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Abstract

The perennial and seasonal wetland diversity of the Moroccan Middle Atlas region provides a valuable "test-bed" for understanding the response of different hydrosystems to climatic variations. A multiproxy study, based on sedimentological descriptions, together with mineralogy, carbonate content, XRF core scanning and biological proxies supported by AMS ^{14}C dates, were applied to the 3-m-long core extracted from "Flowers Marsh", a small Middle Atlas pond. This approach provides evidence for a continuous paleohydrological and paleoenvironmental record during the Mid- to Late Holocene. The investigated aquatic system evolved from a dry or very shallow waterbody towards a system with a progressively rising water level. The dominance of the detrital fraction with poor preservation of bioindicators and eroded pollen, indicate the existence of an ephemeral waterbody from 6000 cal. yr BP until a transitional phase characterized by new sedimentological facies and the appearance of ostracods around 2300 cal. yr BP. This transition, ending at 2000 cal. yr BP, is interpreted as a flooding phase leading to an ephemeral lake. It is certainly fed by the excess water from the nearby Aguelmam Azigza Lake during its high level period. Afterwards, enhanced organic matter deposition and the appearance of well-preserved diatoms until 1400 cal. yr BP corroborate a high water-level trend. Endogenic carbonate to detrital fraction ratios indicate fluctuating, but generally shallow, water levels from 1400 cal. yr BP until 650 cal. yr BP when a relatively rapid rise in water level occurred. Flowers Marsh data are, generally, consistent with most of the existing regional records. The highstand period recorded between 2000 and 1400 cal. yr is a common feature extending to more distant sites from the northern Mediterranean. It corresponds to the wetter Iberian-Roman period. Fluctuating shallow water levels recorded since 1400 cal. yr BP to now could be linked to drier/wetter phases associated with the Medieval Climate Anomaly and the Little Ice Age (650–150 cal. yr BP) respectively, in the western Mediterranean realm. The present study demonstrates the ability of Flowers Marsh to record valuable palaeohydrological changes since the Mid-Holocene and confirms the high sensitivity of Middle Atlas hydrosystems to climatic changes.

Keywords (separated by '-'): Middle Atlas - Palaeohydrology - Mid- to Late-Holocene - Lacustrine sediment - Climatic changes

Footnote Information: **Supporting Information** The online version of this article (https://doi.org/10.1007/s10933-020-00166-6) contains supplementary material, which is available to authorized users.

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Abstract The perennial and seasonal wetland diversity of the Moroccan Middle Atlas region provides a valuable "test-bed" for understanding the response of different hydrosystems to climatic variations. A multiproxy study, based on sedimentological descriptions, together with mineralogy, carbonate content, XRF core scanning and biological proxies supported by AMS ^{14}C dates, were applied to the 3-m-long core extracted from "Flowers Marsh", a small Middle Atlas pond. This approach provides evidence for a continuous paleohydrological and paleoenvironmental record during the Mid- to Late Holocene. The investigated aquatic system evolved from a dry or very shallow waterbody towards a system with a progressively rising water level. The dominance of the detrital fraction with poor preservation of bioindicators and eroded pollen, indicate the existence of an ephemeral waterbody from 6000 cal. yr BP until a transitional phase characterized by new sedimentological facies and the appearance of ostracods around 2300 cal. yr BP. This transition, ending at 2000 cal. yr BP, is interpreted as a flooding phase leading to an ephemeral lake. It is certainly fed by the excess water from the

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nearby Aguelmam Azigza Lake during its high level period. Afterwards, enhanced organic matter deposition and the appearance of well-preserved diatoms until 1400 cal. yr BP corroborate a high water-level trend. Endogenic carbonate to detrital fraction ratios indicate fluctuating, but generally shallow, water levels from 1400 cal. yr BP until 650 cal. yr BP when a relatively rapid rise in water level occurred. Flowers Marsh data are, generally, consistent with most of the existing regional records. The highstand period recorded between 2000 and 1400 cal. yr is a common feature extending to more distant sites from the northern Mediterranean. It corresponds to the wetter Iberian-Roman period. Fluctuating shallow water levels recorded since 1400 cal. yr BP to now could be linked to drier/wetter phases associated with the Medieval Climate Anomaly and the Little Ice Age (650– 150 cal. yr BP) respectively, in the western Mediterranean realm. The present study demonstrates the ability of Flowers Marsh to record valuable palaeohydrological changes since the Mid-Holocene and confirms the high sensitivity of Middle Atlas AQ1 hydrosystems to climatic changes.

Keywords Middle Atlas · Palaeohydrology · Mid- to Late-Holocene · Lacustrine sediment · Climatic changes

Introduction

The Mediterranean basin is one of the most sensitive areas to climate fluctuations (Giorgi 2006). Future climate change projections highlight the exposure of the Western Mediterranean region to increased heat and drought stress (Solomon et al. 2009; Born et al. 2010). The Middle Atlas region is considered to be the main water reservoir of Morocco. This region is host to a variety of perennial and semi-permanent wetlands including natural lakes, rivers and springs. These water resources are relied upon to meet the agricultural and domestic needs of the region. During recent decades, numerous lakes of the karstified Middle Atlas region experienced a significant water deficit as a result of recurrent droughts and human overexploitation, including: Dayet Aoua (Sayad and Chakiri 2010), Aguelmam Sidi Ali (Sayad et al. 2011), Ifrah Lake (Etebaai et al. 2012) and Aguelmam Azigza (Adallal et al. 2019). Examining the past history of lakes in the Middle Atlas region can elucidate the prospective impacts of combined climate change and anthropogenic activity on the hydrological behavior of these lacustrine systems.

Lake sediments have the potential to allow investigation of temporal paleohydrological trends under various environmental conditions. Lacustrine sequences from Middle Atlas wetlands are ideally suited to understanding the response of Mediterranean semi-arid environments and hydrosystems to climatic changes because of the small size of their basins, and because their evolution and sedimentation are directly influenced by regional hydrologic changes (Lamb and van der Kaars 1995). Pioneering paleoenvironmental investigations have demonstrated the high potential of Middle Atlas lake sediments as archives of climate variability (Martin 1981; Lamb et al. 1989). The number of available paleoclimatic and paleoenvironmental reconstructions conducted on lacustrine sequences from the region has greatly increased in the last few decades. Most of these records cover the last glacial period (Rhoujjati et al. 2010; Nour El Bait et al. 2014; Tabel et al. 2016) and the early Holocene (Barker et al. 1994; Cheddadi et al. 1998; Lamb and van der Kaars 1995; Campbell et al. 2017; Zielhofer et al. 2017). The last few millennia are particularly interesting owing to the fact that the main boundary conditions were similar to present-day climate configurations and detailed regional palaeoclimatic reconstructions can be compared to current climate change processes (Corella et al. 2011; Brisset et al. 2019). However, records spanning the Mid-Late Holocene period are rather scarce in the Middle Atlas region (Damnati et al. 2015; Nour El Bait et al. 2016). Nour El Bait et al. (2016) demonstrated that climate has remained relatively stable over the last 6000 cal. yr BP with a trend of aridity and warming towards the present. Results obtained from lacustrine terraces at three Middle Atlas lakes indicate high lake levels at about 2300 cal BP followed by a significant drop in lake level during the last millennium (Damnati et al. 2015).

Most of the paleoclimate and environmental reconstructions in the Middle Atlas are based on fossil pollen assemblages from lake sediments. These studies revealed a common pattern: the limited presence of *Cedrus atlantica* Manetti pollen in the early Holocene, with the general expansion of the species from the Mid-Holocene which has been interpreted primarily as evidence of increased moisture availability (Lamb

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et al. 1989; Cheddadi et al. 1998, 2015, 2019; Rhoujjati et al. 2010; Nour El Bait et al. 2014; Tabel et al. 2016; Campbell et al. 2017). However, a recent study demonstrated a Mid-to Late Holocene summer aridity in the Middle Atlas using stable carbon isotope analysis of isolated fossil *Cedrus* pollen (Bell et al. 2019). Furthermore, several studies detected a Mid-Late Holocene aridification trend from ecological or hydrological records in the western Mediterranean (Jalut et al. 2009; Carrión et al. 2010; Jiménez-Moreno et al. 2015).

In order to strengthen paleolimnological interpretations inferred from a single proxy it is important to combine as many records as possible in a technique known as a multi-proxy approach (Bradley 2015). Some investigations have reconstructed lake paleohydrology in the Middle Atlas region using multi-proxy analysis of lacustrine terraces (Damnati et al. 2015) and of continuous sedimentary records (Nour El Bait et al. 2014; Zielhofer et al. 2017). For example, in Aguelmam Sidi Ali, Zielhofer et al. (2017) reconstructed the Western Mediterranean hydro-climatic variability, seasonality and forcing mechanisms during the last 12,000 year using a multi-proxy approach based on magnetic susceptibility, carbonate and total organic carbon content, core-scanning and quantitative XRF, stable isotopes of ostracod shells, charcoal counts, *Cedrus* pollen abundance, and diatom data. Only a few records span the Late Holocene period and more investigations and a regional review of the available lake records are needed. This would enable details of the contrasting spatial and temporal hydrodynamics of Middle Atlas lakes in response to climate-related variability to be verified.

Here we present continuous and high-resolution records of a sedimentary sequence recovered from "Flowers Marsh" (unofficial name), a karstic waterbody in the SW Middle Atlas, northern Morocco. The approach is based on radiometric techniques for dating, sediment geochemistry using XRF, sediment mineralogy using DRX, as well as biological indicators, including diatoms, coprophilous fungi spores, and ostracods. The overall aim of this paper is to provide a reconstruction of Flowers Marsh development in response to catchment changes and to regional climatic events during the Mid- to Late Holocene. Specifically, we will address the following questions: (1) what was the hydrological behavior of Flowers Marsh during the Mid- to Late Holocene? (2) Is there any synchronicity and/or validation between the proxy records? (3) Are there any similarities with other regional climatic archives? (4) Is there any evidence for a Flowers Marsh response to variability of the Holocene climate at different scales?

Study site

The Middle Atlas is an intracontinental mountain chain in northern Morocco (Fig. 1a). It exhibits a large synclinal trough extending 250 km with a SW–NE trend. The geology of the region ranges from Palaeozoic to Quaternary and is dominated mainly by Triassic red beds covered by karstified Liassic limestones and dolomites, Palaeozoic sandstone, schist, quartzite and doleritic basalt (Martin 1981). The geomorphology and structural features of the region favor the formation of natural permanent or seasonal lakes. The genesis of these wetlands is a product of subsidence related to an intense fault network and karstification of dolomites (Hinaje and Ait Brahim 2002). The climate in the region is a mountain Mediterranean type with sub-humid to cold winters. The mean annual precipitation in the area approaches 900 mm year^{-1}, mostly occurring between October and April (Martin 1981) and the average monthly temperature varies between − 2 °C and 31 °C (Chillasse et al. 2001). Evergreen oak (*Quercus rotundifolia*) and Atlantic cedar (*Cedrus atlantica*) are the main forest vegetation (Flower et al. 1989).

