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Palaeohydrological changes recorded from a small Moroccan Middle Atlas pond during the last 6000 cal. yr BP: a multi-proxy study

Hanane Id Abdellah, Laurence Vidal, Abdelfattah Benkaddour, Ali Rhoujjati, Guillaume Jouve, Tachikawa Kazuyo, Corinne Sonzogni, Florence Sylvestre, Christine Paillès, Jean-Charles Mazure

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Abstract	<p>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 ¹⁴C 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.</p>
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Keywords (separated by '-')	Middle Atlas - Palaeohydrology - Mid- to Late-Holocene - Lacustrine sediment - Climatic changes
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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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3 **Moroccan Middle Atlas pond during the last 6000 cal. yr**
4 **BP: a multi-proxy study**

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6 **Ali Rhoujjati · Guillaume Jouve · Kazuyo Tachikawa · Corinne Sonzogni ·**
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56 **Keywords** Middle Atlas · Palaeohydrology · Mid- to
 57 Late-Holocene · Lacustrine sediment · Climatic
 58 changes

59 Introduction

60 The Mediterranean basin is one of the most sensitive
 61 areas to climate fluctuations (Giorgi 2006). Future
 62 climate change projections highlight the exposure of
 63 the Western Mediterranean region to increased heat
 64 and drought stress (Solomon et al. 2009; Born et al.
 65 2010). The Middle Atlas region is considered to be the
 66 main water reservoir of Morocco. This region is host to
 67 a variety of perennial and semi-permanent wetlands
 68 including natural lakes, rivers and springs. These
 69 water resources are relied upon to meet the agricultural
 70 and domestic needs of the region. During recent
 71 decades, numerous lakes of the karstified Middle Atlas
 72 region experienced a significant water deficit as a
 73 result of recurrent droughts and human overexploita-
 74 tion, including: Dayet Aoua (Sayad and Chakiri 2010),
 75 Aguelmam Sidi Ali (Sayad et al. 2011), Ifrah Lake
 76 (Etebaai et al. 2012) and Aguelmam Azigza (Adallal
 77 et al. 2019). Examining the past history of lakes in the
 78 Middle Atlas region can elucidate the prospective

79 impacts of combined climate change and anthro-
 80 pogenic activity on the hydrological behavior of these
 81 lacustrine systems.

82 Lake sediments have the potential to allow inves-
 83 tigation of temporal paleohydrological trends under
 84 various environmental conditions. Lacustrine
 85 sequences from Middle Atlas wetlands are ideally
 86 suited to understanding the response of Mediterranean
 87 semi-arid environments and hydrosystems to climatic
 88 changes because of the small size of their basins, and
 89 because their evolution and sedimentation are directly
 90 influenced by regional hydrologic changes (Lamb and
 91 van der Kaars 1995). Pioneering paleoenvironmental
 92 investigations have demonstrated the high potential of
 93 Middle Atlas lake sediments as archives of climate
 94 variability (Martin 1981; Lamb et al. 1989). The
 95 number of available paleoclimatic and paleoenviron-
 96 mental reconstructions conducted on lacustrine
 97 sequences from the region has greatly increased in
 98 the last few decades. Most of these records cover the
 99 last glacial period (Rhoujjati et al. 2010; Nour El Bait
 100 et al. 2014; Tabel et al. 2016) and the early Holocene
 101 (Barker et al. 1994; Cheddadi et al. 1998; Lamb and
 102 van der Kaars 1995; Campbell et al. 2017; Zielhofer
 103 et al. 2017). The last few millennia are particularly
 104 interesting owing to the fact that the main boundary
 105 conditions were similar to present-day climate con-
 106 figurations and detailed regional palaeoclimatic recon-
 107 structions can be compared to current climate change
 108 processes (Corella et al. 2011; Brisset et al. 2019).
 109 However, records spanning the Mid-Late Holocene
 110 period are rather scarce in the Middle Atlas region
 111 (Damnati et al. 2015; Nour El Bait et al. 2016). Nour
 112 El Bait et al. (2016) demonstrated that climate has
 113 remained relatively stable over the last 6000 cal. yr BP
 114 with a trend of aridity and warming towards the
 115 present. Results obtained from lacustrine terraces at
 116 three Middle Atlas lakes indicate high lake levels at
 117 about 2300 cal BP followed by a significant drop in
 118 lake level during the last millennium (Damnati et al.
 119 2015).

120 Most of the paleoclimate and environmental recon-
 121 structions in the Middle Atlas are based on fossil
 122 pollen assemblages from lake sediments. These stud-
 123 ies revealed a common pattern: the limited presence of
 124 *Cedrus atlantica* Manetti pollen in the early Holocene,
 125 with the general expansion of the species from the
 126 Mid-Holocene which has been interpreted primarily as
 127 evidence of increased moisture availability (Lamb

128 et al. 1989; Cheddadi et al. 1998, 2015, 2019; Rhou-
129 jjati et al. 2010; Nour El Bait et al. 2014; Tabel et al.
130 2016; Campbell et al. 2017). However, a recent study
131 demonstrated a Mid-to Late Holocene summer aridity
132 in the Middle Atlas using stable carbon isotope
133 analysis of isolated fossil *Cedrus* pollen (Bell et al.
134 2019). Furthermore, several studies detected a Mid-
135 Late Holocene aridification trend from ecological or
136 hydrological records in the western Mediterranean
137 (Jalut et al. 2009; Carrión et al. 2010; Jiménez-Moreno
138 et al. 2015).

139 In order to strengthen paleolimnological interpre-
140 tations inferred from a single proxy it is important to
141 combine as many records as possible in a technique
142 known as a multi-proxy approach (Bradley 2015).
143 Some investigations have reconstructed lake paleohy-
144 drology in the Middle Atlas region using multi-proxy
145 analysis of lacustrine terraces (Damnati et al. 2015)
146 and of continuous sedimentary records (Nour El Bait
147 et al. 2014; Zielhofer et al. 2017). For example, in
148 Aguelmam Sidi Ali, Zielhofer et al. (2017) recon-
149 structed the Western Mediterranean hydro-climatic
150 variability, seasonality and forcing mechanisms dur-
151 ing the last 12,000 year using a multi-proxy approach
152 based on magnetic susceptibility, carbonate and total
153 organic carbon content, core-scanning and quantita-
154 tive XRF, stable isotopes of ostracod shells, charcoal
155 counts, *Cedrus* pollen abundance, and diatom data.
156 Only a few records span the Late Holocene period and
157 more investigations and a regional review of the
158 available lake records are needed. This would enable
159 details of the contrasting spatial and temporal hydro-
160 dynamics of Middle Atlas lakes in response to climate-
161 related variability to be verified.

