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## Land-sea linkages on the Algerian Margin over the last 14 kyrs BP: Climate variability at orbital to centennial timescales

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# Palaeogeography, Palaeoclimatology, Palaeoecology

## Land-sea linkages on the Algerian Margin over the last 14 kyrs BP: climate variability at orbital to centennial timescales

--Manuscript Draft--

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<b>Manuscript Region of Origin:</b>	Europe
<b>Abstract:</b>	<p>Past and present environmental conditions over the Holocene along the Algerian coast involve complex atmosphere-hydrosphere-biosphere interactions and anthropogenic activities on adjacent watersheds. Atlantic Ocean surface waters entering the western Mediterranean Sea at the Gibraltar Strait create the Algerian Current, which flows along the North African coast in a succession of strong and large-scale eddies. Deep-water upwelling plumes are other recurrent hydrological features of the Algerian margin affecting regional environmental features. However, vegetation and paleohydrological changes that have occurred over the Holocene have not yet been described. To bridge this gap, a suite of paleoclimate proxies was analysed in marine core MD04-2801 (2,067 m water depth) at a secular-scale resolution over the last 14 kyrs BP. Terrestrial (pollen grains) and marine (dinoflagellate cysts or dinocysts) palynological assemblages, as well as sedimentological (grain-size analysis and XRD-based quantitative analysis of clay minerals) and biomarkers (alkenones and n-alkanes), were determined to explore the links between past sea surface hydrological conditions and regional environmental changes on nearby watersheds.</p> <p>The over-representation of heterotrophic dinocyst taxa (<i>Brigantedinium</i> spp.) indicates strong planktonic productivity in the study area. Results shows that the links between dryness on land and surface hydrological conditions are expressed by : (i) recurrent upwelling cells during the relatively dry climate conditions of the Younger Dryas (12.7 to 11.7 ka BP), the Early Holocene (11.7 to 8.2 ka BP) and from 6 ka BP onwards, (ii) enhanced fluvial discharges between 8.2 and 6 ka BP during the African Humid Period concomitant with the colonization of coastal lands by Mediterranean forest. Middle to Late Holocene transition around 4.2 ka BP characterizes by the intense event referred to here as the Algerian Mega Drought (4.3 to 3.9 ka BP).</p>
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<b>Response to Reviewers:</b>	



Brest, 10<sup>th</sup> April, 2023

Dear editor,

We would be grateful if you could consider our paper entitled “**Land-sea linkages on the Algerian Margin over the last 14 kyrs BP: climate variability at orbital and multi-centennial timescales**” to be suitable for submission to Palaeogeography, Palaeoclimatology, Palaeoecology.

We confirm that all co-authors have seen and approved the final version of the manuscript being submitted. We warrant that the article is an original work, hasn't received prior publication and isn't under consideration for publication elsewhere.

This paper is based on new marine and continental multi-proxy investigation conducted on a 10m long sediment core from the Algerian Margin, covering the last 14 kyrs BP. The study combines sedimentological (XRD, grain-size, XRF, XRD), palynological (pollen, dinoflagellate cysts and Non-Pollen Palynomorphs based on previous regional modern sediments analysis), biogeochemical analyses (stable isotopes, molecular biomarkers) and climatic reconstructions (pollen and dinocysts MAT). We aim to discuss from climatic control on the hydrological conditions and vegetation dynamics and underline environmental tendencies of the Algerian margin since the last deglaciation. The land-sea linkages is therefore underlined and replaced in the climatic and regional context of the Western Mediterranean basin throughout the Holocene.

All co-authors made substantial contributions to the submission. Details of individual contributions: **Coussin V.** (study conducted in the framework of Coussin's PhD, palynological analysis on all samples, data interpretation, conceptualization, writing original draft), **Penaud A.** (funding acquisition, co-supervision of Coussin's PhD, data interpretation, conceptualization, writing original draft), **Combourieu-Nebout N.** (funding acquisition, co-supervision of Coussin's PhD, data interpretation, conceptualization, writing original draft),

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**Peyron O.** (co-supervision of Coussin's PhD), **Sicre M.-A.** (funding acquisition and biomarker analysis supervising), **Tisnérat-Laborde N.** (radiocarbon dating with the ECHoMICADAS platform), **Babonneau N.** (responsible of the sedimentological part of this work, PI for core MD04-2801), **Cattaneo A.** (responsible of the sedimentological part of this work, PI for core MD04-2801).

We hope that our paper will be considered for revision.

Sincerely,

Vincent Coussin and co-authors



1 **Land-sea linkages on the Algerian Margin over the last 14 kyrs BP: climate**  
2 **variability at orbital to centennial timescales**

3  
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20  
21 **Highlights**

- 22 • Land-sea multiproxy approach on the Algerian Margin over the last 14 kyrs
- 23 • Productivity regimes closely associated with the vigour of the Algerian Current
- 24 • Settlement of modern production conditions since 3 ka BP
- 25 • First record of the Algerian Mega Drought event between 4.3 and 3.9 ka BP
- 26 • NPP fingerprint in marine sediments related to erosion and river runoff

## 29 **Abstract**

30 Past and present environmental conditions over the Holocene along the Algerian coast involve  
31 complex atmosphere-hydrosphere-biosphere interactions and anthropogenic activities on  
32 adjacent watersheds. Atlantic Ocean surface waters entering the western Mediterranean Sea at  
33 the Gibraltar Strait create the Algerian Current, which flows along the North African coast in a  
34 succession of strong and large-scale eddies. Deep-water upwelling plumes are other recurrent  
35 hydrological features of the Algerian margin affecting regional environmental features.  
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44 **The** over-representation of heterotrophic dinocyst taxa (*Brigantedinium* spp.) **indicates** strong  
45 planktonic productivity in the study area. **Results shows that** the links between dryness on land  
46 and surface hydrological conditions **are expressed by** : (i) recurrent upwelling cells during the  
47 relatively dry climate conditions of the Younger Dryas (12.7 to 11.7 ka BP), the Early Holocene  
48 (11.7 to 8.2 ka BP) and from 6 ka BP onwards, (ii) enhanced fluvial discharges between 8.2  
49 and 6 ka BP during the African Humid Period concomitant with the colonization of **coastal**  
50 **lands** by Mediterranean forest. **Middle to Late Holocene transition around 4.2 ka BP**  
51 **characterizes by the intense event reffered to here as the Algerian Mega Drought (4.3 to 3.9 ka**  
52 **BP).**

53

54 *Keywords: Holocene; Dinocysts; Pollen; Biomarkers; Clay analysis; Algerian Current*

55

56 *Abbreviations: AM: Algerian Margin; AC: Algerian Current; WMB: Western Mediterranean*  
57 *Basin; WMDW: Western Mediterranean Deep Waters; LIW: Ligurian Intermediate Waters;*  
58 *MOW: Mediterranean Outflow Waters; YD: Younger Dryas; B/A: Bölling-Alleröd.*

59

## 60 **1. Introduction**

61 Interactions between low- and mid-latitude atmospheric circulations and local-scale  
62 configurations such as orography and coastal geomorphology, have created the specificities of  
63 the Mediterranean climate (Brayshaw et al., 2011). Furthermore, the summer season length  
64 depending on the vigor of the Hadley cell directly impacts summer droughts in the  
65 Mediterranean Basin (Lionello et al., 2006). In contrast, Mediterranean storm activity driving  
66 the main seasonal precipitation is strongly associated with the position and strength of the  
67 North-Atlantic mid-latitude storm tracks (Brayshaw et al., 2010). Consequently, the  
68 interactions between tropical convection and North-Atlantic storm tracks constitute a complex  
69 but essential element in understanding the long-term, rapid climate change that took place in  
70 the WMB during the Holocene. Climate changes during the last climatic cycle (e.g.  
71 Combourieu-Nebout et al., 1999, 2002; Sánchez-Goñi et al., 2002; Beaudouin et al., 2007;  
72 Bout-Roumazeilles et al., 2007; Brauer et al., 2007; Fletcher and Sánchez-Goñi, 2008; Kotthoff  
73 et al., 2008) have driven rapid paleoenvironmental changes in the Mediterranean basin.

74 Global warming, together with the generally high climatic and environmental sensitivity of this  
75 region **raises** questions **concerning** future environmental and human trajectories in the  
76 Mediterranean Basin, in particular due to subtropical aridification (IPCC report, 2019).

77 In this context, the Algerian Margin (AM) appears ideal to investigate both terrestrial (i.e.  
78 landscape changes) and marine (i.e. hydrological changes) ecosystems inherited from climate  
79 change and land-use practices over the Holocene. The AM, and mostly its westernmost part, is  
80 a highly productive area contrasting with the predominantly oligotrophic waters of the Western  
81 Mediterranean Basin (Sournia, 1973; Lohrenz et al., 1988). Strong riverine inputs (i.e. flash-  
82 flood episodes) to coastal waters and upwelling cells result in nutrient-enriched surface waters  
83 (Raimbault et al., 1993). These hydrological patterns provide understanding of the distribution  
84 of planktonic organisms as recently discussed for fossilized dinocysts at the scale of the Western  
85 Mediterranean Basin (WMB) (Coussin *et al.*, 2022).

86 Numerous studies have shown the rapid response of Mediterranean environments to Holocene  
87 climate variability (e.g. Rohling et al., 2002; Fletcher et al., 2013; Chabaud et al., 2014; Sicre  
88 et al., 2016; Jalali et al., 2016; 2017, 2018; Di Rita et al., 2018; Bini et al., 2021), including  
89 research on remote short-term events of the North Atlantic Basin (e.g. Bond et al., 1997, 2001;  
90 Mayewski et al., 2004; Sicre et al., 2021). However, Holocene paleoenvironmental changes  
91 along the northern African margin, between the Alboran Sea (e.g. Combourieu-Nebout et al.,

92 1999, 2009 ; Fletcher et al., 2013) and the Sicilian Strait (e.g. Rouis-Zargouni et al., 2010, 2012;  
93 Desprat et al., 2013 ; Di Rita et al., 2018), remain poorly documented.  
94 Here, we present new results for the AM based on the multi-proxy analysis of the marine core  
95 MD04-2801 (36°30.99'N; 0°30.03'E) over the last 14 kyrs BP, with a focus on the Holocene  
96 interval. This study benefited from a detailed sedimentological description (including X-ray  
97 fluorescence-XRF and grain-size analyses, clay mineral identification and conventional stable  
98 isotopes of O and C), centennial-scale resolution reconstructions of palynological proxies  
99 (pollen grains, dinocysts and other non-pollen palynomorphs or NPP), and molecular  
100 biomarkers (alkenones and n-alkanes). Our main objectives are i) to characterize upwelling  
101 variations through dinocyst assemblages and North-Atlantic atmospheric and hydrological  
102 influences on ecosystem variability, ii) to explore dryness and moisture conditions on land in  
103 relation with river discharge, iii) to assess the non-pollen palynomorphs (NPP) fingerprint in  
104 marine sediments and their relationship with erosion and river runoff on adjacent watersheds,  
105 iv) to evaluate the first pollen- and dinocyst-based quantifications of climate and hydrological  
106 parameters, respectively, in the study area. This dataset finally contributes to improve  
107 knowledge on north to south and west to east climatic and environmental gradients across the  
108 WMB.  
109

## 110 **2. Environmental context**

### 111 **2.1. Geographical and geomorphological background**

112 The marine sediment core MD04-2801 was retrieved on the AM, 24 km from the coast, on the  
113 eastern side of the Kramis deep-sea fan (Babonneau et al., 2012; Figure 1b). From a  
114 geomorphological point of view, the Algerian coast is limited to the south by the Dahra  
115 Mountains (Cretaceous schist clay substratum) that reach an altitude of 1550 m and is bordered  
116 by the Tellian Atlas chain. The study area is surrounded by Tortonian (blue marls and  
117 sandstones), Messinian (gypsum, gypsy marls, diatomites and diatomitic marls), Pliocene  
118 (marine blue marls, sandstones and limestones), and Quaternary (calcareous sandstones, sands  
119 and alluvial deposits) geological land formations (e.g. Perrodon, 1957; Meghraoui et al., 1996;  
120 Belkebir et al., 2008; Osman et al., 2021). The proximity of the AM to high relief means that  
121 its environment includes small coastal watersheds and small, fluctuating river flows (i.e. oueds).  
122 The oued Cheliff, whose mouth is located around 60 km to the west of the MD04-2801 core  
123 site (Figure 1b), is the largest oued of the region and is characterized by an average weak flow  
124 of  $15 \text{ m}^3 \cdot \text{s}^{-1}$ , varying from  $1.5 \text{ m}^3 \cdot \text{s}^{-1}$  during the driest episodes to  $1,500 \text{ m}^3 \cdot \text{s}^{-1}$  during flash-  
125 flood events (Gautier et al., 1998). The source of the oued Kramis (Figure 1b) is located in the  
126 Saharian Atlas and flows to the sea through the Dahra Mountains, distally feeding the Kramis  
127 deep-sea fan (Babonneau et al., 2012).