The studied site, Flowers Marsh (32°59'04''N, 5°27'13''W), is a small pond lying about 1554 m above sea level (asl) in the Middle Atlas Mountains, in the High Oum Er-rbia catchment (Fig. 1a). The waterbody's name comes from the floating hydrophytes that cover the water surface. The surface area of Flowers Marsh varies between 6 and 12 ha depending on the season. During wet climatic periods and high aquifer phases, water levels in Flowers Marsh may be controlled through sub-surface inflows and/or through local rainfall. During low stands, this pond is mainly controlled by the surface runoff. Flowers Marsh is located near Aguelmam (Fig. 1d), one of the largest lakes in the Middle Atlas region (55 ha). Aguelmam Azigza and Flowers Marsh belong to the same basin with a catchment area of 1020 ha (Jouve et al. 2019). Hydrological results from Aguelmam Azigza reveal that lake levels were closely linked to subsurface circulation with a high sensitivity to climate

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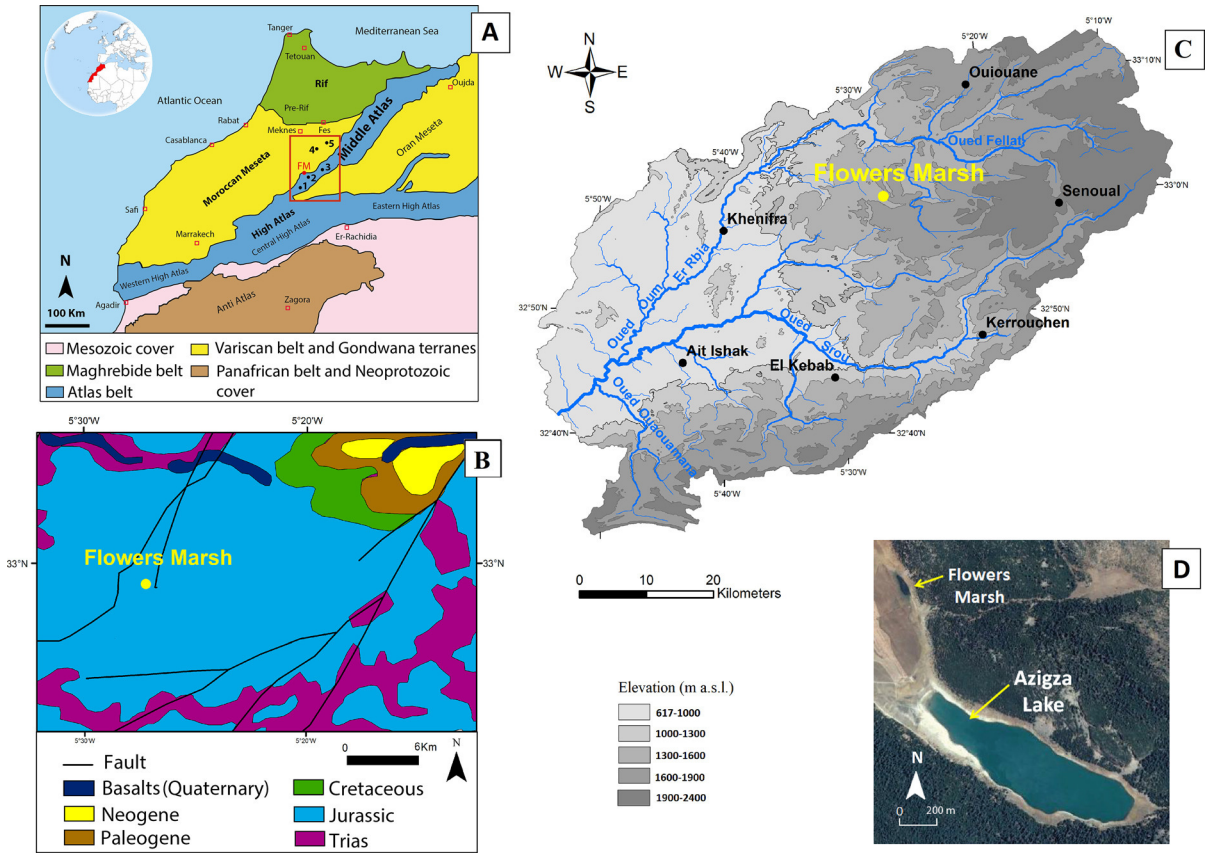

Fig. 1 Location of the studied area. A: Simplified map showing the major geological provinces of Morocco. (modified from Saadi 1982) and the location of the study site (FM) and other paleoclimate studies cited in the text: 1, Ait Ichou Marsh (Tabel et al. 2016); 2, Lake Tigalmamine (Cheddadi et al. 1998; Lamb and van der Kaars 1995; Lamb and van der Kaars 1995; Cheddadi et al. 1998); 3, Aguelmam Sidi Ali (Campbell et al. 2017; Zielhofer et al. 2017); 4, Ras El Ma marsh (Nour El Bait et al. 2014); 5, Lake Iffer (Damnati et al. 2015). B: Simplified geological map of the studied area (derived from the geological map of Morocco 1/1 000 000). C: Map of the High Oum Er-Rbia watershed, including topography and hydrographic network. D: Satellite image (Google Earth-2016) showing Flowers Marsh and Aguelmam Azigza situation

fluctuations especially precipitation (Vidal et al. 2016; Adalall et al. 2019). From observations of paleoshorelines in the catchment (Flower and Foster 1992) and past hydrological reconstructions (Jouve et al. 2019), previous studies inferred that significant variations have occurred in the level of Aguelmam Azigza. High resolution Digital Elevation Models (DEM) from Aguelmam Azigza watershed indicate that lake levels need to be 10–15 m above modern levels for the two waterbodies to be connected. Arial photographs from 1964 suggest that this connection has happened in the past (Jouve et al. 2019).

Materials and methods

The studied cores were recovered in 2016 from Flowers Marsh using a 50-cm-long Russian corer. Two lake-marginal cores were taken: AZA-SUP-1-A-16 and AZA-SUP-1-16. The length of each sequence is 300 cm and 250 cm, respectively. Sediment core stratigraphy was described on-site. The core segments were wrapped in Clingfilm and stored in a cold storage room at 4 °C. The two cores show a good visual agreement and a very similar lithologic and chemical succession (ESM1). Only the long core AZA-SUP-1-A-16 was selected for this study.

In total, 21 subsamples were recovered at 15-cm intervals for particle size analysis. Subsamples were

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analyzed using a Horiba LA-300 laser diffraction analyzer at the Georesources Laboratory (Marrakech, Morocco). Subsamples were not pretreated before analysis and measurements were made on the fine sediment fraction (< 0.5 mm). The abundance of three grain size fractions was determined: clays (< 2 µm), silts (2–67 µm) and sand (> 67 µm).

To examine variations in sediment geochemistry, high-resolution X-ray fluorescence XRF) was undertaken on the fresh core using an Itrax core-scanner (Cox Analytical Systems) at CEREGE (Centre de Recherche et d'Enseignement en Géosciences de l'Environnement), Aix-en-Provence, France. Sediment was analyzed with 500 µm spatial resolution and a molybdenum (Mo) tube at 30 kV, 40 mA and 15 s per interval analyzed. Relative abundance of elements (Fe, Ti, Mn, Si, K, Ca, Sr and Br) as well as incoherent and coherent X-ray backscatter were determined for the sedimentary sequence. Here we use the ratio of incoherent to coherent X-ray scatter (inc/coh) as a proxy for organic matter content in lake sediments, according to Brown et al. (2007). Elemental XRF intensity can be related to processes taking place within the lake. Titanium, K, Fe and Si can represent terrigenous sediment input linked to erosional parameters (Croudace et al. 2006; Olsen et al. 2012). In this research, K intensity is interpreted to reflect variations in detrital input (Aufgebauer et al. 2012). The Ca/Ti ratio mainly reflects Ca derived from within-lake processes and can be used to identify the occurrence of endogenic carbonate concretions in the sediments (Brown et al. 2007). Bromine (Br) has been regarded as a potential proxy for identifying relative variations in organic content in lake sediments (Kalugin et al. 2007; Gilfedder et al. 2011) and the Br/Ti ratio is an important proxy for productivity (Agnihotri et al. 2008). Manganese (Mn) contents may be related to changing redox conditions at the water-sediment interface in the lake (Davies et al. 2015) with high Mn content reflecting oxygenation of bottom waters (Kylander et al. 2011). Strontium (Sr) reflects aragonitic and evaporitic concretions (Arz et al. 2003).

The total carbon (TC%) and total organic carbon (TOC%) contents were determined for ten samples from the AZA-SUP-1-A-16 core with a FlashSmart NC Soil Thermo elemental analyzer at CEREGE. The standard deviation for standard carbonate materials was 0.07%, and the relative error of replicates was < 2.29%. The TOC was measured following standard procedures after acidification (to eliminate the carbonate fraction). Total inorganic carbon (TIC) was determined using the following equation (Espitalié et al. 1977):

$$CaCO_3(\%) = (TC - TOC) \times 8.33$$

Mineralogical composition was examined from bulk sediments for selected representative samples by X-ray diffraction (XRD) with a SmartLab SE at CAC (Centre d'Analyse et de Caractérisation), Marrakech. Relative mineral abundance was determined using peak intensity with PANalytical X'Pert HighScore Plus software. The main minerals occurring are expressed as percentages.

The microstructures and element content of endogenic carbonates were determined using a scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS) at the CAC. The microscope was operated at 10 kV with a magnification of 116. The SEM and EDS allow the acquisition of photographs and elemental content.

Stable isotope analyses were carried out on fossil ostracods retrieved from Flowers Marsh sediments. Core AZA-SUP-1-A-16 was sampled at 1 cm intervals. The samples were sieved through a 63 µm mesh under tap water. Ostracods were only present in the upper 166 cm of the core and were handpicked from each sediment subsample using a binocular microscope and washed in deionized water. Carbon and oxygen isotopic analyses were performed on the two most abundant species separately: *Candona neglecta* and *Illyocipris gibba*. Adult ostracod shell material from *C. neglecta* species was used for C and O stable isotope analyses. In addition, stable isotopes were analyzed on the total dissolved inorganic carbon (TDIC) of Aguelmam Azigza water (lake and spring) and on modern ostracods (*C. neglecta* and *I. gibba*). The isotopic composition of endogenic carbonates extracted from the bulk sediment of the Flowers Marsh sequence was also analyzed. Measurements were performed using a Finnigan Delta Advantage mass spectrometer coupled to a Kiel III Device at CEREGE. The isotopic results were reported relative to the Vienna Peedee Belemnite (VPDB) standard. Analytical precision of $\delta^{18}O$ and $\delta^{13}C$ was 0.07‰ and 0.05‰, respectively.

The AZA-SUP-1-A-16 core was subsampled for diatom analysis at CEREGE. Sediment samples were prepared for smear slide analysis to determine the

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presence of diatoms. Only 9 samples contained abundant diatoms. Wet sediment samples were treated using H_2O_2 (33%) and HCl (10%) in order to remove organic matter and carbonates respectively. Slides were mounted in Naphrax and observed with an optical microscope (Nikon 80i 1000 × magnification with Nomarski optics, n.a.= 1.32). Taxonomic identification and assignment of planktonic and benthic habitats were based primarily on Krammer and Lange-Bertalot (1986–1991) and Marciniak (1986).

Eight samples throughout the core were examined for coprophilous fungal spore abundances and treated according to Fægri and Iversen (1989) at CEREGE. *Lycopodium clavatum* tablets were added to each sample allowing determination of spore concentrations (Stockmarr 1971). Coprophilous fungi spores were identified according to the van Geel classification (2002). Identification was limited to the most abundant species: *Delitschia*-type, *Sordaria*-type, *Tripterospora*-type, UG-1138-type and focusing on *Sporormiella*-type. The latter is an ascomycete fungus used as a specific indicator of herbivore presence (Davis and Schafer 2006; Cugny et al. 2010). Results are expressed as concentrations (spores cm^{-3}).