162 Here we present continuous and high-resolution
163 records of a sedimentary sequence recovered from
164 “Flowers Marsh” (unofficial name), a karstic water-
165 body in the SW Middle Atlas, northern Morocco. The
166 approach is based on radiometric techniques for
167 dating, sediment geochemistry using XRF, sediment
168 mineralogy using DRX, as well as biological indica-
169 tors, including diatoms, coprophilous fungi spores,
170 and ostracods. The overall aim of this paper is to
171 provide a reconstruction of Flowers Marsh develop-
172 ment in response to catchment changes and to regional
173 climatic events during the Mid- to Late Holocene.
174 Specifically, we will address the following questions:
175 (1) what was the hydrological behavior of Flowers
176 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 Palaeo-
zoic to Quaternary and is dominated mainly by
Triassic red beds covered by karstified Liassic lime-
stones 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 (Chi-
lasse et al. 2001). Evergreen oak (*Quercus rotundifo-
lia*) 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 hydro-
phytes 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

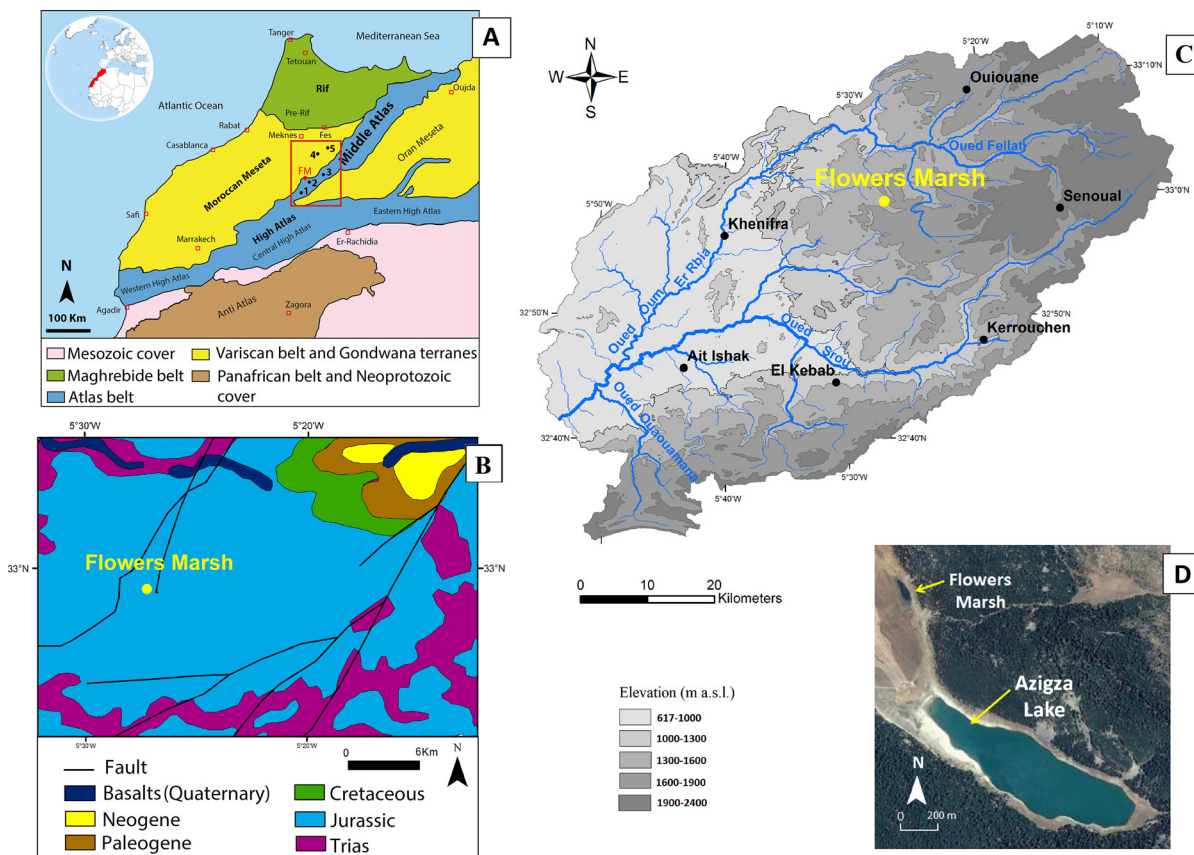


Fig. 1 Location of the studied area. A: Simplified map showing the major geological provinces of Morocco. (modified from Saadi 1982) and the location of the study site (FM) and other paleoclimate studies cited in the text: 1, Ait Ichou Marsh (Tabel et al. 2016); 2, Lake Tigalmamine (Cheddadi et al. 1998; 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 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

224 fluctuations especially precipitation (Vidal et al. 2016;
 225 Adalall et al. 2019). From observations of paleoshore-
 226 lines in the catchment (Flower and Foster 1992) and
 227 past hydrological reconstructions (Jouve et al. 2019),
 228 previous studies inferred that significant variations
 229 have occurred in the level of Aguelmam Azigza. High
 230 resolution Digital Elevation Models (DEM) from
 231 Aguelmam Azigza watershed indicate that lake levels
 232 need to be 10–15 m above modern levels for the two
 233 waterbodies to be connected. Arial photographs from
 234 1964 suggest that this connection has happened in the
 235 past (Jouve et al. 2019).
 236

Materials and methods

237

The studied cores were recovered in 2016 from
 238 Flowers Marsh using a 50-cm-long Russian corer.
 239 Two lake-marginal cores were taken: AZA-SUP-1-A-
 240 16 and AZA-SUP-1-16. The length of each sequence
 241 is 300 cm and 250 cm, respectively. Sediment core
 242 stratigraphy was described on-site. The core segments
 243 were wrapped in Clingfilm and stored in a cold storage
 244 room at 4 °C. The two cores show a good visual
 245 agreement and a very similar lithologic and chemical
 246 succession (ESM1). Only the long core AZA-SUP-1-
 247 A-16 was selected for this study.
 248

In total, 21 subsamples were recovered at 15-cm
 249 intervals for particle size analysis. Subsammles were
 250

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):

$$\text{CaCO}_3(\%) = (\text{TC} - \text{TOC}) \times 8.33$$

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 *Illyocypris 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 Pee Dee Belemnite (VPDB) standard. Analytical precision of δ¹⁸O and δ¹³C 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

348 presence of diatoms. Only 9 samples contained
349 abundant diatoms. Wet sediment samples were treated
350 using H₂O₂ (33%) and HCl (10%) in order to remove
351 organic matter and carbonates respectively. Slides
352 were mounted in Naphrax and observed with an
353 optical microscope (Nikon 80i 1000 × magnification
354 with Nomarski optics, n.a.= 1.32). Taxonomic iden-
355 tification and assignment of planktonic and benthic
356 habitats were based primarily on Krammer and Lange-
357 Bertalot (1986–1991) and Marciniak (1986).

358 Eight samples throughout the core were examined
359 for coprophilous fungal spore abundances and treated
360 according to Fægri and Iversen (1989) at CEREGE.
361 *Lycopodium clavatum* tablets were added to each
362 sample allowing determination of spore concentra-
363 tions (Stockmarr 1971). Coprophilous fungi spores
364 were identified according to the van Geel classification
365 (2002). Identification was limited to the most abundant
366 species: *Delitschia*-type, *Sordaria*-type, *Tripteros-
367 pora*-type, UG-1138-type and focusing on *Sporor-
368 miella*-type. The latter is an ascomycete fungus used
369 as a specific indicator of herbivore presence (Davis
370 and Schafer 2006; Cugny et al. 2010). Results are
371 expressed as concentrations (spores cm⁻³).