128 Two major climate features characterize the study area: i) mild conditions under the strong  
129 influence of mid-latitude westerly atmospheric circulation over the North Atlantic (i.e.  
130 westerlies), especially during winter, and ii) dry conditions (about 3 to 5 months per year) due  
131 to the strengthened Azores High, especially during summer (Lionello et al., 2006). The  
132 meteorological station at Mostaganem (near the Cheliff mouth) reports an average annual  
133 temperature of  $18.7^\circ\text{C}$  (minimum of  $5^\circ\text{C}$  and maximum of  $25^\circ\text{C}$ ) between 1981 and 2010. Over  
134 this period, seasonal flash floods of nearby oueds, mainly during the “humid” season (fall to  
135 spring), represent the largest part of annual precipitation (i.e. average amount of 383 mm/yr,  
136 minimum of 1 mm/month and maximum of 71 mm/month). Flash floods drive huge amounts  
137 of terrigenous sediments (i.e. organic and inorganic particles and nutrients) to coastal waters  
138 due to their high erosive capacity (e.g. Pouquet, 1967; Guizien et al., 2007; Tzoraki and  
139 Nikolaidis, 2007).

140

### 141 **2.2. Landscape**

142 The Mediterranean landscapes shaping the study area are characterized by an altitudinal belt  
143 type organization split into three major subdivisions (Barbero et al., 1981; Polunin and Walters,  
144 1985; Quezel and Medail, 2003). The thermo-Mediterranean belt covers lowlands and areas up  
145 from the coast to a 1,000 m altitude and is composed of *Olea*, *Pistacia*, sclerophyllous  
146 shrublands and xerophytous taxa, associated with steppe and semi-desert representative taxa  
147 (e.g. *Artemisia*, *Amaranthaceae*, *Ephedra*). From 1,000 to 1,500 m, the meso-Mediterranean  
148 belt is composed of the sclerophyllous oak forest (e.g. *Quercus ilex*, *Quercus suber*, *Buxus* and  
149 *Myrtus*) and the humid-temperate oak forest (dominated by deciduous *Quercus* and Ericaceae,  
150 in association with *Juniperus* and *Cupressus*). At higher altitudes, from 1500 to 2300 m, the  
151 supra-Mediterranean belt is characterized by a specific coniferous forest (i.e. North African  
152 species of *Pinus*, *Abies* and *Cedrus*). The oro-Mediterranean belt extends up to 2800 m in the  
153 high Atlas with a high rate of representation of *Juniperus* (open forest taxon or arborescent  
154 matorrals). Finally, the alti-Mediterranean belt (i.e. mountainous regions) is composed of  
155 scattered Chamaephytae taxa (e.g. *Erica*, *Romarinus* and other Lamiaceae, *Ilex* or *Artemisia*)  
156 and represents the highest vegetation belt in the area. It corresponds to the grassland belt of  
157 European mountains (Quezel and Medail, 2003).

158

### 159 **2.3. Hydrological context**

160 The semi-enclosed Mediterranean Sea undergoes excess evaporation over freshwater input,  
161 resulting in a deficient water balance (Béthoux, 1979, 1984). The western Mediterranean Sea  
162 is strongly influenced by the Modified Atlantic Waters (MAW) entering through the Gibraltar  
163 strait, flowing along the Spanish coast and forming two anticyclonic gyres (i.e. the Western  
164 Alboran Gyre-WAG and the Eastern Alboran Gyre-EAG; Figure 1a). The Almeria-Oran front  
165 (35 km wide; 200 m deep; Figure 1a) position and intensity depends on the degree of  
166 development of the EAG (Tintoré et al., 1988; Rohling et al, 1995; Viúdez and Tintoré, 1995;  
167 Rohling et al., 2009). The MAW follow the Almeria-Oran front, which marks a deflection along  
168 the AM, forming the Algerian Current (AC, Figure 1; Millot, 1987; Millot, 1999, Millot and  
169 Taupier-Letage, 2005). The AC undulates eastward up to 30–40 km from the coast to 3°E  
170 (Millot, 1985, 1987; Arnone and La Violette, 1986; Arnone et al., 1990; Perkins and Pistek,  
171 1990) where North African coast irregularities generate wind-driven eddies (cf. dotted arrows  
172 in Figure 1a). These eddies are responsible for northward coastal current extensions as well as  
173 the associated offshore propagation of low-salinity surface waters (Millot, 1999; Millot and  
174 Taupier-Letage, 2005).

175 The AC shows a salinity gradient from the Alboran Sea ( $< 37$  psu; Arnone and La Violette,  
176 1986) to the east and the internal zones of the WMB (psu  $> 37.5$ ). In its coherent form, the AC  
177 marks a haline density front (Arnone et al., 1990; Perkins and Pistek, 1990) responsible for  
178 vertical mixing (i.e. upwelling; Sournia, 1973; Lohrenz et al., 1988; Raimbault et al., 1993),  
179 while the Alboran Sea is characterized by a general oligotrophic regime. On the coastal side of  
180 the density front, isopycnal mixing brings nutrient-enriched waters from the nutricline to the  
181 photic zone while, on the offshore side, diapycnal mixing brings deeper nutrients to the surface  
182 (i.e. nutrient export crossing the haline front; Raimbault et al., 1993), promoting enhanced  
183 productivity (Raimbault et al., 1993; Coussin et al., 2022). Additionally, seasonal offshore  
184 winds induce coastal upwelling, probably supported by low barometric pressure cells due to  
185 solar heating (Bakun and Agostini, 2001).

186 Finally, the regional climate (cf. section 2.1) is responsible for weak and irregular fluvial  
187 discharge especially during the dryest season (i.e. April to September) while strong oued  
188 discharge (i.e. flash floods) occasionally occurs during autumn and winter, transporting  
189 terrigenous material and nutrients to the sea (Guizien et al., 2007; Tzoraki and Nikolaidis,  
190 2007).



### 191 **2.3. Sedimentological context**

192 Core MD04-2801 (36°30.99'N; 00°30.03'E; 24.82 m long; 2,063 m water depth) is located  
193 about 6 km north of the Kramis Canyon, which has an east to west orientation in the lower slope  
194 (Figure 1b). The core is located at the base of the slope and is separated from the canyon by a  
195 canyon terrace. Turbidity current overflow from the canyon to the core site is currently assumed  
196 to be very low (Babonneau et al., 2012). However, a contribution of diluted mud plumes at the  
197 top of the turbidity currents could explain the high sedimentation rates in the area. Finally, a  
198 large sediment wave field develops downslope along the right side of the Kramis Canyon. These  
199 sedimentary features mark the overflow zone of turbidity currents of the Kramis and Khadra  
200 canyons on the Kramis sedimentary ridge. Core MD04-2801 is located at the top of this field  
201 and was affected by intense overflow currents in the early phase of the formation of the Kramis  
202 sedimentary ridge (Babonneau et al., 2012).

203 The uppermost 10 m of MD04-2801 are not affected by gravity-driven sediment instability  
204 processes (i.e. turbidity currents and resulting turbidites; Babonneau et al., 2012). From 1045  
205 cm upward (From section VII to section I; Figure 2), sediment generally consists of hemipelagic  
206 clays. Below 1,045 cm, section VIII consists of fine-grained turbidite beds (of approximately 1  
207 cm thick) within a silty-clay matrix representing repeated destabilization of the shelf sediments  
208 via turbiditic plumes. Silty to sandy deposits lie on the slopes of the fan with a wide dispersal  
209 of turbiditic overflows across the abyssal plain (Babonneau et al., 2012). Around the Kramis  
210 fan, a canyon levee crest, 200 m higher than the channel bottom, only releases overflow of the  
211 largest turbidity currents, resulting in interfingered turbiditic levee deposits of the Kramis  
212 system with hemipelagic sediment (Babonneau et al., 2012). The absence of turbidites in the  
213 upper sections of core MD04-2801 (above 1,045 cm, Sections I to VII; Figure 2) reflects the  
214 isolation of the core site from the turbiditic channel due to aggradation of the levees.

215

## 216 **3. Methodology**

### 217 **3.1. Sediment cores and stable isotope analyses**

218 The log of core MD04-2801 was established through visual description of the sedimentary  
219 facies (Figure 2). The physical properties of the core (i.e. P-wave velocity, magnetic  
220 susceptibility and gamma-ray attenuation density) were measured using a 'Geotek Multi Sensor  
221 Core Logger' (MSCL) with a 2-cm-step (average 30 yrs) resolution at the Ifremer Marine  
222 Geosciences laboratory (Plouzané, France). X-ray fluorescence (XRF) profiles, for the semi-  
223 quantitative chemical composition analysis of the study core, were acquired with an "Avaatech

224 core-scanning XRF” with a 1-cm-step (average 15 yrs) resolution (Ifremer Marine Geosciences  
225 laboratory, Plouzané, France). In sediments, the Ti element is commonly interpreted as a  
226 terrigenous-siliclastic signature while the Ca element is related to carbonate materials of detritic  
227 and/or biogenic sources (Richter et al., 2006). Based on this assumption, the XRF-Ti/Ca ratio  
228 has been commonly used on silico-clastic margins (where Ca mainly originates from biogenic  
229 carbonates) to estimate varying terrigenous inputs to the marine realm. In this study, even if  
230 geological formations on land are mainly composed of carbonates, we will use this ratio  
231 combined with other proxies to track fluvial input to the marine realm.

232 Grain-size analyses were first performed at high resolution on total sediments (Master thesis of  
233 Si Bachir Roza, IUEM) and, in a second step, at a lower resolution on both total and  
234 decarbonated sediments (after HCl 30% treatment) at the IUEM (*Institut Universitaire*  
235 *Européen de la Mer*, Plouzané, France) using a Malvern MASTERSIZER 2000. The software  
236 GRADISTAT was used to produce particle grain-size distribution and size statistics from the  
237 laser granulometer data, including median grain size (D50) as well as sediment volumetric  
238 phase percentages (i.e. clays:  $0 < \emptyset < 10 \mu\text{m}$ , silts:  $10 < \emptyset < 63 \mu\text{m}$ , and sands:  $\emptyset > 63 \mu\text{m}$ ).

239 Semi-quantitative mineralogical composition of the clay fraction was measured by X-ray  
240 diffraction (XRD) at the Ifremer Marine Geosciences laboratory (Plouzané, France) with a  
241 Bruker D2 PHASER set (with a Lynxeye fast detector; Cu X-ray tube; 30 kV voltage; 10 mA  
242 intensity). After decarbonation and decantation to retain only the  $< 2\mu\text{m}$  fraction, the sample  
243 was deposited on oriented glass. Each sample was routinely analyzed from 2 to  $30^\circ$  with a  
244 resolution of  $0.02^\circ$  lasting 1 s, with three XRD runs: i) air-dried, ii) ethylene-glycol saturated  
245 and iii) after calcination at  $490^\circ\text{C}$ . The characterization of each clayey mineral followed the  
246 description of Bout-Roumazeilles et al. (1999). Semi-quantitative estimation of clay mineral  
247 abundances (%) was performed using the Macintosh MacDiff® 4.2.5 software (R. Petschick,  
248 <http://www.geologie.uni-frankfurt.de/Staff/Homepages/Petschick/RainerE.html>).

249 Finally, stable isotopes were performed on planktonic *Globigerinoides bulloides* as well as  
250 endobenthic *Globobulimina affinis* foraminifera, hand-picked in the  $>150 \mu\text{m}$  sediment  
251 fraction. Isotopic analyses were conducted at the “*Pôle Spectrométrie Océan*” (IUEM,  
252 University of Brest, France) on a Finnigan MAT253 equipped with a Kiel-device automated  
253 introduction line. Analytical precisions for this spectrometer are  $<0.05\text{‰}$  for the  $\delta^{18}\text{O}$  and  
254  $<0.03\text{‰}$  for the  $\delta^{13}\text{C}$  using, respectively, the certified NBS-19 and NBS-18 standards.

255 Core KMDJ-23 ( $36^\circ30.006'\text{N}$ ;  $0^\circ15.422'\text{E}$ ; 7.52 m long; 2542 m water depth) was collected  
256 close to core MD04-2801 (Figure 1b). In this study, modern palynological assemblages related  
257 to current hydrological conditions are considered thanks to the top sediments of core KMDJ-

258 23 with radionuclide dating that confirmed the contemporaneous deposits at the study site  
259 (Coussin et al., 2022). We compare dinocyst data (i.e. *O. centrocarpum* for the North Atlantic  
260 influence (i.e. AC strengthening) versus *L. machaerophorum* for the estuarine influence (i.e.  
261 surface stratification) or Ocen/Lmac ratio), pollen data (sum of Mediterranean and Eurosiberian  
262 forest taxa), and alkenone SST, with coeval records of the Gulf of Cadiz (core MD99-2339),  
263 the Alboran Sea (ODP site 976 and core MD95-2043), the Algerian Margin-AM (MD04-2801,  
264 this study) and the Siculo-Tunisian strait (core MD04-2797).

