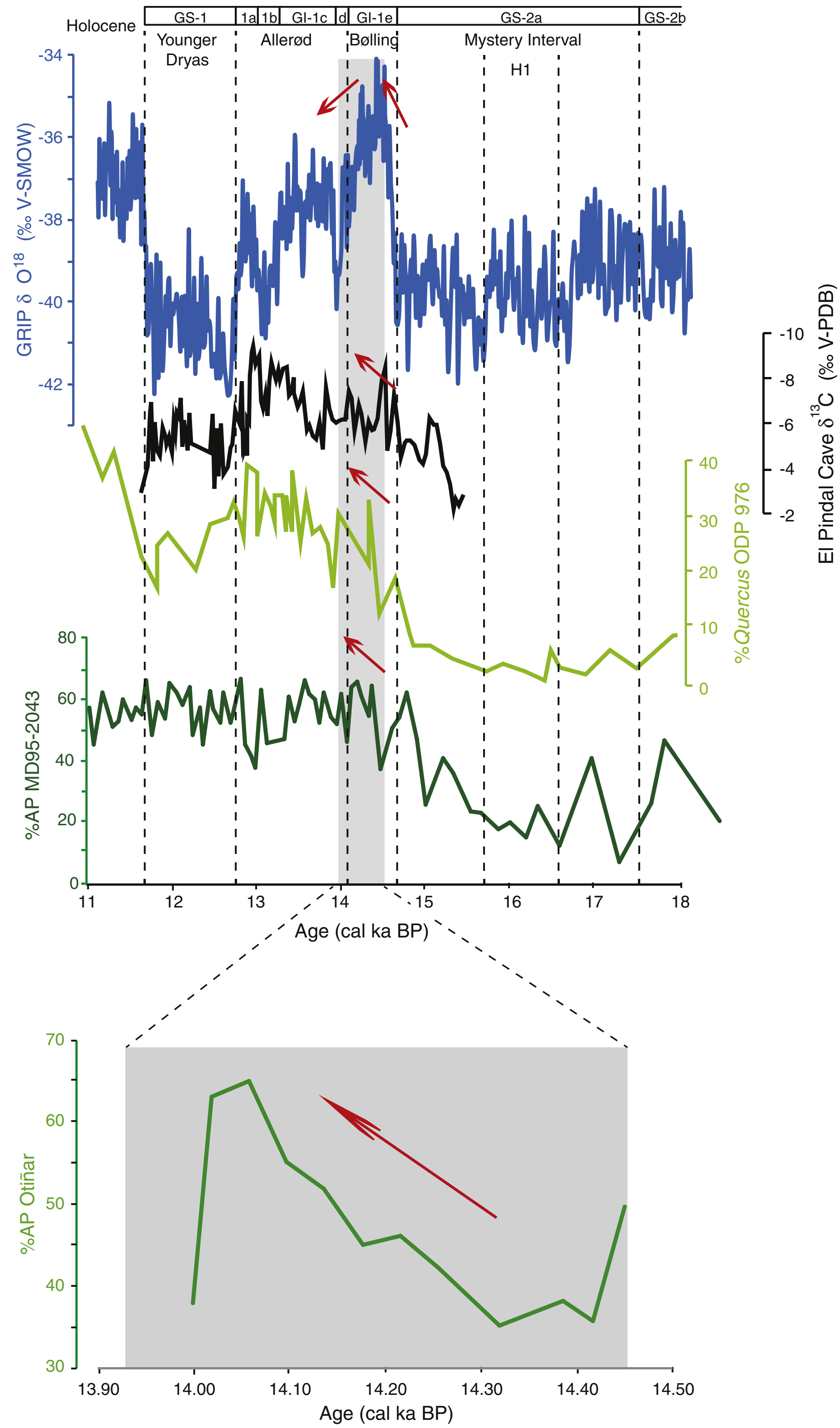

Figure 5. Comparison of the Otiñar arboreal pollen (AP) record with the 18–11 cal ka BP interval of (from bottom to top) AP from MD95-2043 core in the Alborán Sea (Fletcher et al., 2010), AP from ODP Site 976 in the Alborán Sea (Combourieu Nebout et al., 2009), $\delta^{13}C$ values (V-PDB) of a speleothem record from northern Iberian Peninsula (El Pindal Cave: Moreno et al., 2010), and water oxygen isotopic composition (‰ V-SMOW) from GRIP ice core in Greenland (Johnsen, 1999; Johnsen et al., 2001). Arrows show main climatic trends. Grey shading is selecting the studied period. Dashed lines show the possible correlation between the climatic records. See text for age estimation of the Otiñar section.

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Africa (onset of the African Humid Period; deMenocal et al., 2000). Regional pollen data thus point to relatively warm and humid climate conditions at that time, which permitted the development of a Mediterranean forest similar to the present (Combourieu Nebout et al., 2009; Fletcher et al., 2010; this study).