372 The chronology of the lake core was constrained by
373 9 Accelerator Mass Spectrometry (AMS) radiocarbon
374 analyses performed on organic bulk sediments at Beta
375 Analytic Inc laboratory, Florida, USA. Over the
376 300 cm sequence, the age-depth relationship was
377 constructed by linear interpolation of calibrated
378 radiocarbon dates using the classical age modeling
379 code (CLAM) for the statistical software R developed
380 by Blaauw (2010), which also performs the calibration
381 (using the SHCal13.14C, Reimer et al. 2013).

382 Multivariate statistical analyses were applied to the
383 high resolution XRF dataset in order to extract and
384 assess elemental correlations downcore. First, to
385 attenuate non-linear matrix effects and constant sum
386 constraints, the multivariate statistical analysis was
387 applied after centered log-ratio (clr) transformation
388 (Aitchison 1982; Weltje et al. 2015) of the complete
389 set of XRF measurements (n = 5684). This simple
390 transformation provides a reliable basis for statistical
391 analysis of XRF core scanning data, unlike element
392 count intensities or element ratios (Weltje et al. 2015).
393 The following elements were considered for statistical
394 analysis: Si, K, Fe, Ca, Ti, Mn, Sr and inc/coh. The Br
395 was excluded because it frequently presents null
396 values and dealing with clr transformation excludes

397 dealing with zeros. The clr transformation was carried
398 out using CoDaPack, a freely available Excel based
399 software for compositional data transformation (Thió-
400 Henestrosa and Martín-Fernández 2006). As a second
401 step, a normality assumption test was first applied
402 using the Shapiro–Wilk test (Ghasemi and Zahediasl
403 2012) in order to determine the type of correlation
404 analysis to be used. Spearman’s rank correlation
405 coefficient was then performed as a non-parametric
406 measure of correlation between the monitored vari-
407 ables (King and Eckersley, 2019) in order to quantify
408 the strength of correlation between elements within
409 each lithological unit. The correlation matrix was
410 visualized as a heatmap with a dendrogram calculated
411 by hierarchical clustering analysis (HCA) using the
412 “heatmap” function implemented in the R package
413 corrplot (Wei et al. 2017). The “rcorr” function in the
414 Hmisc package (Harrell et al. 2006) was used to
415 compute the significance levels for the Spearman
416 correlations. Correlations with a *p*-value < 0.05 were
417 considered significant.

418 Results

419 Chronological model

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

433 Lithology and mineralogical contents

434 Four sedimentary units were defined on the basis of
435 variations in described sediment lithology and micro-
436 scopic observation (Fig. 3). The basal A unit (bottom-
437 180 cm) comprises massive minerogenic sediments
438 with a compact, gray-to-light-reddish, clayey-silt
439 facies with poor preservation of biologic indicators

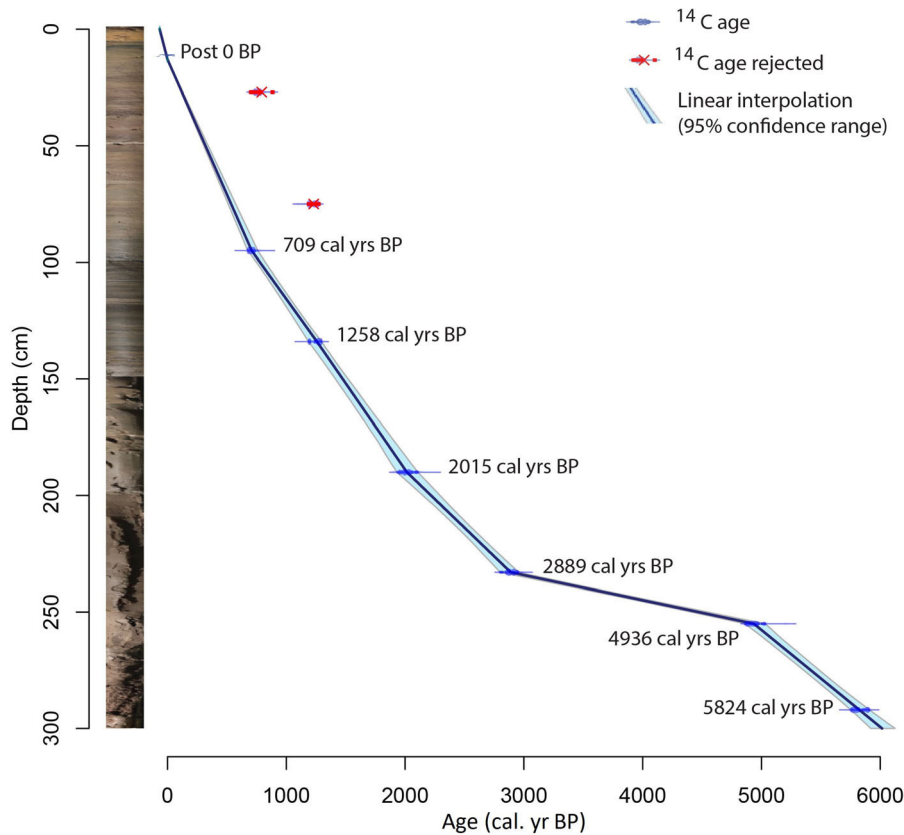


Fig. 2 Chronological model of Flowers Marsh core (AZA-SUP-1-A-16) based on a linear interpolation of calibrated radiocarbon dates

440 and eroded pollen. The sediment of this unit has the
 441 highest proportion of siliciclastic minerals (quartz,
 442 phyllosilicates, goethite), and the lowest proportion of
 443 calcite (Fig. 3). Unit B (between 180 and 150 cm)
 444 represents a transitional interval between the predom-
 445 inantly massive lower unit A and the upper laminated
 446 unit C. This unit B is characterized by a high
 447 proportion of siliciclastic minerals (quartz) and a
 448 gradual increase in carbonate content (Fig. 3). It is
 449 also characterized by well-preserved or fragmented
 450 ostracod shells, gastropods and charophytes. Unit C
 451 (150–90 cm) is formed of massive to faintly-lami-
 452 nated, black to dark-gray, organic-rich facies with
 453 abundant diatoms. It shows a marked up-core increase
 454 in carbonate content. XRD results clearly indicate that
 455 calcite is the dominant carbonate mineral (Fig. 3).
 456 Finally, unit D (the upper 90 cm) is dominated by
 457 laminated brown sediment. It is characterized by high
 458 calcite content and the recurrence of ostracod shells.
 459 Dark laminated facies with abundant diatoms, similar
 460 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 predom-
 inantly 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 “cauliflow-
 ers” 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
 CaCO₃ 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 crys-
 tals is irregular having “cauliflower” shapes and