265

266

## 267 **3.2. Palynological analyses**

### 268 3.3.1. Palynological treatments and palynomorph identifications

269 About 1 to 2 cm<sup>3</sup> of sediments were sampled every 20 cm in the upper MD04-2801 core (0 to  
270 500 cm) at about 100 yrs resolution and every 10 cm in the lower part (500 to 1042 cm) at about  
271 150 yrs resolution. Eighty-six samples were processed using the same palynological protocol  
272 as for palynomorph extraction, allowing direct comparison between terrestrial (pollen, spores,  
273 freshwater microalgae, and other continental non-pollen palynomorphs-NPPs) and marine  
274 (dinocysts and other marine NPPs such as marine microalgae or foraminiferal linings)  
275 microfossils on the same palynological slides. The preparation technique (Geo-Ocean  
276 laboratory, IUEM, France) was performed on the <150 µm fraction following the standardized  
277 palynological protocol of de Vernal et al. (1999), slightly adapted at the EPOC laboratory  
278 (University of Bordeaux, [http://www.epoc.u-](http://www.epoc.u-bordeaux.fr/index.php?lang=fr&page=eq_paleo_pollens)  
279 [bordeaux.fr/index.php?lang=fr&page=eq\\_paleo\\_pollens](http://www.epoc.u-bordeaux.fr/index.php?lang=fr&page=eq_paleo_pollens)). It includes chemical treatments  
280 (cold HCl: 10, 25 and 50%; cold HF: 45 and 70%, to remove carbonates and silicates,  
281 respectively) and sieving through single-use 10 µm nylon mesh screens. To avoid selective  
282 dinocyst degradation during sample treatment, no oxidative agent or heavy liquid technique  
283 was applied. Microscopic identification was performed with a Zeiss (Axio Scope.A1)  
284 microscope at x630 magnification. Absolute concentrations of palynomorphs were calculated  
285 using the marker grain method (Stockmarr, 1971; de Vernal et al., 1999; Mertens et al., 2009).  
286 Accordingly, aliquot volumes of *Lycopodium* spores were added to each sample before  
287 chemical treatment to allow the calculation of palynomorph concentrations as a number of  
288 palynomorphs/cm<sup>3</sup> of dry sediments (i.e. these exotic spores are counted simultaneously with  
289 studied palynomorphs for each sample).

290 A threshold of 100 individuals (> 5% in the total assemblage) is required to identify major  
291 species (Fatela and Taborda, 2002). In this study, 88 samples were analysed, with a minimum

292 count of 100 dinocysts (taxonomy following Fensome et al., 1993) and 150 pollen grains except  
293 for the over-represented taxon *Pinus* (Turon, 1984; Heusser and Balsam, 1985; taxonomy  
294 following Reille, 1992). Minimal counts were not reached for two dinocyst (40-41 and 541-542  
295 cm) and three pollen (20-21, 440-441, 441-442 cm) assemblages. Their corresponding levels  
296 were therefore excluded from the discussion. Among dinocysts, *Brigantedinium* spp. includes  
297 all round-brown cysts, *Echinidinium* spp. includes all brown cysts with typical *Echinidinium*  
298 spine-like processes not determined on a species level, and *Spiniferites* spp. includes all  
299 *Spiniferites* taxa not determined on a species level. In addition, heterotrophic dinocysts (i.e.  
300 derived from dinoflagellates with a strict heterotrophic nutritional strategy) are indirectly related  
301 to food resources, especially diatoms, as commonly shown in upwelling areas (Wall et al., 1977;  
302 Lewis et al., 1990; Marret, 1994; Biebow, 1996; Zonneveld et al., 1997, 2001; Targarona et al.,  
303 1999; Bouimetarhan et al., 2009; Penaud et al., 2016). Therefore, the sum of heterotrophic taxa  
304 was made to account for “strict” heterotrophic dinocysts. Among continental palynomorphs,  
305 “undetermined fungal spores” include all fungal spores that cannot be determined on type-code,  
306 genus or species levels. Regarding relative abundance of pollen assemblages, percentages of  
307 *Pinus* were based on the total pollen sum, while continental NPP relative abundances were  
308 calculated on a total sum that includes the pollen main sum (i.e. without *Pinus*) and the sum of  
309 spores and other continental NPPs (van Geel et al., 1972; Cugny et al., 2010; Miola, 2012).

310

### 311 3.3.2. Statistical analysis on palynological results

312 Palynological diagrams of pollen and dinocyst assemblages were performed with the Tilia  
313 software (Grimm, 1990), also defining the more parsimonious statistically homogeneous  
314 palynological zonation according to the CONNIS model (Grimm, 1987).

315 Taxonomical diversity indexes were calculated using the “PAST version 4.06b” software  
316 (Hammer et al., 2001), including the species richness (i.e. number of taxa per sample), the  
317 Margalef’s richness index (diversity index), and the dominance index (i.e. the value “0”  
318 indicates equal presence of all taxa while the value “1” indicates the dominance of one taxon  
319 in the assemblage). In addition, multivariate analyses (Detrended Correspondence Analysis,  
320 DCA) were performed with the PAST program for semi-quantitative geochemical XRF data  
321 (cf. Data Availability section).

322

### 323 3.3.3. Dinocyst-inferred environmental reconstructions

324 Dinocyst-based sea-surface environmental quantifications were performed using R version  
325 2.7.0 software (R Development Core Team, 2008; <http://www.r-project.org/>) and the Modern  
326 Analogue Technique (MAT; e.g. Guiot, 1990; Guiot and de Vernal, 2007). This method consists  
327 of selecting (based on a dissimilarity index) a limited number of analogue surface dinocyst  
328 assemblages and associated environmental values. A modern surface database is thus required.  
329 Dinocyst fossil assemblages were compared to the most recent standardized Northern  
330 Hemisphere “modern” database (n=1,968 sites; de Vernal et al., 2020), recently upgraded with  
331 new modern assemblages of the Western Mediterranean Basin (WMB; + n=23: 6 in the Gulf of  
332 Lion and 17 in the AM; Coussin et al., 2022). The dinocyst dataset includes 71 different taxa  
333 in relation with 17 modern environmental parameters (de Vernal et al., 2020). Five modern  
334 analogues were found by the MAT, which allowed to calculate environmental parameters  
335 considering an average of related parameter values, with the maximum weight attributed to the  
336 statistically closest analogue (e.g. Guiot and de Vernal, 2007). Considering the statistical  
337 threshold distance of the MAT ( $d_T = 1.2$ ), analogues are considered as i) remote when the  
338 distance  $d > d_T$ , acceptable when  $d_T/2 < d < d_T$ , and good when  $d < d_T/2$  (de Vernal et al., 2005).  
339 Root Mean Square Errors (RMSE) are used to discuss uncertainties in fossil quantifications,  
340 often caused by the lack of corresponding modern analogues of fossil assemblages (Guiot and  
341 de Vernal, 2007; de Vernal et al., 2020). In this study, we have estimated summer and winter  
342 sea surface temperature ( $SST_{winter}$  and  $SST_{summer}$ ; RMSE of 1.2°C and 1.8°C, respectively), sea  
343 surface salinity ( $SSS_{winter}$  and  $SSS_{summer}$ ; RMSE of 1.1 psu and 2.1 psu, respectively), and mean  
344 annual Primary Productivity ( $PP_{annual}$ ; RMSE of 436.1 gC m<sup>-2</sup> yr<sup>-1</sup>).  
345

### 346 3.3.4. Pollen-inferred climate reconstruction

347 Pollen reconstructions were also generated with the MAT applying the same general principles  
348 as for the dinocyst-based reconstructions. In this case, the method calculates a dissimilarity  
349 index between fossil pollen obtained on core MD04-2801 and modern pollen assemblages  
350 extracted from the database updated in Dugerdil et al. (2021). Modern climate parameters  
351 associated with the best analogues are then weighted (according to the similarity of the best  
352 four analogues) to provide values for fossil-pollen assemblages. Climate reconstructions were  
353 obtained with a leave-one-out approach. In this study, the climate variables are Mean  
354 Temperature of the Coldest Month (MTCO; RMSE of 4.7°C), Mean Temperature of the  
355 Warmest Month (MTWA; RMSE of 2.6°C), Annual Temperature (TANN; RMSE of 3.1°C),

356 Annual Precipitation (PANN; RMSE of 199 mm/yr), and Summer Precipitation (SUMMERPR;  
357 RMSE of 51.3 mm/summer). We also calculated a temperature seasonality index as the  
358 difference between MTWA and MTCO reconstructions using the Rioja package in R (Juggins,  
359 2012).

360

### 361 **3.4. Biomarker analyses**

362 Biomarker analyses were performed at a temporal resolution of about 150 years. Lipids were  
363 extracted from 1.5 to 2 g of freeze-dried sediments using a mixture of  
364 dichloromethane/methanol (2:1 v/v). Silica gel chromatography was used to isolate alkenones  
365 and n-alkanes from the total lipid extracts. They were then analysed by gas chromatography,  
366 following Sicre et al. (1990). We used the global calibration from Conte et al. (2006) to convert  
367 the unsaturation ratio of C<sub>37</sub> alkenones ( $U^{k'}_{37} = C_{37:2}/(C_{37:2} + C_{37:3})$ ) into sea surface temperature  
368 (SST) using the following equation ( $SST = -0.957 + 54.293(U^{k'}_{37}) - 52.894(U^{k'}_{37})^2 + 28.321$   
369  $(U^{k'}_{37})^3$ ).

370 Simultaneously, high molecular-weight terrestrial n-alkane concentrations were determined.  
371 The C<sub>29</sub>, C<sub>31</sub>, C<sub>33</sub> and C<sub>35</sub> homologues produced from higher plants were quantified. Their sum,  
372 thereafter named TERR-alkanes, was used to reflect terrestrial inputs to the studied site  
373 (Castañeda et al., 2009; Jalali et al., 2017). Vegetation types can be distinguished based on the  
374 relative homologue distribution of leaf wax n-alkanes. Deciduous trees and shrubs are thought  
375 to mainly produce n-alkanes with n-C<sub>27</sub> and n-C<sub>29</sub> while grasses and herbs mainly produce n-  
376 C<sub>31</sub> and n-C<sub>33</sub> (Vogts et al., 2009; Schäfer et al., 2016; Bliedtner et al., 2018). Average Chain  
377 Length (ACL) of n-alkanes was also calculated to produce information on water availability  
378 and compare this to vegetation-type indicators from pollen analyses (Jalali et al., 2017).

379

380

## 381 **4. Results**

### 382 **4.1. Age model of core MD04-2801**

383 The age model of core MD04-2801 was built by integrating 20 AMS  $^{14}\text{C}$  dates (11 from the  
384 ARTEMIS spectrometer of the Laboratoire de mesure du Carbone 14, CEA Paris-Saclay, and  
385 nine from the ECHoMICADAS spectrometer; Table 1): 18 samples consist of monospecific  
386 planktonic foraminifera (*G. bulloides*) and two samples consist of gastropods (Table 1). All  
387 radiocarbon dates were calibrated using the CALIB 8.2 software (Stuiver and Reimer, 1993)  
388 and the IntCal20 calibration curve (Reimer et al., 2020), first considering a reservoir age of -  
389 400 years (Siani et al., 2000). To establish the age model (Figure 2), the rbacon package  
390 (Blaauw and Christen, 2011) was used under R (version 4.1.0; R Development Core Team,  
391 2021; <http://www.r-project.org/>). Two dates were discarded at 931 cm (large analytical error of  
392 270 years; Table 1) and 31 cm (considered as an outlier regarding the first 4 m of the core;  
393 yellow diamonds in Figure 2).

394 It is worth noting that the stratigraphy of the upper section is suspected to be influenced by a  
395 core disturbance by piston effect. This is supported by decreasing values of the sediment density  
396 from 250 cm upward, with very low  $V_p$  values between 140 and 90 cm (Figure 2). For this  
397 reason, the age model was calculated independently for the upper (431 to 0 cm) and lower  
398 (1,031 to 431 cm) parts of the studied core, and then brought together (Figure 2). Considering  
399 the density as the artefact clue, abrupt change in sedimentation rates at 431 cm (Figure 2) is  
400 suggested while the artefact in the sampling appears from 250 cm upward. Furthermore,  
401 laminations are visible below 400 cm but less clear above this level (especially from 250 cm  
402 upward), where sediments appear to be more homogenous (Figure 2). At the MD04-2801 core  
403 site, situated beyond the crest of a turbidite channel-levee system, the expected sedimentary  
404 record could be composed of hemipelagites and fine-grained turbidites from turbidity currents  
405 overspilling the levee. These high accumulation rates (i.e. around 150 cm/kyr on the 431–0 cm  
406 section; Figure 2) cannot therefore be expected to reflect gravity-driven sedimentary processes.  
407 In light of these features, a coring artefact in MD04-2801 is probable (Figure 2). Overall, a  
408 robust chronology is assumed from 431 cm to the base of the core with average sedimentation  
409 rates of about 40 cm/kyr (stable  $V_p$  and density values with a two-step density trend at around  
410 870 cm; Figure 2), while a less robust chronology is assumed from 431 cm upward with a two-  
411 step trend in physical sediment properties. From 431 to 250 cm, well-layered sediments, as  
412 observed in the basal section, correspond to a strong increase in density values and still stable  
413  $V_p$  values and may be related to an acceleration in sedimentation rates (280 cm/kyr; Figure 2).