The chronology of the lake core was constrained by 9 Accelerator Mass Spectrometry (AMS) radiocarbon analyses performed on organic bulk sediments at Beta Analytic Inc laboratory, Florida, USA. Over the 300 cm sequence, the age-depth relationship was constructed by linear interpolation of calibrated radiocarbon dates using the classical age modeling code (CLAM) for the statistical software R developed by Blaauw (2010), which also performs the calibration (using the SHCal13.14C, Reimer et al. 2013).

Multivariate statistical analyses were applied to the high resolution XRF dataset in order to extract and assess elemental correlations downcore. First, to attenuate non-linear matrix effects and constant sum constraints, the multivariate statistical analysis was applied after centered log-ratio (clr) transformation (Aitchison 1982; Weltje et al. 2015) of the complete set of XRF measurements (n = 5684). This simple transformation provides a reliable basis for statistical analysis of XRF core scanning data, unlike element count intensities or element ratios (Weltje et al. 2015). The following elements were considered for statistical analysis: Si, K, Fe, Ca, Ti, Mn, Sr and inc/coh. The Br was excluded because it frequently presents null values and dealing with clr transformation excludes dealing with zeros. The clr transformation was carried out using CoDaPack, a freely available Excel based software for compositional data transformation (Thió-Henestrosa and Martín-Fernández 2006). As a second step, a normality assumption test was first applied using the Shapiro–Wilk test (Ghasemi and Zahediasl 2012) in order to determine the type of correlation analysis to be used. Spearman's rank correlation coefficient was then performed as a non-parametric measure of correlation between the monitored variables (King and Eckersley, 2019) in order to quantify the strength of correlation between elements within each lithological unit. The correlation matrix was visualized as a heatmap with a dendrogram calculated by hierarchical clustering analysis (HCA) using the "heatmap" function implemented in the R package corrplot (Wei et al. 2017). The "rcorr" function in the Hmisc package (Harrell et al. 2006) was used to compute the significance levels for the Spearman correlations. Correlations with a p-value < 0.05 were considered significant.

Results

Chronological model

The chronological model of the AZA-SUP-1-A-16 core was established based on 9 AMS ^{14}C dates (Fig. 2, ESM2). Two dates were rejected (samples obtained at 27 cm and 75 cm) because they were much older than expected, likely due to reworking of older lake deposits. According to the resulting age model based on the remaining ages, the sedimentary sequence reveals a robust and coherent chronology, providing a continuous record for the last 6,000 years. The mean sedimentation rate is low, about 0.8 mm yr^{-1}, and varies between 0.1 and 2 mm yr^{-1} down core.

Lithology and mineralogical contents

Four sedimentary units were defined on the basis of variations in described sediment lithology and microscopic observation (Fig. 3). The basal A unit (bottom-180 cm) comprises massive minerogenic sediments with a compact, gray-to-light-reddish, clayey-silt facies with poor preservation of biologic indicators

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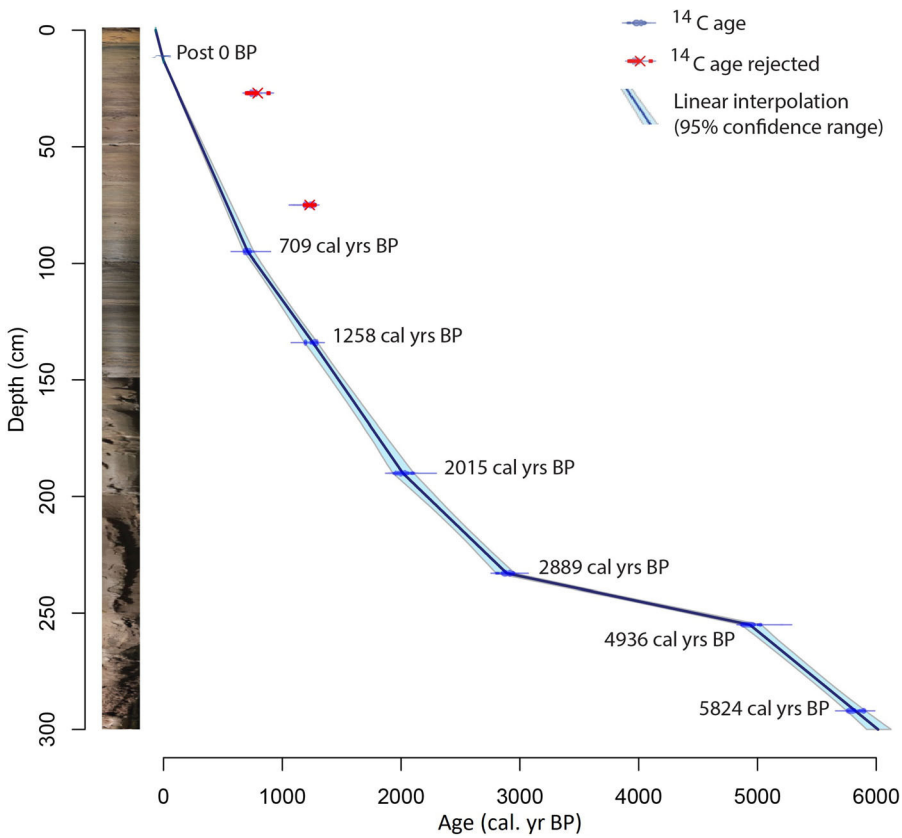

Fig. 2 Chronological model of Flowers Marsh core (AZA-SUP-1-A-16) based on a linear interpolation of calibrated radiocarbon dates

and eroded pollen. The sediment of this unit has the highest proportion of siliciclastic minerals (quartz, phyllosilicates, goethite), and the lowest proportion of calcite (Fig. 3). Unit B (between 180 and 150 cm) represents a transitional interval between the predominantly massive lower unit A and the upper laminated unit C. This unit B is characterized by a high proportion of siliciclastic minerals (quartz) and a gradual increase in carbonate content (Fig. 3). It is also characterized by well-preserved or fragmented ostracod shells, gastropods and charophytes. Unit C (150–90 cm) is formed of massive to faintly-laminated, black to dark-gray, organic-rich facies with abundant diatoms. It shows a marked up-core increase in carbonate content. XRD results clearly indicate that calcite is the dominant carbonate mineral (Fig. 3). Finally, unit D (the upper 90 cm) is dominated by laminated brown sediment. It is characterized by high calcite content and the recurrence of ostracod shells. Dark laminated facies with abundant diatoms, similar to unit C facies, are observed in the upper part of this unit (10–20 cm). Siderite and rhodochrosite, absent in the lowermost units A and B, are present within units C and D in low percentages (Fig. 3).

Grain size analysis of AZA-SUP-1-A-16 showed that the sediments of Flowers Marsh consist predominantly of clay and silts in the lower part of the core (units A and B) while a sandy fraction dominates the upper part of the core (units C and D; Fig. 3). This sandy fraction results mainly from the presence of endogenic carbonate concretions called "cauliflowers" rather than from detrital sand from the watershed area. "Cauliflowers" were only detected in units C and D. The high endogenic carbonate content of units C and D is in good agreement with the TIC and the $CaCO_3$ content, underlining the strong carbonate precipitation in the upper part of the core. High-resolution images of these endogenic carbonates obtained by SEM yielded observation of their microstructures. The morphology of the calcite crystals is irregular having "cauliflower" shapes and

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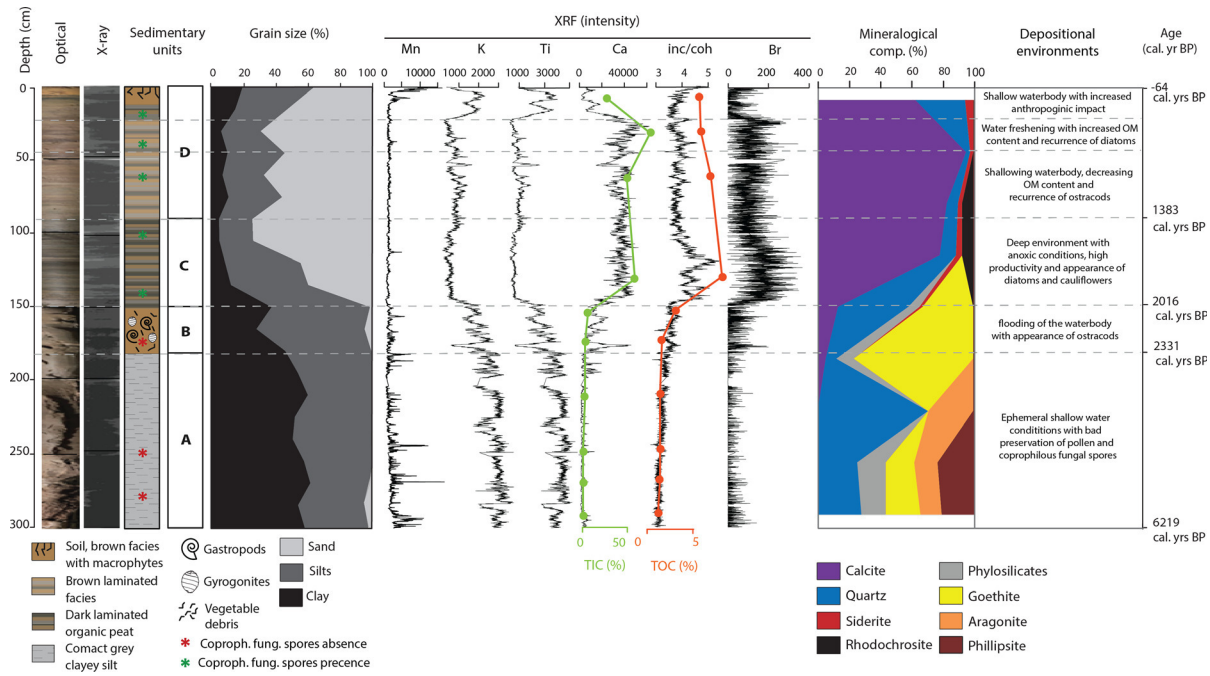

Fig. 3 Physical and lithological properties of Flowers Marsh core sediment. From left to right: Core image, X-ray radiography, schematic lithology, sedimentary units, grain size distribution (clay, silt and sand), X-ray Fluorescence (XRF) core scanner data expressed as intensity (Mn, K, Ti), Ca-XRF and Total Inorganic Carbon (TIC), inc/coh, Total Organic Carbon (TOC) and Br, mineralogical composition, reconstructed depositional environments and chronological scale (in cal. years BP)

shows a rough and porous surface and no obvious internal structure (ESM3-A). The EDS analysis showed that the elemental composition of this mineral includes O, C and Ca and small amounts of Mg, K, and Fe, indicating the calcic nature of these endogenic carbonates (ESM3-B).

Geochemistry

Elemental geochemistry

The main chemical elements and ratios selected for this study are the following: K, Si, Ti, Fe, Ca, Br, inc/coh, Ca/Ti and Br/Ti. Downcore elemental profiles are clearly consistent with the facies distribution (Figs. 3 and 4, ESM4). Si, K, Ti and Fe show comparatively higher values in clastic-dominated intervals in unit A and reveal a decrease in unit B with lower values in units C and D. The top of unit D shows an increase in the elements. Calcium displays an opposite trend, reaching maximum values in the carbonate-rich facies of units C and D. The inc/coh ratio and Br exhibit rather low and constant values in units A and B, then present abrupt increases in organic-rich intervals of unit C, decreasing upwards (Fig. 3, ESM4). The Ca/Ti and Br/Ti ratios display similar trends and present very low values in units A and B and higher values within units C and D. Manganese contents show a variable pattern with higher peaks in unit A and B and in the uppermost layer of unit D (Fig. 3).