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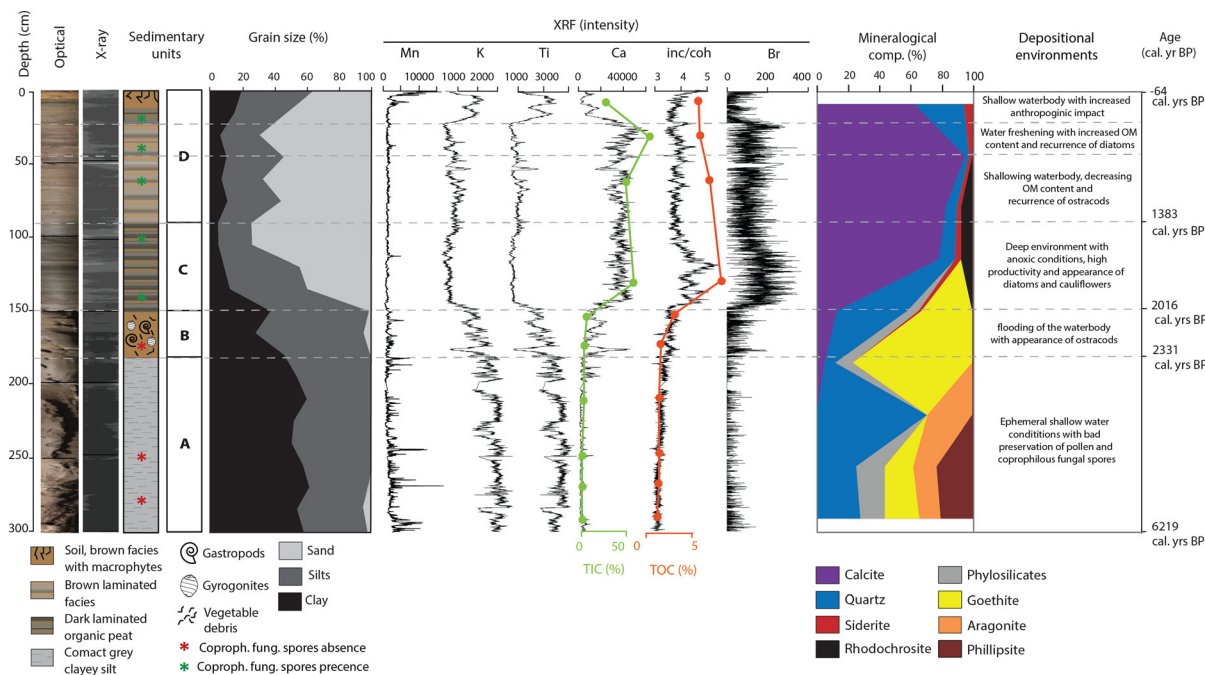


Fig. 3 Physical and lithological properties of Flowers Marsh core sediment. From left to right: Core image, X-ray radiography, schematic lithology, sedimentary units, grain size distribution (clay, silt and sand), X-ray Fluorescence (XRF) core scanner data expressed as intensity (Mn, K, Ti), Ca-XRF and

Total Inorganic Carbon (TIC), inc/coh, Total Organic Carbon (TOC) and Br, mineralogical composition, reconstructed depositional environments and chronological scale (in cal. years BP)

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

488 Geochemistry

489 *Elemental geochemistry*

490 The main chemical elements and ratios selected for
491 this study are the following: K, Si, Ti, Fe, Ca, Br,
492 inc/coh, Ca/Ti and Br/Ti. Downcore elemental profiles
493 are clearly consistent with the facies distribution
494 (Figs. 3 and 4, ESM4). Si, K, Ti and Fe show
495 comparatively higher values in clastic-dominated
496 intervals in unit A and reveal a decrease in unit B
497 with lower values in units C and D. The top of unit D
498 shows an increase in the elements. Calcium displays
499 an opposite trend, reaching maximum values in the
500 carbonate-rich facies of units C and D. The inc/coh
501 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 consid-
erable 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 -