414 From 250 cm upward, the creep of sediments appears very likely affected by the piston effect  
415 (strong decrease in density values at 250 cm and unexpected low Vp values between 120 and  
416 70 cm). According to the age model (Figure 2), the base of the studied core is dated at 14 cal  
417 ka BP.

418

## 419 **4.2. Sedimentological signals**

420 The core MD04-2801 mainly consists of homogeneous silty sediments that can be separated by  
421 six limits (a to f in Figure 3) based on the trends in graphs of sedimentological parameters.

422 KMDJ23 is a core very close to the MD04-2801 coring site whose top sample (water-sediment  
423 interface) was analyzed and presented in Coussin et al., 2022 ([https://doi-org.scd-proxy.univ-  
424 brest.fr/10.1016/j.marmicro.2022.102157](https://doi-org.scd-proxy.univ-brest.fr/10.1016/j.marmicro.2022.102157) ). It constitutes a modern assemblage useful as a  
425 reference point.

426

### 427 4.2.1. X-ray Fluorescence

428 In order to investigate the co-occurrences of major elements of the XRF dataset, we performed  
429 a Detrended Component Analysis (DCA) on selected elements (Ca, Si, Al, K, S, Ti, Fe, Mn,  
430 Sr; cf. Data in brief). In the study area, the silico-clastic detrital signature is well expressed by  
431 Ti and Fe, while Si and Al are the main chemical components of aluminosilicates. Ti, Fe, Si  
432 and Al show similar trends suggesting that these elements potentially relate to the clayey  
433 fraction formed by the chemical alteration of soils. Conversely, common patterns of Sr and Ca  
434 point to biomineralized and/or detrital carbonates. The DCA statistical analysis (Data in Brief)  
435 led to the most relevant XRF ratios for the following discussion. Given the difficulty in  
436 deconvoluting terrigenous and marine sources in the Ca-XRF signature, we considered both  
437 Ca/Al-XRF (mixed detrital-biogenic signature, Figure 3a) and Ti/Al-XRF (detrital signature;  
438 Figure 3b) for the paleoenvironmental interpretation conducted in the AM sediments. Both  
439 ratios generally show similar fluctuations in temporal variations over time and amplitudes,  
440 suggesting a stronger detrital source in the Ca-XRF signature except for two intervals  
441 characterized by high Ca/Al-XRF and low Ti/Al-XRF ratios from the base of the core to 910  
442 cm (limit “b”) and between 575 and 485 cm (limits d and e). The Ti/Ca-XRF ratio is considered  
443 as primarily detrital and linked to silico-clastic *versus* carbonate sources to the AM.

444

### 445 4.2.2. Magnetic Susceptibility and grain size

446 The Magnetic Susceptibility (MS) signal shows distinct fluctuations between 3.8 and 17.5 SI.  
447 Three main phases are identified with average values of 9.2 SI from the base to 910 cm (limit



448 “b”), of 14.3 SI between 910 and 370 cm (limit “f”) and of 11.6 SI from 370 cm upward (Figure  
449 3c).

450 In addition, according to the high-resolution grain-size data of total sediments (Data In Brief),  
451 the 4–63  $\mu\text{m}$  fraction largely dominates (silt, average of 66%), followed by the fraction  $<4$   $\mu\text{m}$   
452 (clay, average of 23%) and the fraction  $>63$   $\mu\text{m}$  (sand, average of 11%). More specifically, from  
453 the base of the sequence to 910 cm (limit “b”), the high proportion of the  $>63$   $\mu\text{m}$  fraction  
454 (Figure 3d) is associated with low amounts of ferro-magnetic minerals (low MS values; Figure  
455 3c), high Ca/Al values *versus* low Ti/Al (Figure 3 a,b), and extremely low median (D50) grain  
456 size of CaCO<sub>3</sub>-free sediments *versus* high D50 grain size of total sediments (Figure 3d). This  
457 may indicate that coarser sediments are mainly inherited from the erosion of carbonate  
458 formations, with little advection of small-sized silico-clastic and ferro-magnetic sediments.

459 Then, from 910 cm (limit “b”) to 370 cm (limit “f”), higher MS values (Figure 3c) combined  
460 with D50 values of CaCO<sub>3</sub>-free sediments higher than D50 values of total sediments (Figure  
461 3d) indicate increasing advection of silico-clastic and ferro-magnetic silto-clayey material with  
462 a lower proportion of detritic carbonate particles. Across limits “b” to “f”, the coarsest detrital  
463 particles of the mix (silicates and carbonates) are particularly evident in the 740–575 cm interval  
464 (between limits “c” and “d” or interval “c-d”), and correspond to two remarkable peaks of sandy  
465 sediments at 580 and 600 cms (Data in Brief). It is worth noting that the 575 to 485 cm interval  
466 (“d-e”) coincides with the second interval of high Ca/Al-XRF values (as in zone “a-b”) and  
467 lower D50 grain-size values (Figure 3d), with coarser sediments corresponding to silty rather  
468 than sandy particles as in the interval “a-b”.

469 From 370 cm (limit “f”) to 250 cm, MS values as well as grain-size properties point to finer  
470 silto-clayey sediments (Figure 3c). Finally, from 250 cm upward, wide ranges of coarse *versus*  
471 fine-sediment fluctuations (Data in Brief), associated with low D50 grain-size values (Figure  
472 3d), can be reconciled by invoking a small proportion of very coarse sediments which would  
473 bias the mean but hardly alter the particle-size medians. A grey band in Figure 3 highlights this  
474 section, suspected to be affected by core disturbance through piston effect.

475

#### 476 4.2.3. Clay mineral composition

477 Clay mineral averages are about 8% of Illite-Smectite (Interstratified), 18% of Chlorite, 32%  
478 of Kaolinite and 43% of Illite (Data In Brief). Clay results are represented as anomalies relative  
479 to the mean of each dataset (Data In Brief). Due to high sedimentation rates (around 50 cm/kyr;  
480 Figure 2), palygorskite was not significantly detected. The boxes in Figure 3g highlight the  
481 Majorly different clay mineral phases (relative to their mean values). The two intervals of

482 enhanced Ca/Al-XRF values (“a-b” and “d-e”) are also characterized by the highest  
483 interstratified values and lowest kaolinite percentages. Conversely, kaolinite percentages  
484 increase during intervals of both increasing proportions of clays and finer grain-size sediments  
485 (“b-c” and “e”-250cm). This suggests that increasing kaolinite values could evidence  
486 strengthened chemical alteration on land. We consequently use the Kaolinite/Illite ratio as a  
487 proxy of chemical alteration throughout the sequence.

488

### 489 **4.3. Stable isotope signals**

#### 490 4.3.1. Carbon isotopes in foraminifera

491 The  $\delta^{13}\text{C}$  values of endobenthic *Globobulimina affinis* and planktonic *Globigerinoides*  
492 *bulloides* foraminifera range between -0.9 and -2.1‰ (mean of -1.6‰) and between -0.6 and -  
493 2‰ (mean of -1.1‰), respectively (Figure 3e). Planktonic and endobenthic  $\delta^{13}\text{C}$  signals show  
494 similar values until 740 cm (limit “c”), but exhibit a significant offset (average of 0.7 ‰) after  
495 575 cm (limit “d”).

496 Heavier planktonic  $\delta^{13}\text{C}$  values observed during the interval “a-b”, as well as after 575 cm (limit  
497 “d”) reveal strong primary productivity. Conversely, the  $\delta^{13}\text{C}$  of endobenthic foraminifera  
498 generally reflects the  $\delta^{13}\text{C}$  of pore waters, which depends on the export flux of organic matter  
499 and availability of dissolved oxygen in bottom waters (e.g. McCorkle et al., 1990; Mackensen  
500 & Licari, 2003; Fontanier et al., 2006). Lighter benthic  $\delta^{13}\text{C}$  values after limit “b” may be  
501 indicative of remineralization of enhanced organic matter in bottom sediments.

502

#### 503 4.3.2. Oxygen isotopes

504 Endobenthic (*G. affinis*) and planktonic (*G. bulloides*)  $\delta^{18}\text{O}$  values range between 2.1 and 4 ‰  
505 (mean of 2.6 ‰) and between 0.4 and 2.2 ‰ (mean of 0.8 ‰), respectively, and show similar  
506 patterns throughout the sequence (Figure 3f). Heavier  $\delta^{18}\text{O}$  values (colder sea surface  
507 temperatures) in the interval “a-b” are reflected by values of 1.9 and 3.8 ‰ for planktonic and  
508 endobenthic taxa, respectively. Lighter mean  $\delta^{18}\text{O}$  values after limit “b” are stable around 0.6  
509 ‰ (standard deviation of 0.2 ‰) and 2.4 ‰ (standard deviation of 0.1 ‰) for planktonic and  
510 endobenthic taxa, respectively. However, wider ranges of planktonic  $\delta^{18}\text{O}$  isotope value  
511 variations, with slightly lower values since interval “b-d”, may be indicative of either  
512 decreasing salinities and/or increasing temperatures.

513

### 514 **4.4. Palynological analyses**

#### 515 4.4.1. Dinoflagellate cysts

##### 516 • *Diversity and concentrations*

517 Thirty-nine different dinocyst taxa were identified over the whole sequence, with a mean  
518 species richness of 18 different taxa per slide (Figure 4a). Species richness is lower than average  
519 from the base of the sequence to limit “a” (1,025 cm), in the “b-d” interval (910–575cm), and  
520 after limit “e”. Conversely, species richness is higher than average in “a-b” (1,025–910 cm) and  
521 “d-e” (575–485 cm) intervals. Both intervals are also characterized by low kaolinite percentages  
522 and high Ca/Al-XRF values, as well as heavy planktonic  $\delta^{13}\text{C}$  values.

523 The dinocyst dominance index (Figure 4a) is systematically explained by the major taxa  
524 *Brigantedinium*. The dinocyst diversity (Figure 4a), as reflected by the Margalef index (similar  
525 to species richness), shows opposite trends compared to *Brigantedinium* spp.; the lowest  
526 diversity being synchronous with high *Brigantedinium* spp. percentages.

527 Total dinocyst concentrations, mainly explained by *Brigantedinium* spp. occurrences, range  
528 between 450 and 29,000 cysts/cm<sup>3</sup>, with mean values of around 3,300 cysts/cm<sup>3</sup> (Figure 4a).  
529 Dinocyst concentrations show higher values during intervals “a-b” (1,025 to 910 cm) and “d-  
530 e” (575 to 485 cm), both previously described by a stronger diversity. We thus plotted the  
531 concentrations of all dinocysts without *Brigantedinium* spp. against the concentrations of  
532 *Brigantedinium* spp. alone in order to evaluate the respective contribution of these heterotrophic  
533 taxa with regards to the rest of the dinocyst community (Figure 4a). Up to limit “b”, other  
534 dinocysts are higher than *Brigantedinium* spp. (around 10,000 *versus* 2,000 cysts/cm<sup>3</sup>). They  
535 follow similar patterns between limits “b” and “e” (around 1,500 cysts/cm<sup>3</sup>) and, after limit “e”,  
536 all other dinocyst concentrations are slightly lower than *Brigantedinium* spp. (1,000 vs. 1,500  
537 cysts/cm<sup>3</sup>). Dinocyst concentrations show lower values but similar evolution compared to  
538 pollen grain concentrations throughout the sequence, except for similar concentrations obtained  
539 from 1040 cm to limit “b” and during the interval “d-e” (575–485 cm).

540

##### 541 • *Dinocyst assemblages and dinocyst zones*

542 Dinocyst assemblages are dominated by eight autotrophic taxa: *Nematosphaeropsis*  
543 *labyrinthus*, *Impagidinium aculeatum*, *Spiniferites mirabilis*, *Operculodinium centrocarpum*,  
544 *Spiniferites bentorii*, *Spiniferites membranaceus*, cysts of *Pentapharsodinium dalei*,  
545 *Lingulodinium machaerophorum* and seven heterotrophic taxa including *Echinidinium* spp.,  
546 *Selenopemphix quanta*, cysts of *Protoperidinium nudum*, *Selenopemphix nephroides*,

547 *Lejeunecysta* spp. (grouping of *L. oliva* and *L. sabrina*), *Trinovantedinium* spp. and  
548 *Brigantedinium* spp. (Figure 5a).