Since changes in the core lithology reveal considerable variation in the lake status, correlation analysis and hierarchical clustering were constructed within each unit to quantify the strength of correlation between the lithology and geochemical composition (Fig. 5). The main detrital elements (K, Ti, and Fe) correlate strongly in all units ($r = 0.58–0.96$, p-value $= < 0.0001$). Silicon shows good correlations with the detrital elements in Unit A, B and D. This is not the case in the diatoms-rich unit C, where Si displays low correlations with these detrital elements. The inc/coh ratio shows a strong correlation with Ca in unit D ($r = 0.84$; $p$value < 0.0001; $n = 1760$), a moderate correlation in unit C ($r = 0.61$; p value < 0.0001; $n = 1154$) and unit B ($r = 0.58$;p-

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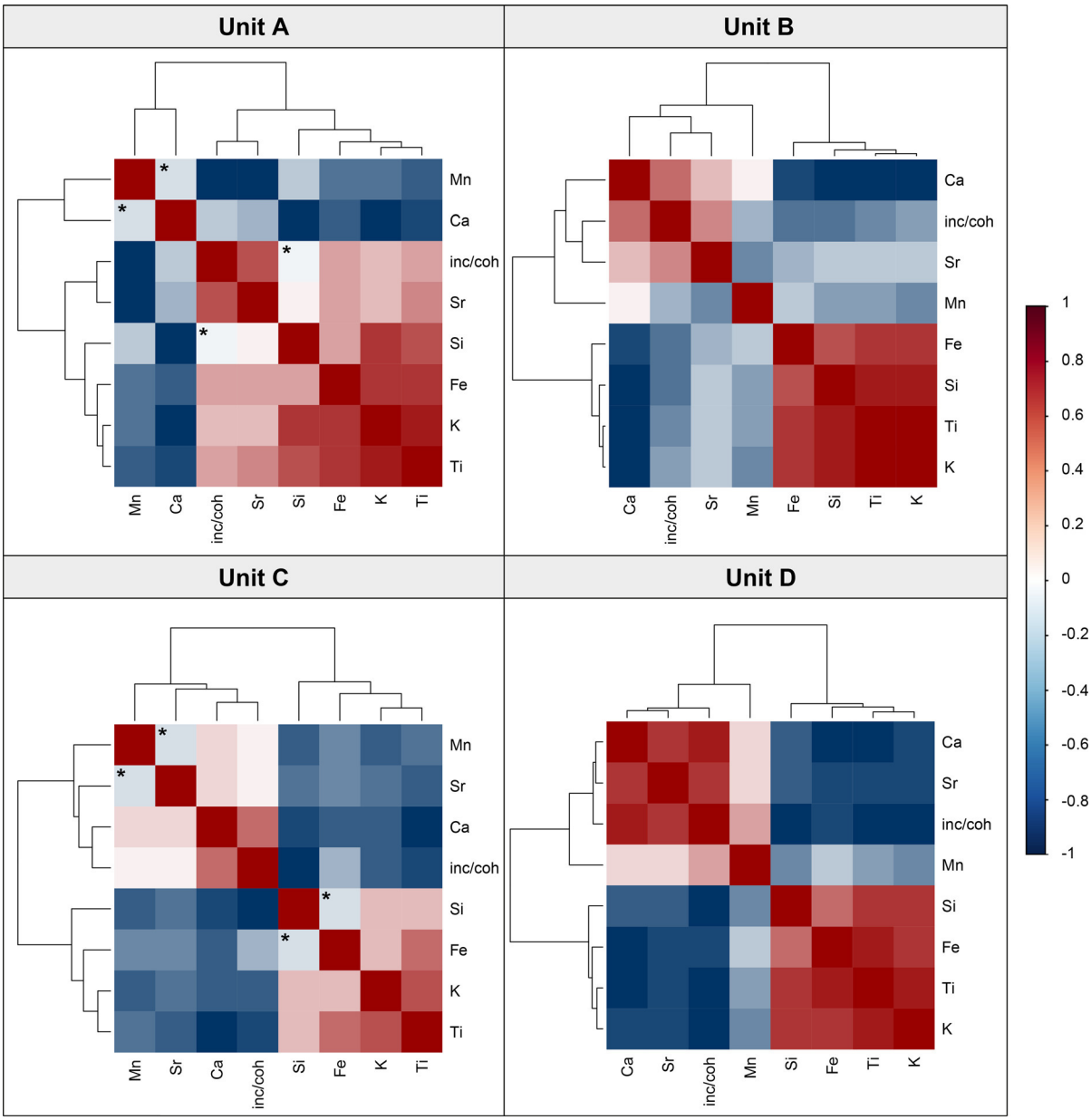

Fig. 4 Spearman correlation matrix and hierarchical clustering of the main XRF elements for the four lithological units (A, B, C and D). Red colors indicate positive correlations and blue colors indicate negative correlations. The color gradient indicates the strength of correlation. The order of the elements determines the ordered clusters. Asterisks refer to correlations with *p*-values > 0.05. Correlations without asterisks have a *p* value < 0.0001 (ESM6)

value < 0.0001; n = 600) and a very low correlation in unit A (r = − 0.09; *p*-value < 0.0001; n = 2170). The Mn does not show any correlation with other elements and likely reflects changes in redox conditions. Generally, the HCA dendrogram shows two clear main clusters: one associated with detrital minerals (Ti, K, Fe and Si) and the second one linked with organic matter and carbonate minerals (inc/coh, Ca and Sr); these two groups are clearly negatively correlated. In unit A, Sr and inc/coh show a weaker connection to the detrital elements group. Manganese is weakly related to the organic matter cluster.

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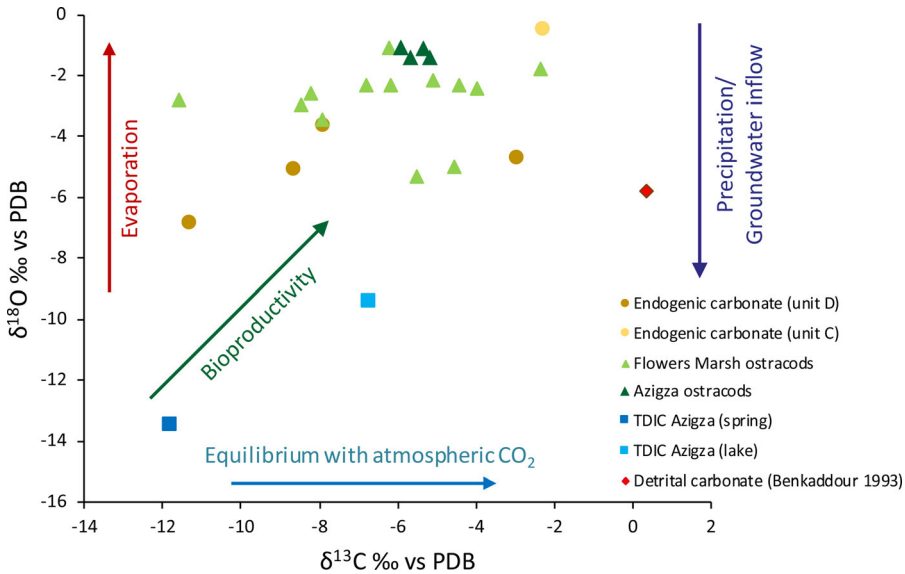

Fig. 5 Crossplot of $\delta^{13}C$ versus $\delta^{18}O$ for the studied endogenic and biogenic carbonates (ostracods) from Flowers Marsh, modern ostracods and TDIC from Aguelmam Azigza and published isotope composition of detrital carbonate obtained from the study area (Benkaddour 1993)

Organic geochemistry

The TOC values of the Flowers Marsh sequence range from 1% to 8% (Fig. 3). The organic content of units A and B is relatively low and constant (oscillating around 1%), increasing in the top of unit B (3.1%) and reaching maximum values of 8.3% in the lower part of unit C. The TOC remains relatively high in unit D (values range between 5 and 7%) with a decreasing trend towards the core top. The inc/coh ratio shows a similar trend to TOC, suggesting it is a reliable proxy for organic content in this system. Similarly, TIC values show a general trend towards increasing values from the bottom (unit A and B) to the top of the core (unit C and D). The highest concentrations of up to 75% occur at 32 cm and the lowest (0.5%) at the base of the core.

Biological proxies

The occurrence of ostracod shells is limited to the upper 166 cm of the Flowers Marsh sequence (166–143 cm and 25–79 cm); no shells were found in units A and B. When ostracods were observed, *Candona neglecta* and *Illyocipris gibba* were the most abundant species.

Diatom content is low throughout most of the record, and diatom remains are poorly 382 preserved. Diatoms present a sharp contrast with the abundance of ostracods. Units A and B were sterile in regards to diatoms. Unit C (150 –90 cm) is dominated by epiphytic species such as *Epithemia adnata* (Kützing), *Sellaphora laevissima* (Kützing) and *Gomphonema pumilum* (Grunow) and by benthic species represented mainly by *Halamphora veneta* (Kützing) and *Cocconeis placentula* (Ehrenberg) (ESM5). In the upper 90 cm, the diatom assemblage is still dominated by benthic forms, except at 47–48 and 38–39 cm where the centric *Cyclotella distinguenda* (Hustedt) dominates the assemblage (ESM5).

The occurrence of coprophilous fungi species and spore concentration throughout the core were examined. The lowest units A and B (280, 250 and 174 cm) present low concentrations and poor preservation of coprophilous fungi spores. The boundary between units B and C (141 cm) is characterized by an increase in values of coprophilous fungi spores with a better preservation and high abundances of the UG-1138 species. In unit C (101 cm), continuation of the high values of UG-1138 is recorded. The exclusive occurrence and high values of *Tripterospora*-type and a

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decrease in UG-1138 values occur in unit D (39 cm). The topmost part of this unit (19 cm) is characterized by the highest values of *Sporormiella*-type and a relatively high abundance of *Delitschia*-type.

$\delta^{13}C$ and $\delta^{18}O$ of Flowers Marsh carbonates

The oxygen isotopic composition values of biogenic carbonates derived from the benthic ostracod species *C. neglecta* were in the range − 5.34 to − 1.09‰. These values are in agreement with ostracod $\delta^{18}O$ records measured on the same species in the larger lake Aguelmam Azigza (this study) and with records carried out on modern ostracods from Lake Tigalmamine (Benkaddour et al. 2005). The $\delta^{18}O$ of ostracods is mostly affected by the isotopic composition of lake water and water temperature at the time of its formation (Xia et al. 1997). In semi-arid, closed small lake settings, ostracod $\delta^{18}O$ reflects primarily the local hydrologic balance (Roberts et al. 2008; Develle et al. 2010).