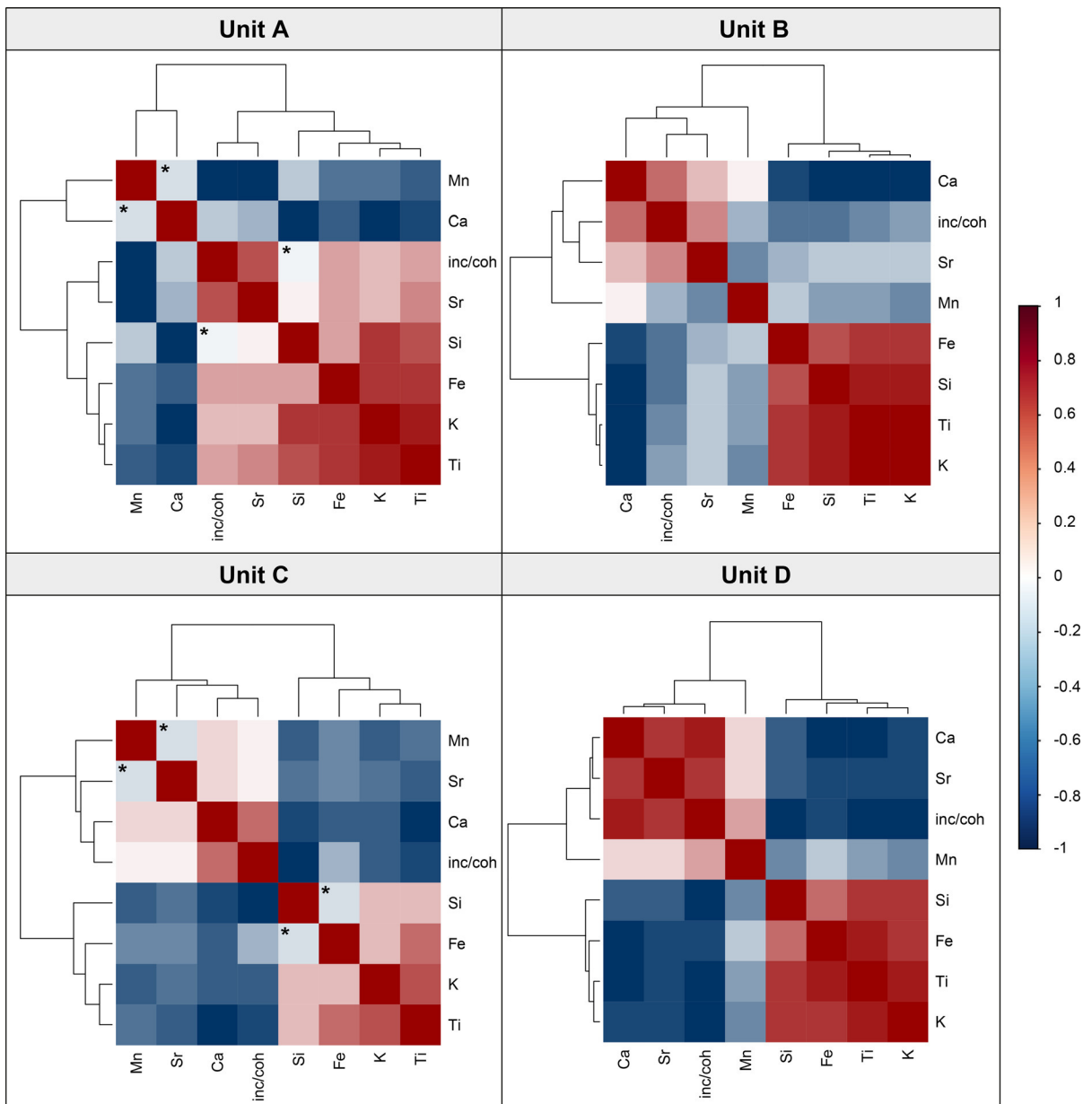


Fig. 4 Spearman correlation matrix and hierarchical clustering of the main XRF elements for the four lithological units (A, B, C and D). Red colors indicate positive correlations and blue colors indicate negative correlations. The color gradient indicates the

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)

525 value < 0.0001 ; $n = 600$) and a very low correlation
 526 in unit A ($r = -0.09$; p -value < 0.0001 ; $n = 2170$).
 527 The Mn does not show any correlation with other
 528 elements and likely reflects changes in redox condi-
 529 tions. Generally, the HCA dendrogram shows two
 530 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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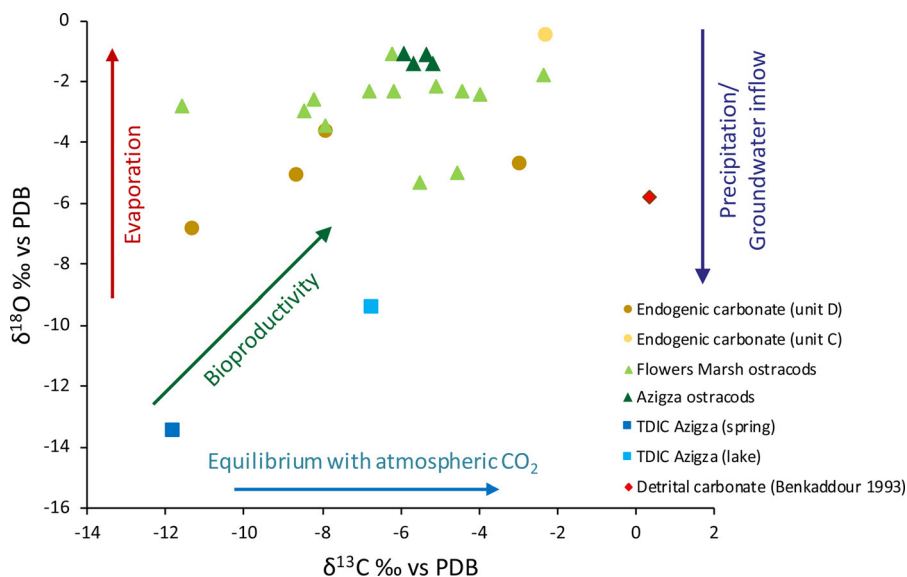


Fig. 5 Crossplot of $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ for the studied endogenic and biogenic carbonates (ostracods) from Flowers Marsh, modern ostracods and TDIC from Aguelmam Azigza and

published isotope composition of detrital carbonate obtained from the study area (Benkaddour 1993)

537

538 *Organic geochemistry*

539 The TOC values of the Flowers Marsh sequence range
540 from 1% to 8% (Fig. 3). The organic content of units A
541 and B is relatively low and constant (oscillating
542 around 1%), increasing in the top of unit B (3.1%) and
543 reaching maximum values of 8.3% in the lower part of
544 unit C. The TOC remains relatively high in unit D
545 (values range between 5 and 7%) with a decreasing
546 trend towards the core top. The inc/coh ratio shows a
547 similar trend to TOC, suggesting it is a reliable proxy
548 for organic content in this system. Similarly, TIC
549 values show a general trend towards increasing values
550 from the bottom (unit A and B) to the top of the core
551 (unit C and D). The highest concentrations of up to
552 75% occur at 32 cm and the lowest (0.5%) at the base
553 of the core.

554 *Biological proxies*

555 The occurrence of ostracod shells is limited to the
556 upper 166 cm of the Flowers Marsh sequence (166–
557 143 cm and 25–79 cm); no shells were found in units
558 A and B. When ostracods were observed, *Candona*

neglecta and *Illyocypris gibba* were the most abundant 559 species. 560

Diatom content is low throughout most of the 561 record, and diatom remains are poorly 382 preserved. 562 Diatoms present a sharp contrast with the abundance 563 of ostracods. Units A and B were sterile in regards to 564 diatoms. Unit C (150–90 cm) is dominated by 565 epiphytic species such as *Epithemia adnata* (Kützing), 566 *Sellaphora laevisissima* (Kützing) and *Gomphonema* 567 *pumilum* (Grunow) and by benthic species represented 568 mainly by *Halamphora veneta* (Kützing) and *Coc-* 569 *coneis placentula* (Ehrenberg) (ESM5). In the upper 570 90 cm, the diatom assemblage is still dominated by 571 benthic forms, except at 47–48 and 38–39 cm where 572 the centric *Cyclotella distinguenda* (Hustedt) domi- 573 nates the assemblage (ESM5). 574

The occurrence of coprophilous fungi species and 575 spore concentration throughout the core were exam- 576 ined. The lowest units A and B (280, 250 and 174 cm) 577 present low concentrations and poor preservation of 578 coprophilous fungi spores. The boundary between 579 units B and C (141 cm) is characterized by an increase 580 in values of coprophilous fungi spores with a better 581 preservation and high abundances of the UG-1138 582 species. In unit C (101 cm), continuation of the high 583 values of UG-1138 is recorded. The exclusive occur- 584 rence and high values of *Tripterospora*-type and a 585