549 The dinocyst assemblages led us to consider four main limits, thus five palynozones (MD04-1  
550 to MD04-5; Fig. 5). These boundaries/zones are based on the CONNISS cluster analysis  
551 performed on dinocyst assemblages (threshold used is 11; Figure 5a). These four limits also  
552 correspond to four sedimentological limits (a-b-d-e; Figs. 3 and 4). Zone MD04-1, from the  
553 base of the sequence to limit “a”, is characterized by the dominance of *Brigantedinium* spp., *S.*  
554 *mirabilis* and *O. centrocarpum*. The second zone MD04-2 (interval “a-b”) is marked by  
555 increasing values of *N. labyrinthus* reaching 20 to 40%, associated with the increase in *B.*  
556 *tepiense*, *S. lazus* and *O. centrocarpum*. Zone MD04-03 (interval “b-d”) is characterized by a  
557 high plateau of *Brigantedinium* spp. up to ca. 40%, associated with the increase in *I. aculeatum*  
558 (up to 15 %) and *S. mirabilis*, especially in the interval “c-d”, and a progressive decrease in *O.*  
559 *centrocarpum* percentages. Zone MD04-4 (interval “d-e”) shows a sharp drop in  
560 *Brigantedinium* spp. percentages reaching 20%, while *S. mirabilis* increases to 30%. Finally,  
561 zone MD04-5 (from limit “e” onward) is characterized by the highest values of *Brigantedinium*  
562 spp. (about half of the total assemblage) associated with *S. mirabilis* (around 15%). A full  
563 description of main dinocyst results is available in Data in Brief.

564

#### 565 4.4.2. Pollen grains

##### 566 • *Diversity and concentrations*

567 Seventy-one different pollen taxa were identified for the whole sequence, with a mean species  
568 richness of 28 different taxa per slide (Figure 4b). Species richness ranges between 18 and 29  
569 taxa per slide with lower values between limits “c” and “f” (740 to 370 cm) which also  
570 correspond to the strongest representation of forest taxa (cf. percentages of total trees and total  
571 trees with *Pinus*; Figure 4b). In contrast, increased diversity coincides with the diversification  
572 of herbaceous plants. Mean total pollen concentrations are approximately of 6200 grains/cm<sup>3</sup>  
573 (ranging between 1300 and 25,000 grains/cm<sup>3</sup>); the highest values are in intervals “a-b” (1,025  
574 to 910 cm) and “d-e” (575 to 485 cm), as for dinocysts, and above 250 cm (removed from the  
575 discussion).

576 *Pinus* concentrations follow the same trend as total pollen concentrations that are mainly driven  
577 by trees (especially *Quercus*). Strong pollen production, enhanced river transport, and finer  
578 grain-sized sediments, are crucial factors contributing to increase pollen-grain concentrations.  
579 However, the strong link between pollen (terrestrial compartment) and dinocyst (marine realm)

580 concentrations point to a common mechanism of organic matter export to the AM and  
581 sedimentation processes.

582

583 • *Pollen and Non-Pollen Palynomorph (NPP) assemblages and pollen zones*

584 The zones defined on the basis of dinocyst assemblages have also been used for pollen  
585 assemblages to facilitate land-sea comparison (Figure 5b). Zone MD04-1 is characterized by  
586 the dominance of herbaceous pollen taxa, mainly Cichorioideae and Poaceae. Zone MD04-2 is  
587 marked by the strong increase in the altitudinal taxa *Cedrus* (reaching maximum percentages  
588 above 40% at 1001 and 961 cm), associated with semi-desert, steppic pollen taxa (i.e. *Ephedra*  
589 and *Artemisia*) and coastal-steppic taxa (i.e. Amaranthaceae). Zone MD04-3 is characterized  
590 by the progressive increase in arboreal taxa (especially *Quercus ilex*), associated with strong  
591 occurrences of herbaceous taxa (Cichorioideae and Poaceae) until 740 cm (limit “c”). In zone  
592 MD04-3, limit “c” corresponds to the onset of the strongest forest representation, largely  
593 represented by *Quercus*, associated with Cupressaceae, as well as Mediterranean forest (*Olea*,  
594 *Pistacia*) and open vegetation (i.e. Cichorioideae and Poaceae) taxa. Interestingly, from limit  
595 “c”, freshwater algae occurrences also increase. Zone MD04-3 is also marked by increasing  
596 abundance of *Glomus* spores and Ascospores. Zone MD04-4 shows a strong representation of  
597 arboreal taxa (up to 40%) associated with a slight decrease in open-vegetation taxa  
598 (Cichorioideae, Poaceae). Coastal-steppic taxa (Amaranthaceae), with slight increases in  
599 *Ephedra* and *Artemisia*, also correspond to decreasing occurrences of *Glomus* spores. Finally,  
600 zone MD04-5 is characterized by the progressive decrease in arboreal taxa (especially *Quercus*)  
601 favoring the synchronous increase in open-vegetation taxa (Cichorioideae, Asteroideae,  
602 Poaceae). Additionally, percentages of semi-desert taxa (*Ephedra* and *Artemisia*) somewhat  
603 increase with those of *Olea*, and *Glomus* spore occurrences progressively increase. Modern  
604 climate-landscape relationships in Eurasia and northern Africa (Woodwards, 1987; Peyron et  
605 al., 1998) will be considered for pollen interpretation. A full description of main pollen results  
606 is available in Data in Brief.

607

608 **4.4. Palynological quantification**

609 For dinocyst-inferred sea-surface reconstructions, the maximum number of selected analogues  
610 is five (Figure 4) Also, a threshold of 1.35 is adopted by the MAT (Modern Analogue  
611 Technique) to exclude too dissimilar assemblages. In this study,  $D_{min}$  varies around an average  
612 value of 0.87: no analogue was selected for six levels (440, 664, 800, 948, 992, 1000 cm), only  
613 one analogue for four levels (60, 746, 860, 932 cm), two analogues for one level (976 cm), three

614 analogues for three levels (976 cm), four analogues for nine levels (340, 532, 696, 760, 872,  
615 880, 920, 1026, 1040 cm) and five analogues for the 63 other levels, testifying for statistical  
616 robustness of the reconstruction for about three quarters of the analysed samples.

617 For pollen-inferred climate reconstructions, the number of selected analogues is always four.  
618 Appropriate analogues are selected through cross-validation based on the leave-one-out  
619 approach. Stable Dmin values are about 0.39 from 1,040 cm to limit “e” and about 0.47 from  
620 limit “e” to the top of the sequence, testifying to the robustness of reconstructed climatic  
621 parameters.

622 Considering hydrological (cf. dinocyst-based quantifications) and climate (cf. pollen-based  
623 quantifications) parameters, SST and SSS are discussed in parallel with annual precipitation  
624 and temperature seasonality. The exhaustive dataset of reconstructed environmental parameters  
625 is available in Data in Brief.

626

#### 627 **4.5. Molecular biomarkers**

628 Concentrations of C<sub>37</sub> alkenones, plotted as the sum of C<sub>37:2</sub> + C<sub>37:3</sub>, range from 18 to 328.5  
629 ng.g<sup>-1</sup>, with a mean value of about 75.6 ng.g<sup>-1</sup> (Figure 4a). The  $\sum C_{37}$  follows the same trend as  
630 that of palynomorph (dinocyst and pollen) concentrations along the sequence, with higher  
631 values in the oldest interval “a-b” (1,025 to 910 cm), highlighting the common pattern in  
632 organic matter export and preservation through both biomarker and palynological approaches.

633 Concentrations of TERR-alkanes range between 354 and 1,071 ng.g<sup>-1</sup>, with a mean value of  
634 643 ng.g<sup>-1</sup> (Figure 4b). Up to limit “b” (910 cm), they decrease to the lowest values of the record  
635 (379 ng.g<sup>-1</sup>). From limits “b” to “d”, TERR-alkane concentrations are generally higher and  
636 highly variable with above average values. They broadly decrease during intervals “d” to “f”  
637 and increase again until 370 cm before decreasing up to the top of the studied core.

638 Finally, the ACL (Average Chain Length; Figure 4b) calculated from the n-alkane distribution  
639 shows increasing values from interval “a” to “d”, suggesting a gradual dryness (expressed by  
640 high ACL values), followed by stable values up to limit “f”, followed by decreasing values  
641 close to the mean of the dataset (30,1) up to the top of the studied sequence. Mean values of the  
642 ACL are generally consistent with our palynological data underlying a strong representation of  
643 open vegetation along the sequence.

## 644 **5. Discussion**

### 645 **5.1. Palynomorph preservation and the signature of *Brigantedinium* spp.**

646 Fine-grained (silty-clayey) sediments and high sedimentation rates (ca. 50 cm/kyr) recorded  
647 with core MD04-2801 may have favored conditions for the preservation of fossilized  
648 palynomorphs (dinocysts and pollen grains). A recent study of the modern distribution of pollen  
649 grains in the WMB suggested that modern pollen assemblages in our study area are  
650 representative of the adjacent vegetation (e.g. *Quercus ilex*, Amaranthaceae and Cichorioideae;  
651 Coussin et al., 2022). However, previous studies have investigated taxa sensibilities to  
652 oxidation effects (e.g. Havinga, 1967, 1971; Lebreton, 2009). It has for exemple been shown  
653 that *Quercus* and Cichorioideae pollen grains are not very sensitive to degradation and could  
654 be overrepresented in pollen assemblages at the expense of other taxa. The intact aspect of all  
655 pollen grains throughout the sequence leads us to hypothesize that pollen are mainly from the  
656 coastal Algerian catchments and that over-representation of the main taxa is unlikely.  
657 Regarding dinocyst taxa, *Brigantedinium* spp. are dominant and show large fluctuations (ca. 10  
658 to 80 %; Figure 4a, 6j) throughout core MD04-2801. *Brigantedinium* spp. are often interpreted  
659 as witnessing upwelling regimes (e.g. Marret, 1994; Zonneveld et al., 1997, 2001;  
660 Bouimetarhan et al., 2009; Penaud et al., 2016; Coussin et al., 2022). Moreover, modern  
661 occurrences of *Brigantedinium* spp. in surface sediments of the western Mediterranean Basin  
662 (around 20%; Coussin et al., 2022) in association with *T. applanatum*, *Lejeunecysta* spp.,  
663 *Echinidinium* spp., *S. nephroides* and grouped *Selenopemphix quanta* and *Protoperidinium*  
664 *nudum*, also allowed to assign these taxa to productive surface waters and were used to highlight  
665 the major haline-upwelling front associated with the AC, itself depending on the vigour of the  
666 Alboran gyres (Coussin et al., 2022). *Brigantedinium* spp. peaking values of ca. 80% over the  
667 Holocene (Figure 6i) were never reached in western Mediterranean modern surface sediments,  
668 even along the AC (Coussin et al., 2022). Since *Brigantedinium* spp., as well as *Echinidinium*  
669 spp., are well-known for their strongest sensitivity to oxic conditions (e.g. Zonneveld et al.,  
670 1997; Kodrans-Nsiah et al., 2008; Bogus et al., 2014), their percentages must be interpreted  
671 carefully as direct tracers of primary productivity. Indeed, it has been shown that their  
672 occurrences in sediments decrease logarithmically with increasing bottom water oxygen  
673 content (Zonneveld et al., 2001, 2007, 2008). Our reconstructions therefore raise questions  
674 about potential taphonomic biases that may have affected dinocyst assemblages.  
675 The MD04-2801 core retrieved at a water depth of 2,063 m is located in the water depth range  
676 of the Western Mediterranean Deep Waters (WMDW). The WMDW, as well as Ligurian

677 Intermediate Waters (LIW), contribute to the Mediterranean Outflow Water (MOW) export at  
678 the Gibraltar Strait (Stommel et al., 1973; Lionello et al., 2006) which varied through time (e.g.  
679 Voelker et al., 2006; Toucanne et al., 2007; Peliz et al., 2009; Rogerson et al., 2010; Bahr et al.,  
680 2014, 2015; Voelker and Aflidason, 2015; Hernández-Molina et al., 2014). Stronger LIW  
681 during cold climate events (Toucanne et al., 2012) such as the Younger Dryas (YD), implying  
682 a stronger WMB ventilation, is also supported by Alboran Sea records (Mc Culloch et al.,  
683 2010). In contrast, warmer Holocene conditions, and especially the Sapropel 1 event ( $10.8 \pm$   
684  $0.4$  to  $6.1 \pm 0.5$  ka BP) in the Eastern Mediterranean Basin (e.g. Kallel et al., 1997; Bar-  
685 Matthews et al., 2000, 2003; Mercone et al., 2000; Rohling et al., 2002; Tachikawa et al., 2015),  
686 are characterized by a weakened/cessation of the LIW formation (e.g. Toucanne et al., 2012).  
687 This shift from well-ventilated bottom waters during the YD to less-ventilated ones during the  
688 Holocene optimum (ca. 9.5-6.5 ka BP) may respectively correspond to low (around 20% such  
689 as today) or high ( $> 40\%$ ) percentages of *Brigantedinium* spp. (Figure 6i). There is therefore a  
690 risk that *Brigantedinium* spp. relative abundances may be modulated by oxygenation conditions  
691 despite the high sedimentation rates recorded at our studied site. In this context, Zonneveld et  
692 al. (2007) suggested to use absolute concentrations of phototrophic rather than heterotrophic  
693 taxa (or total dinocyst) ones, combined with dinocyst diversity (or species richness), to better  
694 assess productivity conditions. In the following discussion, these recommendations are  
695 considered to limit potential biases due to diagenesis or ventilation when discussion dinocyst  
696 assemblage reconstructions.