Figure 6 displays the relationship between $\delta^{13}C$ and $\delta^{18}O$ for all of the carbonate species analyzed in this study. The $\delta^{13}C$ in the studied samples of endogenic carbonates from Flowers Marsh sediments vary considerably and range from − 11.3 to -2.3‰ VPDB, whereas $\delta^{18}O$ of the same samples range from − 6.8 to -0.5‰ VPDB. The dominant controls on the $\delta^{18}O$ of lacustrine endogenic carbonates is controlled are the temperature of its formation and the isotopic composition of the water in which it precipitates (Epstein et al. 1953; Craig 1965). The ^{13}C content of lacustrine carbonates mainly reflects the composition of the TDIC in the lake water and the effects of biological fractionation related to aquatic photosynthesis (Stuiver 1970; McKenzie 1985).

Discussion

Paleoenvironmental interpretation of the deposited sediments requires an accurate understanding of the proxy significance. In the following, different proxies are discussed to provide a reliable paleohydrological reconstruction of Flowers Marsh. A possible connection with Aguelmam Azigza hydrological behavior is discussed so as to understand the hydrological functioning of these hydrosystems at the catchment scale. Finally, comparisons between the regional records are proposed in order to demonstrate the local hydrological differences and the common patterns in response to regional climatic drivers.

Flowers Marsh hydrological development during the last 6000 years

Four main phases were distinguished following the lithologic units, the geochemical zonation derived from the μ-XRF data, the mineralogy and the recurrence of biomarkers (Fig. 4): (A) ephemeral waterbody, (B) flooding and permanent shallow water conditions, (C) medium to deep waterbody and (D) shallow water level.

Unit A—Ephemeral waterbody (6–2.3 cal. kyr BP)

The oldest sediments present in the Flowers Marsh sequence are characterized by a high intensity of Ti, K, Si which are grouped together with Sr and Fe (Fig. 5). These detrital elemental intensities may mostly track high clay and phyllosilicate contents that are deposited during heavy rainfall and thus be related to a relatively high lake level, or they may correspond to evidence of arid conditions and thus be related to lake desiccation. However, the highly clastic nature of unit A made up of clay minerals, phyllosilicates and quartz particles (as determined by XRD and microscope observations) with a very low sedimentation rate suggests that the sediments were originally deposited in a shallow, littoral lacustrine setting. Furthermore, the minimum carbonate values (TIC, DRX calcite and Ca intensities) point to an absence of dissolved calcite from surrounding rocks, as a consequence of CO_2-poor groundwater associated with weakly developed soil and vegetation and/or to low detrital carbonate input as a consequence of decreased runoff. The complete absence of biological fauna with non-preservation of coprophilous fungi spores and eroded pollen also supports oxic conditions typical of a shallow environment with frequent periods of subaerial exposure (González-Sampériz et al. 2008). The low accumulation of organic matter (extremely low TOC content) may indicate a barren landscape with sparse vegetation and low productivity in the waterbody (low Br/Ti). The absence of endogenic calcite (low Ca/Ti) indicates that conditions were not adequate for endogenic calcite precipitation and/or preservation in the sediments. In addition, the relatively high Mn contents

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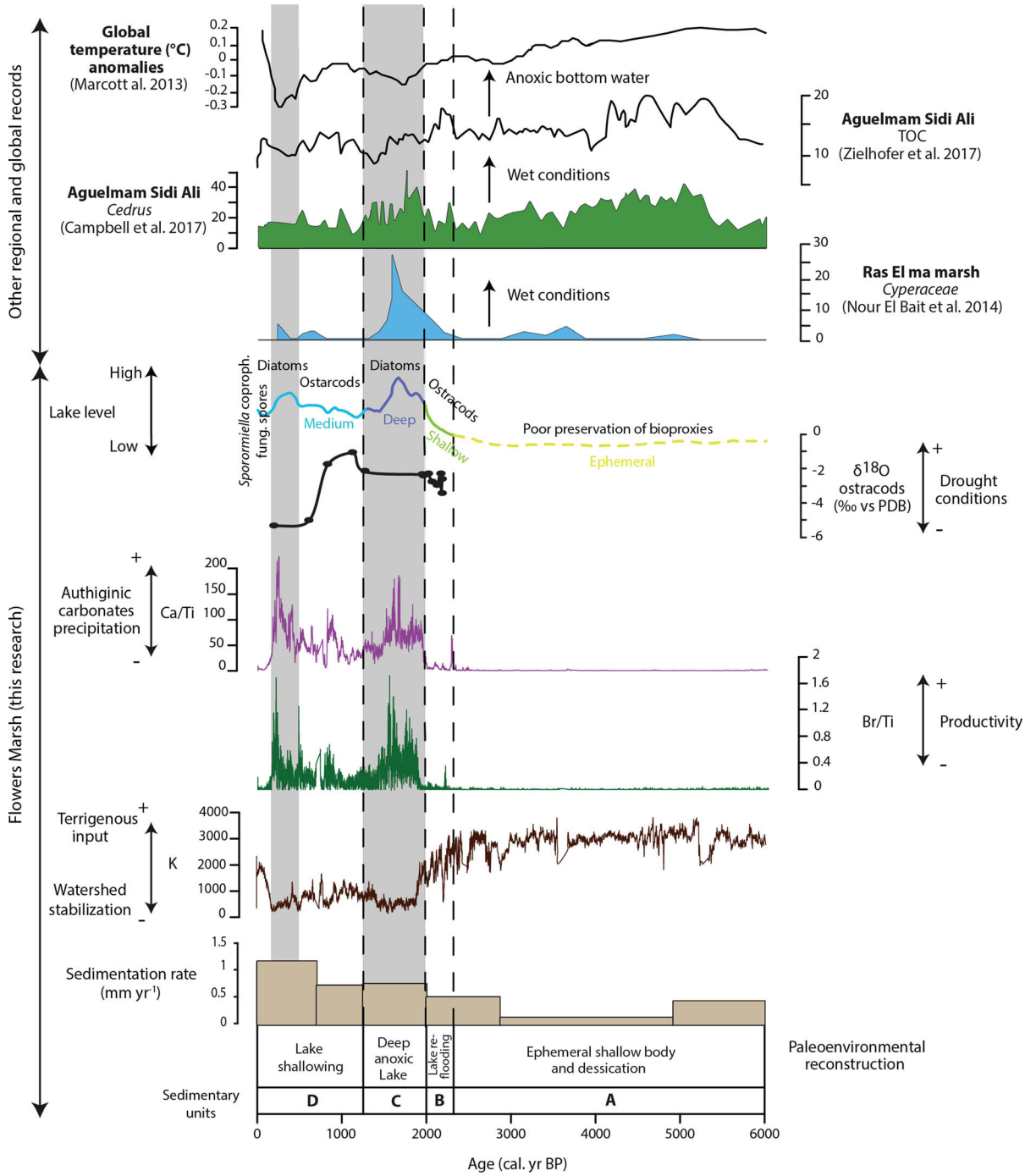

Fig. 6 Selected Flowers Marsh proxies (lower part) compared with other regional and global records (upper part) for the last 6 cal. kyr BP. In the lower section, from bottom to top: calibrated radiocarbon dates, paleoenvironmental reconstruction for the different units (A-B-C-D), sedimentation rate (mm yr^{-1}), K-XRF, Ca/Ti ratio, Br/Ti ratio, $\delta^{18}O$ record from *C. neglecta* and the relative lake-level curve construction using different proxies mentioned in the text. In the upper section: Ras El Ma Marsh aquatic plant records (Nour El Bait et al. 2014), Aguelmam Sidi Ali *Cedrus* records (Campbell et al. 2017), TOC records (Zielhofer et al. 2017) and reconstruction of Global Temperature anomalies at the uppermost part of the record (Marcott et al. 2013). Vertical dotted lines represent temporal subdivisions of units used in the "Discussion" section. Grey shading highlights periods of high stand of Flowers Marsh

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indicate oxygenation of the bottom sediment with increasing preservation of Mn as oxides (Davies et al. 2015). Sedimentological, geochemical and biological evidence from unit A sediments indicates hydrological scenarios that fluctuate between a very shallow and an ephemeral waterbody. This interpretation is consistent with results from other lake sediments with no organic matter content and a high clastic content that were related to periods of shallow lake levels (Valero-Garcés et al. 2000; González-Sampériz et al. 2008; Corella et al. 2011; Nour El Bait et al. 2014).

Unit B—re-flooding and shallow water conditions (2.3–2 cal. yr BP)

Unit B is a transitional phase between the clastic material of Unit A and the laminated organic-rich sediment of the top of the core. It represents a progressive transition towards a shallow wetland environment with calcite formation marked by peaks in Ca/Ti. The high sedimentation rate underlines the increase in carbonate deposition (Fig. 4). This phase is characterized by the appearance of ostracods, especially benthic species (*C. neglecta* and *I. gibba*). Their high abundance indicates that the lake-bottom conditions were predominantly aerobic during this interval (Meisch 2000). The abundance of charophytes and gastropods also indicates a shallower littoral environment (Benkaddour 1993; Soulié-Märsche et al. 2008). The decline of terrigenous element contents can be explained by the stability of the watershed as confirmed by the forest cover expansion during this period (Lamb et al. 1999; Nour El Bait et al. 2014). Unit B deposits characterize the re-flooding of the waterbody marked by changes in the depositional mode which most likely resulted from climate amelioration in the region. Slight fluctuations of ostracod $\delta^{18}O$ values in this unit probably point to a shallow and steady water level (Fig. 4).

Unit C—Medium to deep waterbody (2–1.4 cal. kyr BP)

This unit was deposited under relatively deep water conditions as indicated by the preservation of lamination, the highest TOC values (up to 8%) and diatom- and organic matter-rich facies, indicative of high biological productivity and organic matter preservation in the lake (Martín-Puertas et al. 2011). The low Mn content and the well preservation of pollen and spores point to deposition in a relatively anoxic deep lake (Brauer 2004; Zolitschka 2007; Martín-Puertas et al. 2009). This unit is characterized by a major change in grain size distribution from clay-silt to sand as the dominant particle sizes, associated with an increase in sedimentation rate (Figs. 3 and 4). This sandy fraction is related to the massive endogenic carbonate precipitation indicated by peaks in Ca/Ti (Fig. 4). These carbonate concretions are related to the occurrence of "cauliflowers" irregularly shaped carbonate concretions that have been described as being of algal origin (Magny 1992). They reflect deposition in a shallow-water environment with mobilization to the deep basin during periods of higher runoff. In this unit, endogenic carbonates record the highest isotopic values (Fig. 6). Enriched isotopic values relative to the TDIC values may be related to high productivity (diatom and algal) in the littoral zone (Stuiver 1970; McKenzie 1985). The absence of ostracods during this interval is not due to calcite dissolution processes, as indicated by the presence of endogenic calcite. Most likely, diatom blooms, anoxic conditions and limited water circulation in the lake bottom as indicated by laminated sediments inhibited the survival of benthic ostracods (Valero-Garcés 2003). This unit is also characterized by negative shifts in Ti, K, Fe and Si indicators for allochthonous detrital input (Fig. 3, ESM4). This decrease could be related to the stability of the watershed by forest development and to dilution of the allochthonous input by precipitated calcite as indicated by the negative correlations of Ca with the detrital elements in unit C (Fig. 5). Silicon shows a low correlation with the detrital elements in this unit (Fig. 5), which highlights an additional source (biogenic) of Si provided by diatoms.