586	decrease in UG-1138 values occur in unit D (39 cm).	proposed in order to demonstrate the local hydrologi-	630
587	The topmost part of this unit (19 cm) is characterized	cal differences and the common patterns in response	631
588	by the highest values of <i>Sporormiella</i> -type and a	to regional climatic drivers.	632
589	relatively high abundance of <i>Delitschia</i> -type.		
590	$\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of Flowers Marsh carbonates	Flowers Marsh hydrological development	633
		during the last 6000 years	634
591	The oxygen isotopic composition values of biogenic	Four main phases were distinguished following the	635
592	carbonates derived from the benthic ostracod species	lithologic units, the geochemical zonation derived	636
593	<i>C. neglecta</i> were in the range -5.34 to -1.09% .	from the $\mu\text{-XRF}$ data, the mineralogy and the recur-	637
594	These values are in agreement with ostracod $\delta^{18}\text{O}$	rence of biomarkers (Fig. 4): (A) ephemeral water-	638
595	records measured on the same species in the larger	body, (B) flooding and permanent shallow water	639
596	lake Aguelmam Azigza (this study) and with records	conditions, (C) medium to deep waterbody and	640
597	carried out on modern ostracods from Lake Tigel-	(D) shallow water level.	641
598	mamine (Benkaddour et al. 2005). The $\delta^{18}\text{O}$ of		
599	ostracods is mostly affected by the isotopic composi-	<i>Unit A—Ephemeral waterbody (6–2.3 cal. kyr BP)</i>	642
600	tion of lake water and water temperature at the time of		
601	its formation (Xia et al. 1997). In semi-arid, closed	The oldest sediments present in the Flowers Marsh	643
602	small lake settings, ostracod $\delta^{18}\text{O}$ reflects primarily	sequence are characterized by a high intensity of Ti, K,	644
603	the local hydrologic balance (Roberts et al. 2008;	Si which are grouped together with Sr and Fe (Fig. 5).	645
604	Develle et al. 2010).	These detrital elemental intensities may mostly track	646
605	Figure 6 displays the relationship between $\delta^{13}\text{C}$ and	high clay and phyllosilicate contents that are deposited	647
606	$\delta^{18}\text{O}$ for all of the carbonate species analyzed in this	during heavy rainfall and thus be related to a relatively	648
607	study. The $\delta^{13}\text{C}$ in the studied samples of endogenic	high lake level, or they may correspond to evidence of	649
608	carbonates from Flowers Marsh sediments vary consid-	arid conditions and thus be related to lake desiccation.	650
609	erably and range from -11.3 to -2.3% VPDB,	However, the highly clastic nature of unit A made up	651
610	whereas $\delta^{18}\text{O}$ of the same samples range from -6.8 to	of clay minerals, phyllosilicates and quartz particles	652
611	-0.5% VPDB. The dominant controls on the $\delta^{18}\text{O}$ of	(as determined by XRD and microscope observations)	653
612	lacustrine endogenic carbonates is controlled are the	with a very low sedimentation rate suggests that the	654
613	temperature of its formation and the isotopic composi-	sediments were originally deposited in a shallow,	655
614	tion of the water in which it precipitates (Epstein	littoral lacustrine setting. Furthermore, the minimum	656
615	et al. 1953; Craig 1965). The ^{13}C content of lacustrine	carbonate values (TIC, DRX calcite and Ca intensi-	657
616	carbonates mainly reflects the composition of the	ties) point to an absence of dissolved calcite from	658
617	TDIC in the lake water and the effects of biological	surrounding rocks, as a consequence of CO_2 -poor	659
618	fractionation related to aquatic photosynthesis (Stu-	groundwater associated with weakly developed soil	660
619	iver 1970; McKenzie 1985).	and vegetation and/or to low detrital carbonate input as	661
		a consequence of decreased runoff. The complete	662
620	Discussion	absence of biological fauna with non-preservation of	663
		coprophilous fungi spores and eroded pollen also	664
621	Paleoenvironmental interpretation of the deposited	supports oxic conditions typical of a shallow environ-	665
622	sediments requires an accurate understanding of the	ment with frequent periods of subaerial exposure	666
623	proxy significance. In the following, different proxies	(González-Sampéris et al. 2008). The low accumula-	667
624	are discussed to provide a reliable paleohydrological	tion of organic matter (extremely low TOC content)	668
625	reconstruction of Flowers Marsh. A possible connec-	may indicate a barren landscape with sparse vegeta-	669
626	tion with Aguelmam Azigza hydrological behavior is	tion and low productivity in the waterbody (low Br/	670
627	discussed so as to understand the hydrological func-	Ti). The absence of endogenic calcite (low Ca/Ti)	671
628	tioning of these hydrosystems at the catchment scale.	indicates that conditions were not adequate for endo-	672
629	Finally, comparisons between the regional records are	genic calcite precipitation and/or preservation in the	673
		sediments. In addition, the relatively high Mn contents	674