697

## 698 **5.2. From the Bölling-Alleröd to the Younger Dryas**

### 699 5.2.1. Hydrological conditions

700 Alkenone SSTs show a strong cooling from the Bölling-Alleröd (B/A: zone MD04-1) to the  
701 Younger Dryas (YD: zone MD04-2 or “a-b”; Figure 6) featuring the lowest SST values (i.e.  
702  $15.5^{\circ}\text{C}$ ;  $4.1^{\circ}\text{C}$  below modern annual SSTs), consistent with the heaviest planktonic  $\delta^{18}\text{O}$  values  
703 greater than 2‰ (Figure 6a,b). These low temperatures corresponds to the lowest reconstructed  
704 seasonality values (Figure 7h). This cold SST trend is synchronously observed in both the  
705 WMB sequences (Figure 8d,h,k,n,q). During the YD, cool-water dinocyst taxa (*N. labyrinthus*,  
706 *B. tepikiense* and *S. lazus* ; Figure 6c) dominating today polar to subpolar environments  
707 (Rochon et al., 1999; Van Nieuwenhove et al., 2020) show maximum percentages, while  
708 dinocyst-derived SSTs are not able to provide modern analogues representative of the  
709 environmental conditions of this cold climate event (Figure 6b). Indeed, all selected analogues



710 had statistical distances higher than the accepted threshold (cf. Data in Brief). SSTs lower by  
711 3.5 and 8.5°C with respect to present-day winter conditions were reconstructed using  
712 foraminifera and dinocysts in SW Portugal and Cadiz-NW Morocco, respectively (Penaud et  
713 al., 2011). At these northeastern Atlantic subtropical sites, the same YD assemblages (*N.*  
714 *labyrinthus*, *B. tepikiense* and *S. lazus*) were observed with slight differences in percentages: *B.*  
715 *tepikiense* hardly occurred in the Gulf of Cadiz and further south, while *S. lazus* was not found  
716 off Portugal (Penaud et al., 2011). These observations support the mixed northern and  
717 subtropical North Atlantic influences in the AM. Also, as observed in the Alboran Sea (Turon  
718 and Londeix, 1988), *N. labyrinthus*, a stratigraphical marker of the YD, testifies of the  
719 southward shift of the bioclimatic belts during this cold event of the last deglaciation. In the  
720 AM, percentages around or slightly higher than 30% are closer to those reconstructed off the  
721 Iberian margin (slightly higher than 20%) than in NW Morocco (about 5%), and point to an  
722 enhanced advection of cold Atlantic waters in the WMB. In addition, *O. centrocarpum* (i.e.  
723 North Atlantic taxon) shows four-time stronger representation than *L. machaerophorum*  
724 estuarine taxon, suggesting the prevailing oceanic influence in the AM and associated low  
725 fluvial input (Figure 5a). This is supported by the higher values of Ocen/Lmac dinocyst ratio  
726 for all the compared WMB sites (Fig. 8)

727 Heavy planktonic  $\delta^{13}\text{C}$  values (Figure 6g) and higher concentrations of alkenones (Figure 4a)  
728 and phototrophic dinocyst concentrations (Figure 6f) as well as a strong dinocyst diversity  
729 (Figure 4a) suggest enhanced primary productivity, despite lower percentages of  
730 *Brigantedinium* spp. (Figure 6i) that may result from a lower preservation of heterotrophic cysts  
731 under stronger bottom-water ventilation (cf. section 5.1). More productive conditions may be  
732 attributed to a stronger vigour of the AC resulting from the strengthening of the Alboran gyres  
733 during the YD (Combourieu-Nebout et al., 1999; Barcena et al., 2001; Penaud et al., 2011;  
734 Rouis-Zargouni et al., 2012; Ausín et al., 2015). This finding can also be explained by enhanced  
735 vertical mixing triggered by stronger winds replenishing surface waters with deep water  
736 nutrients.

### 737 5.2.2. Climate and continental context

738 Enhanced YD productivity could result from fertilization of the photic zone by Saharan dust  
739 deposition (Moreno et al., 2002; Bout-Roumazelles et al., 2007; Jimenez-Espejo et al., 2008;  
740 Rodrigo-Gamiz et al., 2011; Bout-Roumazelles et al., 2013). Unfortunately, the clayey fraction  
741 of core MD04-2801 only represents ca. 20% of the sediment lithology. The high sedimentation  
742 rates (ca. 50 cm/kyr), mainly characterized by silts, do not allow characterizing aeolian-

743 transported clayey minerals such as the typical palygorskite signature which is drowned in other  
744 clayey minerals amount signals.

745 During the YD, the strong representation of semi-arid (*Artemisia*, *Ephedra*) and steppic-coastal  
746 (Amaranthaceae) taxa, and the weak representation of Mediterranean forest taxa indicate  
747 extremely dry conditions characterized by an open and steppic landscape (Figure 7g). This open  
748 landscape is expressed by the lowest forest taxa representation in the WMB sequences (Figure  
749 8g,j,m,p). Previous studies in the Western Mediterranean Sea already showed this cold-dry  
750 event as characterized by a first dry phase followed by a more humid period (e.g. Combourieu  
751 Nebout et al., 1998, 2002; Turon et al., 2003; Naughton et al., 2007; Kotthoff et al., 2008;  
752 Fletcher and Sanchez-Goñi, 2008; Dormoy et al., 2009; Combourieu-Nebout et al., 2009;  
753 Desprat et al., 2013). This bipartite structure is not obvious at the resolution of our study, except  
754 for a slight decreasing trend of *Artemisia* from the start to the end of the YD (Figure 5b).  
755 Additionally, increasing ACL values from 29.8 to 30.2 (Figure 4b) are consistent with a higher  
756 plant adaptation to water stress.

757 The YD sedimentary facies of core MD04-2801 highlights coarse carbonate sediments with  
758 minor advection of small-sized silico-clastic and ferro-magnetic sediments (Figure 3d).  
759 Consequently, arid conditions during the YD, as revealed by pollen grains, may have favored  
760 erosion of sedimentary formations onland and aeolian transport of carbonate particles amplified  
761 by strengthened atmospheric circulation. Indeed, low Kaolinite values (cf. Data in Brief)  
762 suggest reduced chemical alteration, while low concentrations of *Glomus* spores evidence weak  
763 runoff due to low precipitations (Figure 7c). Sporadic but intense erosive runoff events may be  
764 linked to peaks of reworked cysts originating from the alteration of Tertiary carbonate  
765 formations (Figure 5a). Indeed, Algerian oued discharge intensifies during intense rainfalls  
766 events responsible for flash floods with strong erosive effects. However, the scarce occurrences  
767 of continental NPPs and generally low concentrations of reworked dinocysts rather attest low  
768 alteration and low fluvial delivery to the AM.

769 Finally, unusual occurrences of *Cedrus* (about 20 %, peaking at 40 % ; Figure 7j) are recorded.  
770 Considering the modern distribution of *Cedrus atlantica* in Northern Africa (Bell et al., 2019),  
771 in the highest altitudinal vegetation belts (Ben Tiba and Reille, 1982; Stambouli-Essassi et al.,  
772 2007), and the modern distribution of *Cedrus* percentages (around 0.5%) in KMDJ-23 core  
773 (Coussin et al., 2022), we suggest that a wider altitudinal *Cedrus-Pinus* forest developed in the  
774 high reliefs of the Tell Atlas. Even if stronger aeolian transport of coniferous pollen grains  
775 better dispersed by winds than other pollen grains is possible under stronger atmospheric  
776 circulation, synchronous peaks of *Cedrus* and reworked cyst concentrations (Figure 4), rather

777 suggest remaining mild conditions in altitudinal zones enhancing fluvial transport (i.e. strong  
778 seasonal erosive runoff) of *Cedrus*, even under the prevailing arid conditions of the YD.

779

### 780 **5.3. The Early Holocene (11.7–8.2 ka BP)**

#### 781 5.3.1. Delayed Mediterranean forest expansion

782 The Early Holocene is characterized by a strong decrease of the semi-arid and coastal-steppic  
783 vegetation (Figure 7g), replaced by typical matorrals (xerophytous open vegetation) mainly  
784 represented by Cichorioideae (Figure 5b). At the same time, the altitudinal forest represented  
785 by *Cedrus* is no longer recorded along the Holocene with high percentages (i.e. values close to  
786 modern ones; Figure 7j), due to reduced extent of these altitudinal vegetation belts in the Atlas  
787 Mountains in a context of increasing temperatures allowing other taxa to colonise altitudinal  
788 belts. Previous studies also discussed the limited altitudinal area where *Cedrus* retracted at the  
789 YD-Holocene transition, while warmer Holocene conditions favors the evergreen *Quercus*  
790 forest expansion (Marret and Turon, 1994; Cheddadi et al., 1998, 2009; Zielhofer et al., 2017).  
791 Until 8 ka BP, the progressive increase of Mediterranean forest taxa, combined with the  
792 persistent signature of the open vegetation (e.g. Cichorioideae, Poaceae; Figure 7 f,g), suggest  
793 a progressive increase of moisture, which is a critical limiting factor for the forest expansion in  
794 the southern Mediterranean area (Quezel, 1999). Increasing moisture is also supported by  
795 sedimentological, bioindicator, and biochemical runoff tracers (i.e. higher magnetic  
796 susceptibility (Figure 7e) and Ti/Ca-XRF values (Figure 6h), higher concentrations of *Glomus*  
797 spores (Figure 7c) and of pre-quaternary cysts (Figure 4a), higher TERR-alkane fluxes (Figure  
798 7d)). In the AM, *Quercus* maximal values thus appear delayed, while Mediterranean matorrals  
799 (mainly represented by Cichorioideae, Poaceae and Asteraceae) associated with typical  
800 sclerophytous trees (*Olea* and *Pistacia*), are still observed.

801 The delayed expansion of forest appears consistent with current Mediterranean observations  
802 suggesting that, following moisture deficiency, three millennia are necessary for a full  
803 Mediterranean forest recovery (e.g. Combourieu-Nebout et al., 1998, 2002; Allen et al., 2002;;  
804 Turon et al., 2003; Naughton et al., 2006; Fletcher and Sanchez-Goñi, 2008; Jalut et al., 2009;  
805 Tzedakis, 2007; Fletcher et al., 2010; Zielhofer et al., 2017). The Early Holocene corresponds  
806 to the highest values of boreal summer insolation (Berger and Loutre, 1991; Figure 8b),  
807 responsible for high summer temperatures that may have enhanced summer Mediterranean  
808 droughts, therefore slowing down the development of trees, especially evident in the more  
809 sensitive eastern part of the basin (Figure 8m,p). Previous studies conducted in northwestern

810 Africa also discussed the maximal forest development at around 8.5 ka BP (Ballouche, 1986;  
811 Brun 1989; Lamb et al., 1989), consistently with the maximal values reached at the end of the  
812 Early Holocene in our study core (ca. 8 ka BP). Climate quantifications also suggest relatively  
813 low precipitation before 8.5 ka BP while the temperature seasonality indicates a strong thermal  
814 amplitude explained by high summer temperatures (Figure 7h). The Alboran Sea and by  
815 extension the AM are extremely sensitive to the Atlantic moisture through the influence of  
816 westerlies (i.e. for Mediterranean cyclogenesis). From 11.7 to 10 ka BP, the extended dry period  
817 post-YD has also been reported across the SW and NE Mediterranean basin (Dormoy et al.,  
818 2009) and is probably linked to a still weak influence of westerly cyclones (Kotthoff et al.,  
819 2008). Indeed, the North Atlantic storm tracks may have been maintained in a southern position  
820 under the influence of the Fennoscandian Ice Sheet still persistent until 9 ka BP (Magny et al.,  
821 2003). There, the forest expansion is directly in phase with the climate change of northern  
822 Atlantic latitudes (cf. NGRIP oxygen isotopes *versus* Alboran Sea forest signal in Figure 8a,g,j),  
823 in agreement with numeric simulations (Carlson et al., 2008). The Atlantic influence, and  
824 associated moisture transport, follows a decreasing gradient from west to east (Figure 8h,j,m,p)  
825 between the Alboran Sea to Algeria, whatever the climate interval considered over the last 14  
826 kyrs.

827

### 828 5.3.2. Warmer oligotrophic conditions

829 In parallel with the Mediterranean forest expansion (Combourieu-Nebout et al., 1998, 1999,  
830 2002, 2009), alkenone, dinocyst and planktonic  $\delta^{18}\text{O}$  data (Figure 6a,b,c) point to a strong  
831 increase of SSTs at the start of the Holocene, with a 4.5°C increase of alkenone-based annual  
832 SST (i.e. from 16°C during the YD to ca. 20.5°C during the Holocene). It is worth noting that  
833 alkenone-based SSTs exhibit mean annual values consistent with the dinocyst-based SST  
834 seasonal variability range (Figure 6b). Furthermore, both alkenone- and dinocyst-derived SST,  
835 as well as percentages of cold water dinocyst taxa, point to slightly cooler SST conditions  
836 during the Early Holocene regarding the following conditions of the Middle Holocene. The  
837 warmest conditions are therefore not reached yet during the Early Holocene, and the prevalence  
838 of runoff signatures (significant peaks of *Glomus* and pre-Quaternary cysts; Figure 4a, 7a) may  
839 result from increasing moisture combined with a still high erodability of soils in a continental  
840 context of persistent opened landscape.