Unit D—Fluctuating and shallow pond (After 1.4 cal. kyr BP)

During this period, Flowers Marsh sediments reflect the change from dark laminations (unit C) to brown-white laminations and several productivity proxies point to a slight decrease (TOC, inc/coh, Br/Ti and diatom abundance). A minor drop in carbonate precipitation also occurred, extending until ~ 650 cal. yr BP. This decline in primary productivity and carbonate production together with more positive ostracod $\delta^{18}O$ values, compared to the onset

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of unit C, could be related to more arid conditions (Fig. 4). Also, the replacement of diatoms by ostracods points to a major shift in the lake level toward shallow waters (Benkaddour 1993). A transitory increase in the deposition of organic matter (high Br/Ti) and calcite precipitation (high Ca/Ti) between 650 and 150 cal. yr BP points to a period of enhanced biological productivity that allowed the precipitation and preservation of endogenic calcite concretions (Fig. 4). The diatom record is dominated by *Cyclotella distinguenda* which indicates an enhanced lake level and the dominance of a period of stable stratification (Interlandi and Kilham 2001). A drop in ostracod $\delta^{18}O$ values may reflect a short phase of more humid conditions during this period (Fig. 4). Since 150 cal. yr BP, another phase characterized by indicators of lower productivity (decreases in TOC, inc/coh and Br/Ti ratio) and increases in clastic input to the lake occurred (Fig. 3). Stronger reduction of the waterbody prevailed during this period as revealed by the high Mn content indicating oxygenation of the lake bottom. More arid conditions leading to enhanced littoral erosion and sediment delivery to the pond may explain the increase in detrital element contents. Nevertheless, these trends could also be related to the anthropogenic degradation of the landscape by increased farming or land use practices including high pastoralism activities. An anthropogenic effect is supported by the presence of anthropogenic markers such as the high concentrations of *Sporormiella* (Cugny et al. 2010; Williams et al. 2011; Currás et al. 2012) in recent sediments (recorded at 180 cal. yr BP). This reflects an increase in livestock grazing activity which is the main anthropogenic pressure on soils in the area (Campbell et al. 2017). Given the low temporal resolution of this part of the core, the sub-millennial variability should be interpreted cautiously in this part of the record.

Connection between Flowers Marsh and Aguelmam Azigza

The Flowers Marsh paleohydrological reconstruction reveals interesting links to Aguelmam Azigza. The flooding at 2.3 cal. kyr BP may be interpreted as a period of enhanced surface and groundwater flux to the pond. Earlier and recent studies from the nearby Aguelmam Azigza indicate metric water level fluctuations at interannual and decadal scales (Flower et al. 1989; Adalall et al. 2019; Jouve et al. 2019). Precise geomorphological mapping of the watershed shows that a connection existed between the two waterbodies owing to a lake level increase at Azigza of about 15 meters, a level that was also reached in the late 1960s (Jouve et al. 2019). We suggest that the re-flooding period evidenced at the Flowers Marsh could correspond to an equivalent Azigza lake-level high stand at about 2.3 kyr BP. This would imply that the highest Azigza lake level was probably reached at that time. Precise geomorphological observations of the basin catchments are consistent with a past high stand (Jouve et al. 2019).

Comparison with Mid-Late Holocene regional records

In Europe and in the Mediterranean region, the Holocene period reveals diverse spatial and temporal patterns of climate variability induced by large-scale changes in atmospheric circulation and complex interactions of various forcing factors (Di Rita et al. 2018). The linkage between phases of aridity and humidity on a sub-regional to regional scale is highly challenging (Carrión 2002). The Moroccan Middle Atlas is part of this Mediterranean periphery and has also demonstrated local and regional sensitivity in the response of lakes to climatic variation.

During the Mid-Holocene (6000–2300 cal. yr BP), Flowers Marsh records ephemeral water conditions with recurrent desiccation periods. This picture contrasts with evidence of a moister climate recorded in the Middle Atlas region. Humid conditions were highlighted by the arrival and expansion of cedar after ~ 6 cal. kyr BP, recorded in Aguelmam Sidi Ali (Campbell et al. 2017), Lake Tigalmamine (Lamb et al. 1999), the Ras El Ma marsh (Nour El Bait et al. 2014), and the Ait Ichou marsh (Tabel et al. 2016). This Mid-Holocene expansion of *Cedrus* was related to increasing available moisture and suggests a climatic transition toward generally cooler and more humid conditions with reduced summer drought (Campbell et al. 2017). However, other Middle Atlas paleohydrological studies have detected a striking mismatch between the local hydrological water balance and plant available moisture reflected by the abundance of *Cedrus* pollen. For instance, a maximum in plant available moisture recorded at Lake Tigalmamine coincides with low lake levels (Lamb and van der Kaars 1995). Equally, the *Cedrus* pollen in the

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Aguelmam Sidi Ali record indicates more humid conditions during the Late Holocene, while the majority of the lake level proxies point to a general lake level lowering trend during this period (Zielhofer et al. 2017). The authors interpreted *Cedrus* pollen increases not as an indicator of more precipitation but rather as an indicator for more available moisture that may be the result of lower summer temperatures (Lamb et al. 1999; Zielhofer et al. 2017). The low lake level recorded in Flowers Marsh sediments during the Mid- to Late Holocene may be related to a reduction in winter precipitation which would have significantly reduced groundwater recharge. During the Mid-Holocene, arid conditions were recorded in lake sediments in the Middle Atlas region (Rhoujjati et al. 2012; Campbell et al. 2017; Bell et al. 2019), and also in more distant sites from the northern Iberian Peninsula (Santos et al. 2000; Morellón et al. 2008). For instance, most of the saline lakes in the Central Ebro valley (northeastern Spain) were desiccated or ephemeral during the Mid-Holocene (González-Sampériz et al. 2008). In Arreo Lake, the presence of coarse alluvial facies at the base of the sequence points to more arid conditions prior to 2250 BP (Corella et al. 2013).

The Late Holocene is characterized by a transitional phase towards a sustainable water supply to the pond with a higher water level at Flowers Marsh (2300 cal. yr BP–1800 cal. yr BP), particularly evident in lamination preservation and in organic matter increase. Wet conditions during this period were also recorded in Lake Iffer as indicated by an increase in lake productivity and rising lake level (Damnati et al. 2015). At Tigalmamine Lake, increased precipitation at about 2600 year BP, with equivalent troughs in winter and summer temperatures were reconstructed from pollen records (Cheddadi et al. 1998). Higher lake levels are documented by the dominance of aquatic plants (*Typha* L., *Potamogeton* Linn., *Myriophyllum* L. and Cyperaceae) in the pollen diagram from Ras El Ma marsh, with a high stand between 2000 and 1400 cal. yr BP (Fig. 4) (Nour El Bait et al. 2014). A relative increase in TOC around 2,200 cal. yr BP was also recorded in Aguelmam Sidi Ali indicating a high lake level and high productivity (Zielhofer et al. 2017). This period coincides with the wetter Iberian Roman period in the northern Mediterranean. A humid phase during the Iron Age and the Roman Optimum from 2700 to 1600 year, inferred from lake and fluvial records (Macklin et al. 2006; Martín-Puertas et al. 2008), has been found in the Iberian Peninsula. Furthermore, a decrease in temperature around 2000 cal. yr BP was identified at a global scale (Marcott et al. 2013).

The shallowing water level recorded at Flowers Marsh since 1.4 kyr cal. BP coincides with decreasing tree pollen abundance at other regional Lakes, such as Aguelmam Sidi Ali where there was a reduction in the arboreal/non-arboreal pollen ratio (AP/NAP) after 1300 cal. yr BP (Cambell et al. 2017). Most of the Middle Atlas records reflect forest cover degradation during this period, which might be related to more arid conditions. This stage coincides with the Medieval Climate Anomaly (MCA) which was marked by a global increase in temperature (Marcott et al. 2013). It has also been described in previous paleoclimatic reconstructions across the Mediterranean Basin (Magny 2004; Moreno et al. 2012). Aside from the increase in arid conditions, the intensification of anthropogenic activity during this period also had a strong impact on the forest and the environmental variability in the region (Reille 1976; Benkaddour 1993) where significant anthropogenic alteration of forest cover was recorded, especially in the last two millennia (Cheddadi et al. 2015). However, coprophilous fungal spore evidence in the Flowers Marsh record did not indicate increased anthropogenic pressure during this period. A high stand period was recorded at Flowers Marsh from 650 to 150 cal. yr BP. Considering the uncertainties of the chronological model for this time interval, this phase could coincide with the Little Ice Age (LIA), a generally cold period (Mann et al. 2009). This short humid phase is synchronous with decreased drought stress in the Middle Atlas documented in *Cedrus atlantica* ring width data (Esper et al. 2007) and in speleothem records (Wassenburg et al. 2013). Cooling episodes favoring the expansion of *Cedrus* were recorded during this period at Tigalmamine Lake (Lamb et al. 1989) and in Aguelmam Sidi Ali sediments (Campbell et al. 2017).

Conclusions

The multiproxy study (sedimentological, geochemical, mineralogical, biological—spores of coprophilous fungi, ostracods and diatoms, and AMS ^{14}C dating),

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carried out on the Flowers Marsh sedimentary sequence from the Middle Atlas region, provides a paleohydrological and paleoenvironmental reconstruction (of the area) since 6000 cal. yr BP, interpreted in terms of climate and environment variability. This study demonstrates the ability of a pond such as Flowers Marsh to show significant palaeohydrological evolution and confirms the high sensitivity of Middle Atlas hydrosystems to climatic changes in the Mediterranean region as highlighted in previous studies.

The Flowers Marsh record shows arid conditions prior to 2300 cal. yr BP represented by highly clastic sediments and poor preservation of bioproxies. A large increase in water availability, marked by enhanced organic matter and endogenic calcite preservation was recorded during the wetter Iberian-Roman period, particularly between 2000 and 1400 cal. yr BP and during the Little Ice Age (650– 150 cal. yr BP). Lower lake levels, a response to increasing regional aridity, were recorded during the Medieval Climate Anomaly (1400–650 cal. yr BP). Intensification of human pressure by pastures in the Flowers Marsh catchment is recorded since the last 150 year.

Comparison of the main hydrological phases in Flowers March with other Middle Atlas and Mediterranean records demonstrates a coherent pattern of the main climatic phases in the region during the last 6000 years, at the same time highlighting spatial and temporal variability due to latitudinal differences and some site specific patterns.