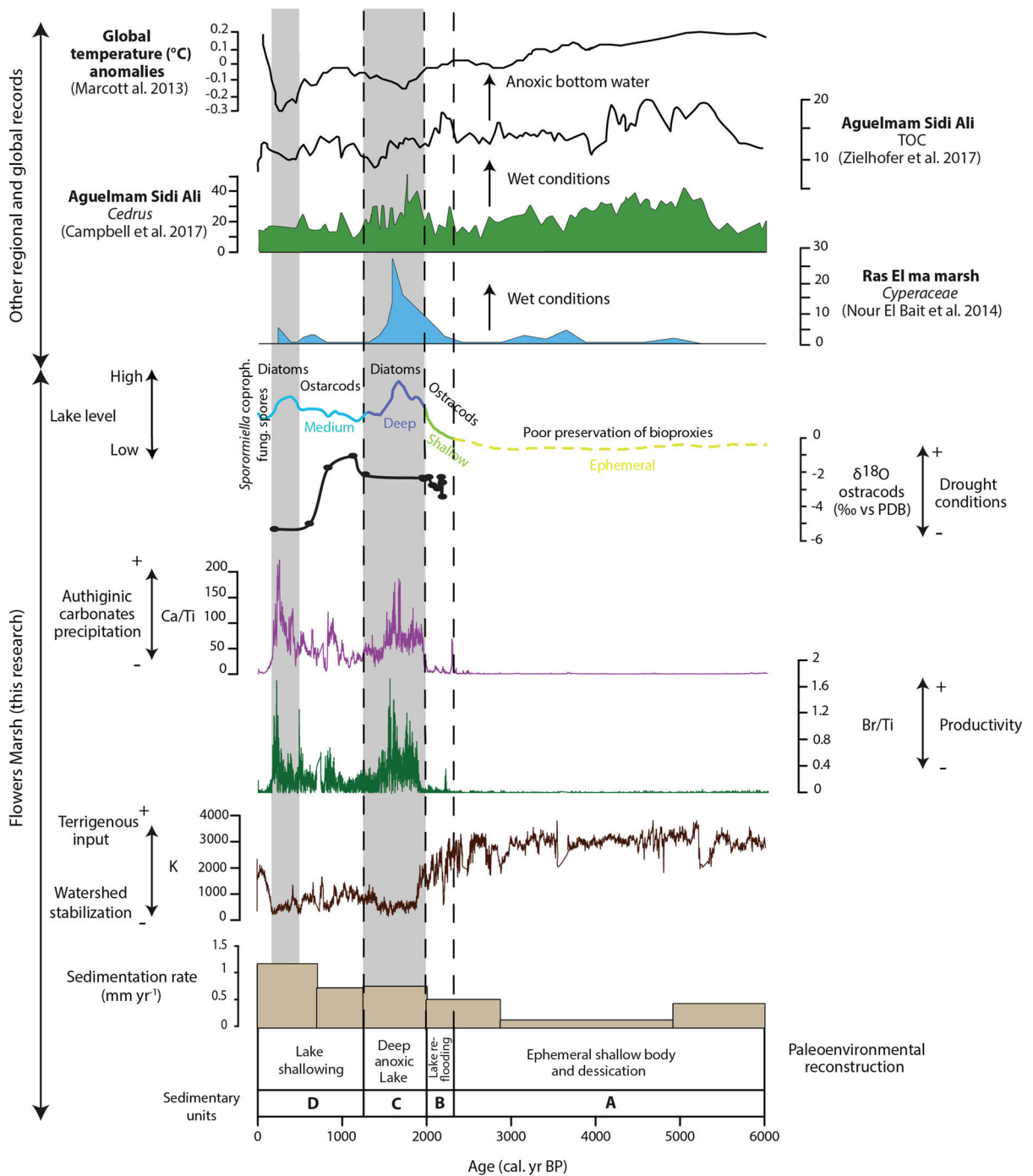


Fig. 6 Selected Flowers Marsh proxies (lower part) compared with other regional and global records (upper part) for the last 6 cal. kyr BP. In the lower section, from bottom to top: calibrated radiocarbon dates, paleoenvironmental reconstruction for the different units (A-B-C-D), sedimentation rate (mm yr⁻¹), K-XRF, Ca/Ti ratio, Br/Ti ratio, δ¹⁸O record from *C. neglecta* and the relative lake-level curve construction using different proxies mentioned in the text. In the upper section:

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

675 indicate oxygenation of the bottom sediment with
676 increasing preservation of Mn as oxides (Davies et al.
677 2015). Sedimentological, geochemical and biological
678 evidence from unit A sediments indicates hydrological
679 scenarios that fluctuate between a very shallow and an
680 ephemeral waterbody. This interpretation is consistent
681 with results from other lake sediments with no organic
682 matter content and a high clastic content that were
683 related to periods of shallow lake levels (Valero-
684 Garcés et al. 2000; González-Sampériz et al. 2008;
685 Corella et al. 2011; Nour El Bait et al. 2014).

686 *Unit B—re-flooding and shallow water conditions*
687 *(2.3–2 cal. yr BP)*

688 Unit B is a transitional phase between the clastic
689 material of Unit A and the laminated organic-rich
690 sediment of the top of the core. It represents a
691 progressive transition towards a shallow wetland
692 environment with calcite formation marked by peaks
693 in Ca/Ti. The high sedimentation rate underlines the
694 increase in carbonate deposition (Fig. 4). This phase is
695 characterized by the appearance of ostracods, espe-
696 cially benthic species (*C. neglecta* and *I. gibba*). Their
697 high abundance indicates that the lake-bottom condi-
698 tions were predominantly aerobic during this interval
699 (Meisch 2000). The abundance of charophytes and
700 gastropods also indicates a shallower littoral environ-
701 ment (Benkaddour 1993; Soulié-Märsche et al. 2008).
702 The decline of terrigenous element contents can be
703 explained by the stability of the watershed as
704 confirmed by the forest cover expansion during this
705 period (Lamb et al. 1999; Nour El Bait et al. 2014).
706 Unit B deposits characterize the re-flooding of the
707 waterbody marked by changes in the depositional
708 mode which most likely resulted from climate ame-
709 lioration in the region. Slight fluctuations of ostracod
710 $\delta^{18}\text{O}$ values in this unit probably point to a shallow and
711 steady water level (Fig. 4).

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

714 This unit was deposited under relatively deep water
715 conditions as indicated by the preservation of lamina-
716 tion, the highest TOC values (up to 8%) and diatom-
717 and organic matter-rich facies, indicative of high
718 biological productivity and organic matter preserva-
719 tion in the lake (Martín-Puertas et al. 2011). The low

Mn content and the well preservation of pollen and
720 spores point to deposition in a relatively anoxic deep
721 lake (Brauer 2004; Zolitschka 2007; Martín-Puertas
722 et al. 2009). This unit is characterized by a major
723 change in grain size distribution from clay-silt to sand
724 as the dominant particle sizes, associated with an
725 increase in sedimentation rate (Figs. 3 and 4). This
726 sandy fraction is related to the massive endogenic
727 carbonate precipitation indicated by peaks in Ca/Ti
728 (Fig. 4). These carbonate concretions are related to the
729 occurrence of “cauliflowers” irregularly shaped car-
730 bonate concretions that have been described as being
731 of algal origin (Magny 1992). They reflect deposition
732 in a shallow-water environment with mobilization to
733 the deep basin during periods of higher runoff. In this
734 unit, endogenic carbonates record the highest isotopic
735 values (Fig. 6). Enriched isotopic values relative to the
736 TDIC values may be related to high productivity
737 (diatom and algal) in the littoral zone (Stuiver 1970;
738 McKenzie 1985). The absence of ostracods during this
739 interval is not due to calcite dissolution processes, as
740 indicated by the presence of endogenic calcite. Most
741 likely, diatom blooms, anoxic conditions and limited
742 water circulation in the lake bottom as indicated by
743 laminated sediments inhibited the survival of benthic
744 ostracods (Valero-Garcés 2003). This unit is also
745 characterized by negative shifts in Ti, K, Fe and Si
746 indicators for allochthonous detrital input (Fig. 3,
747 ESM4). This decrease could be related to the stability
748 of the watershed by forest development and to dilution
749 of the allochthonous input by precipitated calcite as
750 indicated by the negative correlations of Ca with the
751 detrital elements in unit C (Fig. 5). Silicon shows a
752 low correlation with the detrital elements in this unit
753 (Fig. 5), which highlights an additional source (bio-
754 genic) of Si provided by diatoms.
755

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

757 During this period, Flowers Marsh sediments reflect
758 the change from dark laminations (unit C) to brown-
759 white laminations and several productivity proxies
760 point to a slight decrease (TOC, inc/coh, Br/Ti and
761 diatom abundance). A minor drop in carbonate
762 precipitation also occurred, extending until
763 ~ 650 cal. yr BP. This decline in primary productiv-
764 ity and carbonate production together with more
765 positive ostracod $\delta^{18}\text{O}$ values, compared to the onset
766

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 $\delta^{18}\text{O}$ 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.