841 The Holocene transition is also characterized by a pronounced drop of dinocyst and alkenone  
842  $\text{C}_{37}$  concentrations (Figure 4a), as well as lighter planktonic  $\delta^{13}\text{C}$  values (Figure 7f), likely

843 accounting for less productive conditions. Interestingly, heterotrophic cyst percentages (Figure  
844 7j) increase with a plateau of high values (about 50 %) persistent until 6.5 ka BP. However, the  
845 Early Holocene also corresponds to the maximum of the boreal summer insolation and the  
846 related northward migration of the intertropical convergence zone. This configuration drives  
847 the formation of Sapropel S1 (cf. Figure 6; Rohling, 1994; Rohling et al., 2004, 2015) added to  
848 the enhanced river discharge in the Eastern Mediterranean Basin, as observed eastward in the  
849 Siculo-Tunisian strait between ca. 9.5–6 ka BP (Bout-Roumazeille et al., 2013). We suggest  
850 that enhanced African monsoons (e.g. Emeis et al., 2000 ; Kallel et al., 1997 ; De Menocal et  
851 al., 2000 ; Tachikawa et al., 2015 ; Siani et al., 2013), associated with the cessation of deep and  
852 intermediate water formation (Frigola et al., 2007; Toucanne et al., 2012), may have favored  
853 organic matter and therefore heterotrophic cyst preservation, and especially that of the most  
854 sensitive taxa *Brigantedinium* spp., under anoxic bottom waters in the Mediterranean Sea. Low  
855 productive conditions in the AM, as also confirmed by significant co-occurrences of *I.*  
856 *aculeatum* and *S. mirabilis* (Coussin et al., 2022), resonate with the oligotrophic conditions  
857 recorded in the Gulf of Cadiz (Penaud et al., 2016) that may have propagated in the WMB  
858 through advection of nutrient-poor subtropical North Atlantic Central Waters.

859

#### 860 **5.4. Middle Holocene (8.2–4.2 ka BP)**

861 After an increasing trend across the Early Holocene, the Mediterranean forest reaches maximal  
862 values higher than 20% during the Mid-Holocene, while the Eurosiberian taxa do not show a  
863 significant increase (Figure 7f). These latter arboreal taxa require high moisture conditions and  
864 a reduced seasonality in the precipitation regime, therefore suggesting still moderate  
865 precipitation in the southern Mediterranean Basin as also confirmed by sclerophyllous and  
866 matorral observations (Figure 7g). The best coincidence interval for high-forest percentages in  
867 the three western Mediterranean sequences is recorded between 10 and 5.5 ka BP (green colored  
868 band in Figure 8). More specifically, the Mid-Holocene can be subdivided into three main  
869 phases.

##### 870 5.4.1. The “8.2 ka BP” event

871 The first event, centered around 8.2 ka BP, lasting for about 100 to 200 years, is characterized  
872 by a significant drop in forest distribution (Figure 7f). This is reminiscent of the so-called “8.2  
873 ka event” (Alley et al., 1997) that led to cold climate and hydrological conditions in the  
874 Northern Hemisphere and also affected the WMB (Combourieu Nebout et al., 1998, 2002;  
875 Magny et al., 2003; Zanchetta et al., 2007; Fletcher and Sanchez-Goñi, 2008; Pross et al., 2009;

876 Depreux et al., 2021) by limiting the precipitation pattern (Berger and Guilaine, 2009; Morrill  
877 et al., 2013). During this arid event, anomalously low fluvial discharge may be responsible for  
878 lower concentrations of pre-Quaternary cysts, *Glomus* spores, and freshwater microalgae in the  
879 AM (Figure 5a, 7b,c). This drought interval is also obvious with low values of the ratios Ti/Ca-  
880 XRF ratio (Figure 6h) and Kaolinite/Illite (Figure 7a) thus respectively suggesting both lower  
881 river runoff and chemical alteration. The 8.2 ka BP event is also known as a cold event with  
882 lowered SSTs, as recorded by alkenone SST (Figure 6b).

#### 883 5.4.2. The African Humid Period

884 Between 8 and 6 ka BP, evergreen oaks largely dominated the Mediterranean forest (Figure 5b,  
885 7f), with the maxima recorded at that time, associated with the highest representation of *Pistacia*  
886 and *Olea*, and the lowest representation of coastal-steppic and semi-arid taxa (Figure 7g),  
887 suggesting decreasing summer aridity and mild winters. From 8 to 6 ka BP, this important  
888 increase in moisture is consistent with previous studies conducted in the southwestern  
889 Mediterranean lowland areas (Fletcher et al., 2013; Jaouadi et al., 2016).

890 In addition, high river discharges are highlighted by increasing pre-Quaternary cyst and *Glomus*  
891 spore concentrations, as well as by the first significant increases in freshwater microalgae  
892 concentrations (Figure 7b) and significant low excursions of dinocyst-based SSS estimates  
893 (salinity drops of around 1.5 psu; Figure 6d). Simultaneously, higher Kaolinite (Figure 7a) and  
894 Ti/Ca-XRF (Figure 6h) values attest to increasing chemical alteration and river runoff, in a  
895 context of warmer SSTs suggested by dinocyst-derived and alkenone reconstructions (1.5°C  
896 higher than present; Figure 6b,c). This interval of increased precipitation in the Algerian  
897 highlands is synchronously recorded by several studies in the Maghreb region (Jaouadi et al.,  
898 2016; Lebreton et al., 2019; Depreux et al., 2021) and by Mediterranean simulations (Brayshaw  
899 et al., 2011; Peyron et al., 2017). At this time, rains grew stronger and spread northward into  
900 the Sahara with enhanced summer rainfall in Africa and other parts of the tropics (e.g. de  
901 Menocal et al., 2000; McGee et al., 2013). No monsoon precipitations are recorded in the  
902 studied Western Mediterranean area (Tzedakis, 2007; Brayshaw et al., 2011), but increasing  
903 moisture attests to the strongest phase of summer rainfall (average annual precipitation of 650  
904 mm; 270 mm higher than the present) in a context of enhanced temperature seasonality (Figure  
905 7h).

906 After the oligotrophic cooler conditions of the Early Holocene, higher nutrient-enriched fluvial  
907 discharge may explain a slight increase in productivity, as suggested by increasingly heavy  
908 values of planktonic  $\delta^{13}\text{C}$  and a slight increase in phototrophic cyst concentrations (Figure 6f,g).

909 However, the Middle Holocene also records the strongest representation of the subtropical  
910 taxon *I. aculeatum*, concomitantly with Alboran Sea and Gulf of Cadiz sequences (Penaud et  
911 al., 2011, 2016; Rouis-Zargouni et al., 2012), this taxon signing for warmer-oligotrophic sea  
912 surface conditions. We therefore suggest that the high mid-Holocene SSTs may have prolonged  
913 the seasonal length of water column stratification and thus the deepening of the thermocline.  
914 We hypothesize that the subsequent deepening of the nutricline mitigated the productive  
915 conditions, explaining the low contrast between early and Middle Holocene productivity  
916 regimes.

917 At ca 8 ka BP, the shift between the Early and Middle-Holocene is marked by the onset of the  
918 Western Alboran Gyre circulation (Rohling et al., 1995; Pérez-Folgado et al., 2003; Ausín et  
919 al., 2015), promoting enhanced Atlantic water inflow into the Mediterranean Basin and the  
920 onset of the AC flow through the east, consistently with the increased Ocen/Lmac ratio from  
921 Cadiz to Algeria (Figure 8f,i,l,o). Interestingly, from 8 ka BP, the easternmost Ocen/Lmac  
922 signature shows an inverse trend to that of all western Mediterranean sequences, suggesting a  
923 strong depletion of the Atlantic influence from the Middle-Holocene at the Siculo-Tunisian  
924 strait, while increasing Ocen/Lmac ratios were synchronously recorded for the cold YD from  
925 west to east in the five sediment cores (Figure 8f,i,l,o,r).

926

#### 927 5.4.3. Mediterranean forest retreat onset

928 From 6 ka BP, the progressive decline in forest taxa and the increase in coastal-steppic taxa  
929 percentages, associated with decreasing fluxes of TERR-alkanes as well as decreasing  
930 concentrations of pollen, *Glomus* spores, freshwater microalga and pre-Quaternary cysts  
931 (Figure 7b,c,d,f,g) suggest decreasing precipitation rates and runoff in the AM. Summer  
932 precipitation therefore gradually declined (Figure 7i), due to the decrease in summer solar  
933 radiation in the tropics (Berger and Loutre, 1991), and climate conditions became too dry for  
934 plants. The sharp drops in Ti/Ca-XRF (Figure 6h) and Kaolinite values (Figure 7a) also suggest  
935 dusty-desert conditions, in agreement with previous western Mediterranean aridification signals  
936 (e.g. Fletcher and Zielhofer, 2013; Depreux et al., 2021), therefore characterizing the end of the  
937 AHP (Shanahan et al., 2015). The aridity trend, that started after 6 ka BP, ranged from about  
938 5.5 to 3 ka BP (yellow band identified between limits “d” and “e” in Figures 6 and 7),  
939 consistently with an extremely dry interval described in western Mediterranean studies at the  
940 end of the African Humid Period (Cacho et al., 2001; Combourieu-Nebout et al., 2009), and  
941 also corresponding to increasing flash floods in Tunisia and Morocco due to erodible soils in

942 open landscape (Zielhofer and Faust, 2008; Depreux et al., 2021). During this interval,  
943 phototrophic productivity and higher dinocyst diversity (Figure 4a) coincide with ever-  
944 increasing heavy values of planktonic  $\delta^{13}\text{C}$  (Figure 6g). Productive conditions are related to  
945 decreasing percentages of *I. aculeatum* (i.e. SST cooling) and increasing percentages of *S.*  
946 *mirabilis* (i.e. Atlantic water influence), suggesting, as for the YD (section 5.2.a.), a stronger  
947 vigour of the AC resulting from the strengthening of the Alboran gyres. Lower *Brigantedinium*  
948 spp. values may result from a lower preservation under stronger ventilation of Mediterranean  
949 bottom waters at that time.

950

## 951 **5.5. Late Holocene (4.2 ka BP to present)**

### 952 5.5.1. The “4.2 ka BP” event

953 Peak values of coastal-steppic and semi-arid taxa percentages culminated between 4.3 and 3.9  
954 ka BP, coupled with the lowest *Glomus* spore concentrations recorded in the sequence, and may  
955 correspond to a phase of megadrought in Algeria (MDA in Figure 7) that lasted for about 400  
956 years (Figure 7g), consistent with a regional speleothem study from Ruan et al. (2016). The  
957 highest summer droughts recorded in the study area therefore appear synchronous with the well-  
958 known 4.2 ka BP event (e.g. Jalali et al., 2016; Bini et al., 2019, Kaniewski et al., 2019; Di Rita  
959 and Magri, 2019), within the 5.5–3 ka BP interval. This also coincides with the development of  
960 the plateau of the heaviest planktonic  $\delta^{13}\text{C}$  values (i.e. strongest productivity from 4.2 ka BP  
961 onward) in a context where the lowest percentages of *Brigantedinium* spp. were recorded, likely  
962 due to a strengthening of deep-water circulation at 4.2 ka BP (Figure 6g,i).

963

### 964 5.5.2. Settling of Modern conditions

965 The Late Holocene is characterized by the end of the 5.5–3 ka BP most arid Holocene interval  
966 followed by the last 3 kyrs BP occurring in a context of orbitally-driven climate aridity. From  
967 the Middle to Late Holocene, Mediterranean landscapes are strongly influenced by human  
968 impacts and fire activity (Pausas and Vallejo 1999, Vanni re et al., 2008; Mercuri et al., 2019).  
969 Over the last 3 kyrs BP, two phases are identifiable in this study. First, from 3 to 1.5 ka BP,  
970 strong river discharge to the AM and associated runoff are recognized through increasing Ti/Ca-  
971 XRF (Figure 6h) and Kaolinite/Illite (Figure 7a) values. Pre-Quaternary cyst (Figure 5a),  
972 *Glomus* spore and freshwater microalgae (Figure 7b,c) concentrations, even reached their  
973 highest values over this period. Stronger signals of alteration-erosion and river runoff to the



974 AM directly follow the 5.5–3 ka BP interval, as observed during the Early Holocene right after  
975 the YD. Only the freshwater algae remain stable with low values during the Early Holocene  
976 compared with the 3–1.5 ka BP interval. The 3 to 1.5 ka BP interval also corresponds to  
977 increasing advection of Anthropogenic Pollen Indicators (*Rumex*, *Cerealia*-type and *Plantago*  
978 *lanceolata*) as well as Amaranthaceae and *Artemisia* (Figure 5b), likely resulting from pastures,  
979 as previously suggested in arid climates (Jaouadi et al., 2010; Florenzano et al., 2012;  
980 Florenzano et al., 2015). Two factors may have amplified the signature of river erosion-runoff:  
981 i) the arid conditions prevailing that favored strong erodability of soils, and ii) the superimposed  
982 growing anthropic impacts opening the landscapes in adjacent watersheds (e.g. Pastoralism,  
983 culture parcels and land clearing).