Increases and decreases in tree species (i.e., *Quercus*) during the late Pleistocene and Holocene have been interpreted as indicating forest development during relatively warm and humid periods (i.e., interglacials or interstadials) and contractions during more arid and cold periods, respectively (Fletcher et al., 2007; Fletcher and Sanchez Goñi, 2008; Combourieu Nebout et al., 2009; Fletcher et al., 2010; Jiménez-Moreno and Anderson, 2012; Jiménez-Moreno et al., 2013). Therefore, the increase in forest species, in particular *Pinus*, *Quercus* and *Olea*, from pollen zones 1 to 2 most-likely points to a warming and an increase in humidity during the Bølling in the Otiñar area. This increase in humidity can also be observed in the plant remain isotopic composition from this record (see above). This interpretation is consistent with other pollen records from the region that show similar increases in Mediterranean forest during the Bølling period (Combourieu Nebout et al., 2009; Fletcher et al., 2010).

From a global perspective, the Bølling–Allerød interstadial was a relatively warm period, but a general cooling climatic trend occurred in Greenland and North Europe from the Bølling to Allerød period (von Grafenstein et al., 1999; Rasmussen et al., 2006; Lowe et al., 2008; Rasmussen et al., 2008; among others). However, southwestern Mediterranean data (Genty et al., 2006; Combourieu Nebout et al., 2009; Moreno et al., 2010; Morellón et al., 2011; Rodrigo-Gámiz et al., 2013) and the record from Otiñar Lake suggest the opposite trend: a warming and an increase in humidity during this interval. Although Muñoz Sobrino et al. (2013) suggested that records from NW Iberian Peninsula, such as Laguna de La Roya agree, in general, with those of Greenland (Dansgaard et al., 1993), discrepancies between the temperature trends can be observed during the Bølling period between these two sites. These evident climatic differences between middle and high latitudes in the Northern Hemisphere resemble the present interannual–decadal NAO patterns. In this way, Hurrel (1995) suggested that although the NAO can be characterised as having inter-annual variability, several periods of anomalous circulation patterns have persisted over many winters suggesting that a multi-decadal component also exists (Hurrel, 1995). Therefore, all these data presented here point towards an increasing trend towards a more persistent negative NAO "like" conditions during the Bølling with southward migration of the westerlies (e.g., Rodrigo Gámiz et al., 2011), probably linked with the re-assumption of the North Atlantic Thermohaline circulation and warmer Eastern North Atlantic Central Waters (ENAC) (Hatun et al., 2005; Johnson and Gruber, 2007). These atmospheric conditions could explain relatively the general warm-wet climatic trend conditions from Bølling to Allerød period in western Mediterranean, and the cold-dry trend from higher latitudes; however, more high-resolution records are needed to decipher the short-term climatic conditions during this period.

Conclusions

The high-resolution multiproxy paleoenvironmental record from the Otiñar paleo-lake provided one of the few continental records of the Bølling in Southern Iberia. Our study shows warm and humid conditions during the Bølling period in the area. Mesic conditions favoured the development of forested environments in Southern Iberia during this period, as suggested by the Otiñar pollen record. This agrees with previous late Pleistocene pollen records from the western Mediterranean area. The origin of this paleo-lake was probably related with these humid conditions, which could have boosted the slope instability and landslide, which dammed the Otiñar River. These humid conditions agree with high river discharge-evaporation ratio needed for maintaining the lacustrine conditions during the ca. 500 yr of basin sedimentary infilling. The end of these deposits was related with the total infill of the depression, and the subsequent erosional phase.

An increase in forest species occurred throughout the record. This vegetation trend points to a warming and an increase in humidity during the Bølling in the Southern Iberian Peninsula. The described climatic warm-humid trend during the studied period agrees with other western Mediterranean records, and contrasts with those from higher latitudes, which show an opposite pattern. Increasing persistent negative NAO mode during the Bølling in the area may have caused this climatic scenario. However more high-resolution records are needed to improve our knowledge about the behaviour of the NAO in the past and its effects on the environment. Understanding the past natural changes of this climate mode is key to estimate its economic and social effect at present and future, such as changes in agricultural harvests, water management, energy supply and demand, and fishery yields in some regions.

The isotopic values from organic matter and carbonates are almost invariant through the section, suggesting that the environmental conditions in the catchment basin and the hydrological features of the lacustrine system remained almost constant during the studied period, as well as the carbon budget of the paleo-lake. Differences in the tendencies between the pollen and isotope records can be due to the effect of continuous groundwater supply to the paleo-lake, which did not change during the history of the lake, keeping similar lacustrine conditions through time, in contrast to the pollen record, which shows the regional evolution of a larger area.

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