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References

Adallal R, Vallet-Coulomb C, Vidal L, Benkaddour A, Ali Rhoujjati A, Sonzogni C (2019) Modelling lake water and isotope mass balance variations under Mediterranean climate: Lake Azigza in the Moroccan Middle Atlas. Reg Environ Change 19(8):2697–2709

Agnihotri R, Altabet MA, Herbert TD, Tierney JE (2008) Subdecadally resolved paleoceanography of the Peru margin during the last two millennia. Geochem Geophys Geosyst 9:Q05013

Aitchison J (1982) The statistical analysis of compositional data. J Roy Stat Soc B Met 44:139–177

Arz HW, Pätzold J, Müller PJ, Moammar MO (2003) Influence of Northern Hemisphere climate and global sea level rise on the restricted Red Sea marine environment during termination I. Paleoceanography 18:1053

Aufgebauer A, Panagiatopoulos K, Wagner B, Schaebitz F, Viehberg FA, Vogel H, Zanchetta G, Sulpizio R, Leng MJ, Damaschke M (2012) Climate and environmental change over the last 17 ka recorded in sediments from Lake Prespa (Albania/F.Y.R. of Macedonia/Greece). Quatern Int 274:122–135

Barker PA, Roberts N, Lamb HF, van der Kaars S, Benkaddour A (1994) Interpretation of Holocene lake-level change from diatom assemblages in Lake Sidi Ali, Middle Atlas, Morocco. J Paleolimnol 12:223–234

Bell BA, Fletcher WJ, Cornelissen HL, Campbell JF, Ryan P, Grant H, Zielhofer C (2019) Stable carbon isotope analysis on fossil Cedrus pollen shows summer aridification in Morocco during the last 5000 years. J Quat Sci 34(4–5):323–332

Benkaddour A (1993) Changements hydrologiques et climatiques dans le Moyen-Atlas marocain; chronologie, minéralogie, géochimie isotopique, et élémentaire des sédiments lacustre de Tigalmamine. Thèse de l'Université de Paris XI-France, p. 199

Benkaddour A, Lamb H, Leng M, Gasse F (2005) Stable isotope records of Holocene environmental change from Moroccan lakes: an emerging synthesis. http://www.pages-igbp.org/download/docs/meeting-products/posters/2005-osm2/Benkaddour-A.pdf [26.01.2015]

Blaauw M (2010) Methods and code for 'classical' age-modelling of radiocarbon sequences. Quat Geochronol 5:512–518

Born K, Fink AH, Knippertz P (2010) Dry and wet periods in the northwestern Maghreb for present day and future climate conditions. Meteorol Z 17(5):533–551

Bradley RS (2015) Paleoclimatology: Reconstructing climates of the Quaternary, Amsterdam, Elsevier, pp 675

Brauer A (2004) Annually laminated lake sediments and their palaeoclimatic relevance. In: Fischer H, Kumke T, Lohmann G, Flöser G, Miller G, von Storch H, Negendank JFW (eds) Towards a synthesis of Holocene proxy data and ClimateModels. Springer, Berlin, pp 109–128

Brisset E, Djamali M, Bard E, Borschneck D, Gandouin E, Garcia M, Stevens L, Tachikawa K (2019) Late Holocene hydrology of Lake Maharlou, Southwest Iran, inferred from high-resolution sedimentological and geochemical analyses. J Paleolimnol 61(1):111–128

Brown E, Johnson T, Scholz C, Cohen A, King J (2007) Abrupt change in tropical African climate linked to the bipolar seesaw over the past 55,000 years. Geophys Res Lett 34(20)

Campbell JFE, Fletcher WJ, Joannin S, Hughes PD, Rhanem M, Zielhofer C (2017) Environmental Drivers of Holocene forest development in the Middle Atlas, Morocco. Front Ecol Environ 5(September):1–22

UNCORRECTED PROOF

Journal : Medium 10933 | Dispatch : 18-1-2021 | Pages : 19
Article No. : 166 | ☐ LE | ☐ TYPESET
MS Code : JOPL-D-19-00075R2 | ☑ CP | ☑ DISK

Author Proof

Carrión JS (2002) Patterns and processes of Late Quaternary environmental change in a montane region of southwestern Europe. Quaternary Sci Rev 21:2047–2066

Carrión JS, Fernández S, Jiménez-Moreno G, Fauquette S, Gil-Romera G, González-Sampériz P, Finlayson C (2010) The historical origins of aridity and vegetation degradation in Southeastern Spain. J Arid Environ 74(7):731–736

Cheddadi R, Lamb HF, Guiot J, Van Der Kaars S (1998) Holocene climatic change in Morocco: A quantitative reconstruction from pollen data. Clim Dyn 14(12):883–890

Cheddadi R, Nourelbait M, Bouaissa O, Tabel J, Rhoujjati A, López-Sáez JA, Alba-Sánchez F, Khater C, Ballouche A, Dezileau L, Lamb H (2015) A history of human impact on Moroccan Mountain landscapes. Afr Archaeol Rev 32:233–248

Cheddadi R, Palmisano A, López-Sáez JA, Nourelbait M, Zielhofer C, Tabel J, Rhoujjati A, Khater C, Woodbridge J, Lucarini G, Broodbank C, Fletcher WJ, Roberts N (2019) Human demography changes in Morocco and environmental imprint during the Holocene. Holocene 29(5):816–829

Chillasse L, Dakki M, Abbassi M (2001) Valeurs et fonctions écologiques des zones humides du Moyen Atlas. Humed Mediterr 1:139–146

Corella JP, Moreno A, Morellón M, Rull V, Giralt S, Rico MT, Pérez-Sanz A, Valero- Garcés BL (2011) Climate and human impact on a meromictic lake during the last 6000 years (Montcortès Lake, Central Pyrenees, Spain). J Paleolimnol 46:351–367

Corella JP, Stefanova V, El Anjoumi A, Rico E, Giralt S, Moreno A, Plata-Montero A, Valero-Garcés BL (2013) A 2500-year multi-proxy reconstruction of climate change and human activities in northern Spain: the Lake Arreo record. Palaeogeogr Palaeocl 386:555–568

Craig H (1965) The measurement of oxygen isotope palaeotemperatures. In: Tongiorgi E (ed) Stable isotopes in oceanographic studies and palaeotemperatures. Pisa, Consiglio Nazionale delle Ricerche Laboratorio di Geologia Nucleare, pp 161–182

Croudace IW, Rindby A, Rothwell RG (2006) ITRAX: description and evaluation of a new multi-function X-ray core scanner. Geol Soc Spec Publ London 267(1):51–63

Cugny C, Mazier F, Galop D (2010) Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): the use of coprophilous fungi to reconstruct pastoral activity. Veg Hist Archaeobot 19:391–408

Currás A, Zamora L, Reed JM, Garciá-Soto E, Ferrero S, Armangol X, Mezquita-Joanes F, Marqués MA, Riera S, Julià R (2012) Climate change and human impact in central Spain during Roman times: high-resolution multi-proxy analysis of a tufa lake record (Somolinos, 1280 m asl). Catena 89:31–53

Damnati B, Etebaai I, Benjilani H, El Khoudri K, Reddad H, Taieb M (2015) Sedimentology and geochemistry of lacustrine terraces of three Middle Atlas lakes: paleohydrological changes for the last 2300 cal BP in Morocco (western Mediterranean region). Quatern Int 404:163–173

Davies SJ, Lamb HF, Roberts SJ (2015) Micro-XRF core scanning in palaeolimnology: recent developments. In: Micro-XRF studies of sediment cores. Springer, Dordrecht, pp 189–226

Davis OK, Schafer D (2006) *Sporormiella* fungal spores, a palynological means of detecting herbivore density. Palaeogeogr Palaeocl 237:40–50

Develle AL, Herreros J, Vidal L, Sursock A, Gasse F (2010) Controlling factors on a paleo-lake oxygen isotope record (Yammoûneh, Lebanon) since the Last Glacial Maximum. Quat Sci Rev 29(7–8):865–886

Di Rita F, Fletcher WJ, Aranbarri J, Margaritelli G, Lirer F, Magri D (2018) Holocene forest dynamics in central and western Mediterranean: periodicity, spatio-temporal patterns and climate influence. Sci Rep-UK 8(1):1–13

Epstein S, Buchsbaum R, Lowenstam HA et Urey HC (1953) Echelle de température isotopique révisée eau-carbonate. Bull Soc Géol Amérique 64(11):1315–1326

Esper J, Frank D, Büntgen U, Verstege A, Luterbacher J, Xoplaki E (2007) Long-term drought severity variations in Morocco. Geophys Res Lett 34:L17702

Espitalié J, Laporte JL, Madec M, Marquis F, Leplat P, Paulet J, Boutefeu A (1977) Méthode rapide de caractérisation des roches-mère, de leur potentiel pétrolier et de leur degré d'évolution. Rev Inst Tranc Petrol (32): 23–42

Etebaai I, Damnati B, Raddad H, Benhardouz H, Benhardouz O, Miche H, Taieb M (2012) Impacts climatiques et anthropiques sur le fonctionnement hydrogéochimique du Lac Ifrah (Moyen Atlas marocain). Hydrol Sci J 57(3):547–561

Fægri K, Iversen J (1989) Textbook of pollen analysis. Wiley, Chichester-New York-Brisbane-Toronto-Singapore

Flower RJ, Foster IDL (1992) Climatic implications of recent changes in lake level at Lac Azigza (Morocco). Bull Soc Géol France 163:91–96

Flower RJ, Stevenson AC, Dearing JA, Foster ID, Airey A, Rippey B, Wilson JPF, Appleby PG (1989) Catchment disturbance inferred from paleolimnological studies of three contrasted sub-humid environments in Morocco. J Paleolimnol 1:293–322

Ghasemi A, Zahediasl S (2012) Normality tests for statistical analysis: a guide for non-statisticians. Int J Endocrinol 10:486–489

Gilfedder BS, Petri M, Wessels M, Biester H (2011) Bromine species fluxes from Lake Constance's catchment and a preliminary lake mass balance. Geochim Cosmochim Ac 75:3385–3401

Giorgi F (2006) Climate change hot-spots. Geophys Res Lett 33(8):L08, 707

González-Sampériz P, Valero-Garcés BL, Moreno A, Morellon M, Navas A, Machin J, Delgado-Huertas A (2008) Vegetation changes and hydrological fluctuations in the Central Ebro Basin (NE Spain) since the Late Glacial period: saline lake records. Palaeogeogr Palaeocl 259:136–115

Harrell Jr, Frank E, Dupont C (2006) Le paquet Hmisc. Version du package R, 3 (0–12), 3

Hinaje S, Ait Brahim L (2002) Les bassins lacustres du Moyen Atlas (Maroc): un exemple d'activité tectonique polyphasée associée à des structures d'effondrement. Comunicações do Instituto Geológico e Mineiro 89:283–294

Interlandi SJ, Kilham SS (2001) Limiting resources and the regulation of diversity in phytoplankton communities. Ecology 82:1270–1282

UNCORRECTED PROOF

Journal : Medium 10933 | Dispatch : 18-1-2021 | Pages : 19
Article No. : 166 | ☐ LE | ☐ TYPESET
MS Code : JOPL-D-19-00075R2 | ☑ CP | ☑ DISK

Author Proof

Jalut G, Dedoubat JJ, Fontugne M, Otto T (2009) Holocene circum-Mediterranean vegetation changes: climate forcing and human impact. Quatern Int 200:4–18

Jiménez-Moreno G, Rodríguez-Ramírez A, Pérez-Asensio JN, Carrión JS, López-Sáez JA, Villarías-Robles JJ, Celestino-Pérez S, Cerrillo-Cuenca E, León A, Contreras C (2015) Impact of late-Holocene aridification trend, climate variability and geodynamic control on the environment from a coastal area in SW Spain. Holocene 25(4):607–617

Jouve G, Vidal L, Adallal R, Rhoujjati A, Benkaddour A, Chapron E, Tachikawa K, Bard E, Courp T, Dezileau L, Hebert B, Rapuc W, Simonneau A, Sonzogni C, Sylvestre S (2019) Recent hydrological variability of the Moroccan Middle-Atlas Mountains inferred from micro-scale sedimentological and geochemical analyses of lake sediments. Quat Res 91(1):414–430

Kalugin I, Daryin A, Smolyaninova L, Andreev A, Diekmann B, Khlystov O (2007) 800-yr-long records of annual air temperature and precipitation over southern Siberia inferred from Teletskoye Lake sediments. Quatern Int 67:400–410

King A, Eckersley R (2019) Statistics for biomedical engineers and scientists: how to visualize and analyze data. Academic Press, Cambridge

Krammer K, Lange-Bertalot H (1986–1991) Bacillariophyceae. Süsswasserflora von Mitteleuropa, 2/1–2/4. G. Fischer Verlag, Stuttgart