804 *Connection between Flowers Marsh and Aguelmam* 805 *Azigza*

806 The Flowers Marsh paleohydrological reconstruction
807 reveals interesting links to Aguelmam Azigza. The
808 flooding at 2.3 cal. kyr BP may be interpreted as a
809 period of enhanced surface and groundwater flux to
810 the pond. Earlier and recent studies from the nearby
811 Aguelmam Azigza indicate metric water level fluctu-
812 ations at interannual and decadal scales (Flower et al.
813 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 corre-
spond 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 con-
trasts 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 bal-
ance and plant available moisture reflected by the
abundance of *Cedrus* pollen. For instance, a maximum
in plant available moisture recorded at Lake Tigal-
mamine coincides with low lake levels (Lamb and van
der Kaars 1995). Equally, the *Cedrus* pollen in the

861 Aguelmam Sidi Ali record indicates more humid
 862 conditions during the Late Holocene, while the
 863 majority of the lake level proxies point to a general
 864 lake level lowering trend during this period (Zielhofer
 865 et al. 2017). The authors interpreted *Cedrus* pollen
 866 increases not as an indicator of more precipitation but
 867 rather as an indicator for more available moisture that
 868 may be the result of lower summer temperatures
 869 (Lamb et al. 1999; Zielhofer et al. 2017). The low lake
 870 level recorded in Flowers Marsh sediments during the
 871 Mid- to Late Holocene may be related to a reduction in
 872 winter precipitation which would have significantly
 873 reduced groundwater recharge. During the Mid-
 874 Holocene, arid conditions were recorded in lake
 875 sediments in the Middle Atlas region (Rhoujjati
 876 et al. 2012; Campbell et al. 2017; Bell et al. 2019),
 877 and also in more distant sites from the northern Iberian
 878 Peninsula (Santos et al. 2000; Morellón et al. 2008).
 879 For instance, most of the saline lakes in the Central
 880 Ebro valley (northeastern Spain) were desiccated or
 881 ephemeral during the Mid-Holocene (González-Sam-
 882 périz et al. 2008). In Arreo Lake, the presence of
 883 coarse alluvial facies at the base of the sequence points
 884 to more arid conditions prior to 2250 BP (Corella et al.
 885 2013).

886 The Late Holocene is characterized by a transi-
 887 tional phase towards a sustainable water supply to the
 888 pond with a higher water level at Flowers Marsh
 889 (2300 cal. yr BP–1800 cal. yr BP), particularly evi-
 890 dent in lamination preservation and in organic matter
 891 increase. Wet conditions during this period were also
 892 recorded in Lake Iffer as indicated by an increase in
 893 lake productivity and rising lake level (Damnati et al.
 894 2015). At Tigalmamine Lake, increased precipitation
 895 at about 2600 year BP, with equivalent troughs in
 896 winter and summer temperatures were reconstructed
 897 from pollen records (Cheddadi et al. 1998). Higher
 898 lake levels are documented by the dominance of
 899 aquatic plants (*Typha* L., *Potamogeton* Linn., *Myrio-
 900 phyllum* L. and Cyperaceae) in the pollen diagram
 901 from Ras El Ma marsh, with a high stand between
 902 2000 and 1400 cal. yr BP (Fig. 4) (Nour El Bait et al.
 903 2014). A relative increase in TOC around 2,200 cal. yr
 904 BP was also recorded in Aguelmam Sidi Ali indicating
 905 a high lake level and high productivity (Zielhofer et al.
 906 2017). This period coincides with the wetter Iberian
 907 Roman period in the northern Mediterranean. A humid
 908 phase during the Iron Age and the Roman Optimum
 909 from 2700 to 1600 year, inferred from lake and fluvial

910 records (Macklin et al. 2006; Martín-Puertas et al. 910
 911 2008), has been found in the Iberian Peninsula. 911
 912 Furthermore, a decrease in temperature around 912
 913 2000 cal. yr BP was identified at a global scale 913
 914 (Marcott et al. 2013). 914

915 The shallowing water level recorded at Flowers 915
 916 Marsh since 1.4 kyr cal. BP coincides with decreasing 916
 917 tree pollen abundance at other regional Lakes, such as 917
 918 Aguelmam Sidi Ali where there was a reduction in the 918
 919 arboreal/non-arboreal pollen ratio (AP/NAP) after 919
 920 1300 cal. yr BP (Cambell et al. 2017). Most of the 920
 921 Middle Atlas records reflect forest cover degradation 921
 922 during this period, which might be related to more arid 922
 923 conditions. This stage coincides with the Medieval 923
 924 Climate Anomaly (MCA) which was marked by a 924
 925 global increase in temperature (Marcott et al. 2013). It 925
 926 has also been described in previous paleoclimatic 926
 927 reconstructions across the Mediterranean Basin 927
 928 (Magny 2004; Moreno et al. 2012). Aside from the 928
 929 increase in arid conditions, the intensification of 929
 930 anthropogenic activity during this period also had a 930
 931 strong impact on the forest and the environmental 931
 932 variability in the region (Reille 1976; Benkaddour 932
 933 1993) where significant anthropogenic alteration of 933
 934 forest cover was recorded, especially in the last two 934
 935 millennia (Cheddadi et al. 2015). However, coprophil- 935
 936 ous fungal spore evidence in the Flowers Marsh 936
 937 record did not indicate increased anthropogenic pres- 937
 938 sure during this period. A high stand period was 938
 939 recorded at Flowers Marsh from 650 to 150 cal. yr BP. 939
 940 Considering the uncertainties of the chronological 940
 941 model for this time interval, this phase could coincide 941
 942 with the Little Ice Age (LIA), a generally cold period 942
 943 (Mann et al. 2009). This short humid phase is 943
 944 synchronous with decreased drought stress in the 944
 945 Middle Atlas documented in *Cedrus atlantica* ring 945
 946 width data (Esper et al. 2007) and in speleothem 946
 947 records (Wassenburg et al. 2013). Cooling episodes 947
 948 favoring the expansion of *Cedrus* were recorded 948
 949 during this period at Tigalmamine Lake (Lamb et al. 949
 950 1989) and in Aguelmam Sidi Ali sediments (Campbell 950
 951 et al. 2017). 951

952 Conclusions

953 The multiproxy study (sedimentological, geochemi- 953
 954 cal, mineralogical, biological—spores of coprophilous 954
 955 fungi, ostracods and diatoms, and AMS ¹⁴C dating), 955

956 carried out on the Flowers Marsh sedimentary
957 sequence from the Middle Atlas region, provides a
958 paleohydrological and paleoenvironmental recon-
959 struction (of the area) since 6000 cal. yr BP, inter-
960 preted in terms of climate and environment variability.
961 This study demonstrates the ability of a pond such as
962 Flowers Marsh to show significant palaeohydrological
963 evolution and confirms the high sensitivity of Middle
964 Atlas hydrosystems to climatic changes in the
965 Mediterranean region as highlighted in previous
966 studies.

967 The Flowers Marsh record shows arid conditions
968 prior to 2300 cal. yr BP represented by highly clastic
969 sediments and poor preservation of bioproxies. A large
970 increase in water availability, marked by enhanced
971 organic matter and endogenic calcite preservation was
972 recorded during the wetter Iberian-Roman period,
973 particularly between 2000 and 1400 cal. yr BP and
974 during the Little Ice Age (650–150 cal. yr BP). Lower
975 lake levels, a response to increasing regional aridity,
976 were recorded during the Medieval Climate Anomaly
977 (1400–650 cal. yr BP). Intensification of human
978 pressure by pastures in the Flowers Marsh catchment
979 is recorded since the last 150 year.

980 Comparison of the main hydrological phases in
981 Flowers March with other Middle Atlas and Mediter-
982 ranean records demonstrates a coherent pattern of the
983 main climatic phases in the region during the last 6000
984 years, at the same time highlighting spatial and
985 temporal variability due to latitudinal differences
986 and some site specific patterns.

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