Kylander M, Ampel L, Wohlfarth B, Veres D (2011) High-resolution X-ray fluorescence core scanning analysis of Les Echets (France) sedimentary sequence: new insights from chemical proxies. J Quat Sci 26:109–117

Lamb HF, Eicher U, Switsur VR (1989) An 18,000-Year record of vegetation, lake-level and climatic change from Tigalmamine, Middle Atlas, Morocco. J Biogeogr 16(1):65–74

Lamb HF, Roberts N, Leng M, Barker PH, Benkaddour A, Van Der Kaars S (1999) Lake evolution in a semi-arid mountain environment: response to catchment change and hydroclimatic variation. J Paleolimnol 21(3):325–343

Lamb HF, van der Kaars S (1995) Vegetational response to Holocene climatic change: pollen and palaeolimnological data from the Middle Atlas, Morocco. The Holocene 5(4):400–408

Macklin MG, Benito G, Gregory KJ, Johnstone E, Lewin J, Michczyñska DJ, Soja R, Starkel L, Thorndycraft VR (2006) Past hydrological events reflected in the Holocene fluvial record of Europe. Catena 66:145–154

Magny M (1992) Sédimentation et dynamique de comblement dans les lacs du jura au cours des 15 derniers millénaires. Revue d'Archéométrie 16:27–49

Magny M (2004) Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quat Int 113:65–79

Mann ME, Zhang Z, Rutherford S, Bradley RS, Hughes MK, Shindell D, Ammann C, Faluvegi G, Ni F (2009) Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. Science 326:1256–1260

Marciniak B (1986) Late glacial Fragilaria flora from lake sediments of the Tatra Mts. and the Alps. In: Round FE (1988) Proceedings of the Ninth International Diatom Symposium: Bristol, August 24–30, 1986. Biopress Limited pp 233–243

Marcott SA, Shakun JD, Clark PU, Mix AC (2013) A reconstruction of regional and global temperature for the past 11,300 years. Science 339:1198–1201

Martin J (1981) Le Moyen Atlas Central: étude géomorphologique. Notes et Mémoires du Service Géologique du Maroc, Rabat: Editions du service géologique du Maroc, No. 258 bis, 1–447

Martín-Puertas C, Valero-Garcés BL, Brauer A, Mata MP, Delgado-Huertas A, Dulski P (2009) The Iberian–Roman humid period (2600–1600 cal yr BP) in the Zoñar Lake varve record (Andalucía, southern Spain). Quat Res 71:108–120

Martín-Puertas C, Valero-Garcés BL, Mata MP, González-Sampériz P, Bao R, Moreno A, Stefanova V (2008) Arid and humid phases in southern Spain during the last 4000 years: the Zoñar Lake record, Cordoba. Holocene 18(6):907–921

Martín-Puertas C, Valero-Garcés BL, Mata MP, Moreno A, Giralt S, Martínez-Ruiz F, Jiménez-Espejo F (2011) Geochemical processes in a Mediterranean Lake: a high-resolution study of the last 4,000 years in Zonar Lake, southern Spain. J Paleolimnol 46(3):405–421

McKenzie JA (1985) Carbon isotopes and productivity in the lacustrine and marine Environment. In: Stumm W (ed) Chemical processes in lakes. Wiley, New York, pp 99–118

Meisch C (2000) Freshwater Ostracoda of western and central Europe. Spektrum Akademischer Verlag, Heidelberg, p 522

Morellón M, Valero-Garcés BL, Moreno A, González-Sampériz P, Mata P, Romero O, Maestro M, Navas A (2008) Holocene palaeohydrology and climate variability in Northeastern Spain: the sedimentary record of lake Estanya (Pre-Pyrenean range). Quatern Int 181:15–31

Moreno A, Pérez A, Frigola J, Nieto-Moreno V, Rodrigo-Gámiz M, Martrat B, González-Sampériz P, Morellón M, Martín-Puertas C, Corella JP, Belmonte Á, Sancho C, Cacho I, Herrera G, Canals M, Grimalt JO, Jiménez-Espejo F, Martínez-Ruiz F, Vegas-Vilarrúbia T, Valero-Garcés BL (2012) The Medieval climate anomaly in the Iberian Peninsula reconstructed from marine and lake records. Quat Sci Rev 43:16–32

Nour El Bait M, Rhoujjati A, Benkaddour A, Carré M, Eynaud F, Martinez P, Cheddadi R (2016) Climate change and ecosystems dynamics over the last 6000 years in the Middle Atlas, Morocco. Clim Past 12:1029–1042

Nour El Bait M, Rhoujjati A, Eynaud F, Benkaddour A, Dezileau L, Wainer K, Goslar T, Khater C, Tabel J, Cheddadi R (2014) An 18 000-year pollen and sedimentary record from the cedar forests of the Middle Atlas, Morocco. J Quat Sci 29(5):423–432

Olsen J, Anderson JN, Knudsen MF (2012) Variability of the North Atlantic Oscillation over the past 5200 years. Nat Geosci 5:808–812

Reille M (1976) Analyse pollinique de sédiments postglaciaires dans le Moyen-Atlas et le Haut- Atlas marocains: premiers résultats. Ecol Mediterr 2:153–170

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté

UNCORRECTED PROOF

Journal : Medium 10933 | Dispatch : 18-1-2021 | Pages : 19
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MS Code : JOPL-D-19-00075R2 | ☑ CP | ☑ DISK

Author Proof

C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887

Rhoujjati A, Cheddadi R, Taieb M, Baali A, Ortu E (2010) Past environmental changes during the last 25,000 years in the Middle Atlas (Morroco): A record from lake Ifrah. J Arid Environ 74(7):737–745

Rhoujjati A, Nourelbait M, Benkaddour A, Damnati B, Baali A, Taieb M, Decobert M, Malek F, Cheddadi R (2012) Palaeoenvironmental context inferred from Holocene deposits of lake Iffer (Middle Atlas, Morocco). Quaternaire 23(3):241–252

Roberts N, Jones MD, Benkaddour A, Eastwood WJ, Filippi ML, Frogley MR, Lamb HF, Leng MJ, Reed JM, Stein M, Stevens L, Valero-Garces B, Zanchetta G (2008) Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis. Quat Sci Rev 27:2426–2441

Saadi M, Maroc. Direction des mines et de la géologie, et Maroc. Service géologique (1982) Carte structurale du Maroc. Service géologique du Maroc

Santos L, Vidal Romani JR, Jalut G (2000) History of vegetation during the Holocene in the Courel and Queixa Sierras, Galicia, Northwest Iberian Peninsula. J Quat Sci 15:621–632

Sayad A, Chakiri S (2010) Impact de l'évolution du climat sur le niveau de Dayet Aoua dans le Moyen Atlas marocain. Science et changements planétaires/Sécheresse 21(4):245–251

Sayad A, Chakiri S, Martin C, Bejjaji Z, Echarfaoui H (2011) Effet des conditions climatiques sur le niveau du lac Sidi Ali (Moyen Atlas, Maroc). Physio-Géo Géographie physique et environnement, (Volume 5), 251–268

Solomon S, Plattner G, Knutti R, Friedlingsteind P (2009) Irreversible climate change due to carbon dioxide emissions. P Nalt A Sci 106(6):1704–1709

Soulié-Märsche I, Benkaddour A, El Khiati N, Gemayel P, Ramdani M (2008) Charophytes, indicateurs de paléobathymétrie du lac Tigalmamine (Moyen Atlas, Maroc). Geobios 41:435–444

Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. Pollen Spore 13:615–621

Stuiver M (1970) Oxygen and carbon isotope ratios of freshwater carbonates as climatic indicators. J Geophys Res 75:5247–5257

Tabel J, Khater C, Rhoujjati A, Dezileau L, Bouimetarhan I, Carre M, Vidal L, Benkaddour A, Nourelbait M, Cheddadi R (2016) Environmental changes over the past 25000 years in the southern Middle Atlas, Morocco. J Quat Sci 31(2):93–102

Thió-Henestrosa S, Martín-Fernández JA (2006) Detailed guide to CoDaPack: a freeware compositional software. Compositional Compositional data analysis in the geosciences: from theory to practice, Buccianti A, Mateu-Figueras G, Pawlowsky-Glahn V (eds) Geol Soc Spec Publ, London 264(1): pp 101–118

Valero-Garcés BL (ed) (2003) Limnogeologia en España: Un Tributoa Kerry Kelts (Vol. 14). Editorial CSIC-CSIC Press

Valero-Garcés BL, Navas A, Machin J, Stevenson T, Davis B (2000) Responses of a saline lake ecosystem in a semiarid region to irrigation and climate variability: the history of Salada Chiprana, Central Ebro Basin, Spain. Ambio, 344–350

Van Geel B (2002) Non-pollen palynomorphs. In: Smol JD, Birks JB, Last WM (eds) Tracking environmental change using lake sediments, vol 3. Terrestrial, algal, and siliceous indicatorsKluwer, Dordrecht, pp 99–119

Vidal L, Rhoujjati A, Adallal R, Jouve G, Bard E, Benkaddour A, Chapron E, Courp T, Dezileau L, Garcia M, Hebert B, Simmoneau A, Sonzogni C, Sylvestre F, Tachikawa K, ValletCoulomb C, Viry E (2016) Past hydrological variability in the Moroccan Middle Atlas inferred from lakes and lacustrine sediments. In: Sabrié M-L, Gibert-Brunet E, Mourier T (eds) The Mediterranean Region under climate change. IRD, AllEnvi, pp 57–69

Wassenburg JA, Immenhauser A, Richter DK, Niedermayr A, Riechelmann S, Fietzke J, Scholz D, Jochum KP, Fohlmeister J, Schröder-Ritzrau A, Sabaoui A (2013) Moroccan speleothem and tree ring records suggest a variable positive state of the North Atlantic Oscillation during the Medieval warm period. Earth Planet Sci Lett 375:291–302

Wei T, Simko V, Levy M, Xie Y, Jin Y, Zemla J (2017) Package 'corrplot'. Statistician 56:316–324

Weltje GJ, Bloemsma MR, Tjallingii R, Heslop D, Röhl U, Croudace IW (2015) Prediction of geochemical composition from XRF core scanner data: a new multivariate approach including automatic selection of calibration samples and quantification of uncertainties. In: Croudace IW, Rothwell RG (eds) Micro XRF Studies of sediment cores (DPER 17). Springer, Dordrecht, pp 507–534

Williams JJ, Gosling WD, Coe AL, Brooks SJ, Gulliver P (2011) Four thousand years of environmental change and human activity in the Cochabamba Basin, Bolivia. Quat Res 76:58–68

Xia J, Ito E, Engstrom DR (1997) Geochemistry of ostracode calcite: Part 1. An experimental determination of oxygen isotope fractionation. Geochim Cosmochim Ac 61(2):377–382

Zielhofer C, Fletcher WJ, Mischke S, Batist M, De Campbell JFE, Joannin S, Tjallingii R, El Hamouti N, Junginger A, Stele A, Bussmann J, Schneider B, Lauer T, Spitzer K, Strupler M, Brachert T, Mikdad A (2017) Atlantic forcing of Western Mediterranean winter rain minima during the last 12,000 years. Quaternary Sci Rev 157:29–51

Zolitschka B (2007) Varved lake sediments. In: Elias SA (ed) Encyclopedia of quaternary science. Elsevier, Amsterdam, pp 3105–3114

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