984 The second phase, from 1.5 ka BP to the top of the sequence, presents a sharp drop in  
985 Mediterranean forest taxa percentages in parallel with the highest Kaolinite/Illite (strongest  
986 chemical alteration ; Figure 7a) and Ti/Ca-XRF values (strongest erosional-runoff processes;  
987 Figure 6h). The antagonist pattern between “*Glomus* spore - freshwater microalgae”  
988 concentrations and Kaolinite/Illite values (i.e. opposite their general covariation during the  
989 whole sequence) lead to interpret this interval as driven by anthropogenic forcing.

990 Regarding surface waters, the plateau of heavy planktonic  $\delta^{13}\text{C}$  values, starting at 3 ka BP  
991 coincides with decreasing *Impagidinium* spp. percentages and concentrations. At this period,  
992 *Brigantedinium* spp. percentages and concentrations maintain their highest values, with  
993 concentrations of heterotrophic cysts (Figure 6f) even significantly exceeding those of  
994 autotrophic cysts for the first time of the whole study sequence. From 3 ka BP, the upwelling  
995 taxon *T. applanatum* reaches its highest percentages and concentrations (Figure 5a). We  
996 therefore argue for the development of the current hydrographic conditions (cf. Figure 1a),  
997 where productivity is sustained by both vertical mixing due to the AC in the AM (wind-driven  
998 eddies) and nutrient-enriched fluvial discharge intensified by anthropic-driven land-use.  
999 Interestingly, the threshold previously highlighted at 1.5 ka BP (limit “f” in Figure 6)  
1000 corresponds to a marked drop in alkenone and dinocyst-derived SST estimates, that also  
1001 corresponds to reduced dinocyst-derived SSS estimates. From 1.5 ka BP to present, this SST  
1002 and SSS decrease would confirm that strong advection of continental waters, accelerated by  
1003 anthropic-driven erosional processes, can be superimposed on the post-3 ka BP setup of modern  
1004 sea surface conditions, participating in the present-day primary productivity in the AM.

1005

## 1006 **5.6. West to East Mediterranean Basin transect**

### 1007 5.6.1. Regional disparities in hydrological-climatic trends along the Holocene

1008 Pollen records from north-eastern Algeria, and more specifically marine records from the  
1009 Siculo-Tunisian Strait, show a progressive Late Holocene evolution characterized by higher  
1010 precipitation rates (Figure 8g, j, m, p). This may be due to the Mediterranean storm track  
1011 carrying increased moisture from the Atlantic through the Gulf of Lion to the north-eastern  
1012 Algeria, northern Tunisian and Sicilian areas (Desprat et al., 2013; Lionello et al., 2016). During  
1013 the Late Holocene, the northward storm track, affecting less frequently the westernmost  
1014 Mediterranean regions (i.e. Alboran Sea for instance characterized by increasing aridity despite  
1015 lower summer temperatures), would be responsible for stronger Mediterranean storms from the  
1016 Gulf of Lion to the Central Mediterranean Sea as presently observed (Lionello et al., 2006).  
1017 This dichotomy between climate trends recorded in the Alboran Sea and AM is furthermore  
1018 reflected by highest alkenone SST reached between 10–8 ka BP westward (and decreasing  
1019 afterwards following NGRIP temperatures; cf. ODP 976 data in Figure 8a, h). These  
1020 temperature ranges are reached from 8 ka BP eastward (particularly obvious with core MD04-  
1021 2801 data in Figure 8n). The increasing SST gradient from west to east is also evident whatever  
1022 the interval considered over the last 14 kyrs.

1023

#### 1024 5.6.2. Rapid Holocene climate changes

1025 Rapid decline of forest at the infra-millennial timescale suggests events of enhanced continental  
1026 aridity, synchronously with alkenone SST coolings at 9, 8.2, 7.3 and 6.5 ka BP (horizontal  
1027 dotted lines in Figure 8). These cold, arid events have already been described in marine and  
1028 continental studies from SW Iberia to the WMB (Cacho et al., 2001; Frigola et al., 2007; Jalut  
1029 et al., 2000, 2009; Fletcher and Sanchez-Goñi, 2008; Combourieu-Nebout et al., 2009; Chabaud  
1030 et al., 2014; Jalali et al., 2016; Azuara et al., 2020) and are associated with the North Atlantic  
1031 Bond events (Bond et al., 2001; Figure 8e). Several studies suggest that changes in North  
1032 Atlantic thermohaline circulation could have triggered the multi-centennial scale climate  
1033 variability of the WMB (Bianchi and McCave, 1999; Bond et al., 2001; Oppo et al., 2006;  
1034 Fletcher and Sanchez-Goñi, 2008; Combourieu-Nebout et al., 2009, Chabaud et al., 2014).

1035 From the Early Holocene, the AM forest decline events are generally synchronous with lower  
1036 alkenone SST and higher *O. centrocarpum* occurrences figured out by positive values of the  
1037  $O_{cen}/L_{mac}$  ratio (Figure 8n,o). This suggests enhanced inflow of Atlantic waters in the WMB  
1038 and stronger moisture transport by the westerlies track directed northward and affecting to a  
1039 lesser extent the westernmost part of the Mediterranean Sea. By analogy, this would correspond  
1040 to recurrent positive modes of the North Atlantic Oscillation (NAO). Interestingly, these

1041 positive “NAO-like” events are expressed in contrast in the Siculo-Tunisian strait with lower  
1042 *O. centrocarpum* and higher values of *L. machaerophorum* occurrences, suggesting stronger  
1043 river discharge eastward. This pattern could illustrate the west-east modeled dipole response to  
1044 NAO-like changes in the SW Mediterranean Basin according to Bini et al. (2019) and Perşoiu  
1045 et al. (2019).

1046 Drier conditions, under enhanced wind strength in northern Atlantic latitudes (i.e. Bond event  
1047 under recurrent phases of positive “NAO-like” conditions), may therefore explain lower tree  
1048 percentages (Fletcher et al., 2010, 2013), and reversely higher tree percentages during recurrent  
1049 phases of negative “NAO-like” conditions (Figure 8). Our study reveals the rapid response of  
1050 Mediterranean vegetation and hydrological dynamics and the strong influence of the North  
1051 Atlantic climate through atmosphere-ocean interactions and ocean circulation at a multi-  
1052 centennial time scale.

1053

## 1054 **6. Conclusion**

1055 Multiproxy investigation of dinoflagellate cysts, pollen, non-pollen palynomorphs, stable  
1056 isotopes, clay mineral assemblages, grain-size analyses, marine and continental biomarkers,  
1057 and climate and hydrological quantitative reconstructions were conducted on the marine core  
1058 MD04-2801 on the Algerian Margin (AM). This study reveals the strong influence of orbital,  
1059 multi-centennial and centennial forcing on hydrological conditions and vegetation dynamics  
1060 over the last 14 kyrs BP. We show that dry and cold conditions prevailed during the Younger  
1061 Dryas as well as strong marine productivity. Warmer conditions of the Early to Middle  
1062 Holocene allowed for Mediterranean forest expansion, while the AM became oligotrophic until  
1063 6 ka BP. At an orbital timescale, the end of the African Humid Period led to aridification of the  
1064 western Mediterranean at the Middle to Late Holocene transition, with a dramatic forest retreat,  
1065 particularly pronounced between 4.3 and 3.9 ka BP. This event is referred to here as the  
1066 Algerian Mega Drought event, that appeared synchronously with the « 4.2 ka BP » event.  
1067 Sensitivity of the western Mediterranean to Northern Atlantic climate is also evidenced at an  
1068 infra-orbital timescale through several cold-dry events around 9, 8.1, 7.3 and 6.5 ka BP. The  
1069 forest decline from the Alboran Sea to the AM may result from the coupling of the North  
1070 Atlantic Bond events with prevailing positive modes of the North Atlantic Oscillation (NAO)  
1071 with a marked west to east dipole highlighted between the northern African coast up to Algeria  
1072 and Tunisia. Finally, over the last 3 kyrs BP, we have underlined the development of modern  
1073 productive conditions on the AM due to both vertical mixing (haline front and wind-driven  
1074 eddies of the Algerian Current) and nutrient-enriched fluvial discharge intensified by anthropic-  
1075 driven land-use.

1076

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1083 PaleoMex part. We thank Yannick Miras for his help in Non Pollen Palynomorph determination  
1084 and discussions on their ecological signature. Thanks also to ISEM for their contribution.

1085

## 1086 **8. Data availability**

1087 MD04-2801 data discussed in the manuscript are available in the SEANOE repository:  
1088 <https://doi.org/10.17882/89514>

1089

## 1090 **9. Table captions**

1091 **Table 1:** MD04-2801 AMS-<sup>14</sup>C dates. Grey cells represent levels averaged for the final age  
1092 model. Dates in italic (with the annotation « \* ») were rejected for the final age model (Figure  
1093 2).

1094

1095 **Table 2:** This table presents MD04-2801 palynological data discussed in this study and  
1096 describes each pollen zone for dinocyst and pollen grains assemblages.

1097

## 1098 **10. Figure captions**

1099 **Figure 1:** a) Map presenting studied part of the Western Mediterranean Basin (WMB) on the  
1100 globe (red square on global scale map) , sea-surface temperature, as well as major sea-surface  
1101 and atmospheric currents (a simplified vegetation model according to Tassin (2012). b) Map  
1102 presenting the local scale map (red square on regional scale map) figure topography and  
1103 hydrographic network, high-resolution bathymetric data from the Algerian Margin (Babonneau  
1104 et al., 2012), morphological entities of the Kramis deep-sea fan and location of the study core  
1105 and selected corresponding modern sediments (Coussin et al., in prep.).

1106

1107 **Figure 2:** Age model for core MD04-280 based on the combination of age model a (lower  
1108 section (1031 to 431 cm)) and age model b (upper section (431 to 0 cm)) from rbacon package  
1109 calculation (Blaauw and Christen, 2011) performed under the R interface (version 4.1.0; R  
1110 Development Core Team, 2021; <http://www.r-project.org/>) and rejected dates. Stratigraphic  
1111 data includes the corresponding section number and photography, lithology, sediments density  
1112 ( $\text{g/cm}^3$ ), sedimentation rates (cm/kyrs) and Vp (m/s) values. Core disturbance by potential  
1113 piston effect is represented as a red square on the age model.

1114

1115 **Figure 3:** Sedimentological data of core MD04-2801 in function of depth, core section and  
1116 lithology. a) XRF Ca/Al ratio, b) XRF Ti/Al ratio, c) Magnetic susceptibility (SI). d) Low

1117 resolution total sediment D50 ( $\mu\text{m}$ ) in blue reported in faded blue on high-resolution total grain-  
1118 size (d) and  $\text{CaCO}_3$ -free D50 in red. e) Planktonic (*G. bulloides*; in green) and endobenthic (*G.*  
1119 *affinis*; in yellow)  $\delta^{13}\text{C}$  (‰ VPDB), higher planktonic signal suggests stronger primary  
1120 productivity while lower endobenthic signal suggests stronger organic matter remineralisation.  
1121 f) Planktonic (*G. bulloides*; in red) and endobenthic (*G. affinis*; in violet)  $\delta^{18}\text{O}$  (‰). g) Clay  
1122 mineral fractions of Interstratified Illite-Smectite (In), Chlorite (Ch), Kaolinite (Kao) and Illite  
1123 (Il).

1124

1125 **Figure 4:** MD04-2801 a) marine and b) continental palynological, biomarkers and MAT  
1126 reconstruction data against depth (cm). a) Dinocyst diversity indexes are shown in red and blue,  
1127 in parallel with percentages of the major species *Brigantedinium* spp. (red dotted line).  
1128 Concentration of the total sum of dinocysts is shown in black, total sum of dinocysts without  
1129 *Brigantedinium* spp. is represented in blue and *Brigantedinium* spp. concentration is  
1130 represented in red. Concentration of  $\text{C}_{37}$  alkenones is represented in light blue (sum of  $\text{C}_{37}$ ,  
1131 ng/g). Total dinocyst (blue) and pollen with *Pinus* (orange) concentrations are represented in  
1132 the logarithmic scale. b) Pollen diversity indexes are in green, in parallel with percentages of  
1133 total trees (green) and total trees with *Pinus* (orange). Concentration of the total sum of pollen  
1134 is shown in orange, total sum of dinocysts without *Pinus* in green. Concentration of TERR-  
1135 alkanes in brown (sum of TERR-alkanes, ng/g) and Average Chain Length (ACL) in yellow  
1136 with average sequence value as a dotted line.

1137

1138 **Figure 5:** a) Dinocyst diagram (percentages of selected taxa exceeding at least once 1% in all  
1139 studied samples) of the MD04-2801 core, with related ecological groups (cf. Coussin et al.,  
1140 2022). Dinocyst zones are based on a CONISS statistical analysis on the Tilia program. b)  
1141 Pollen diagram (percentages of selected taxa when exceeding at least once 1% in all studied  
1142 samples, *Pinus* excluded from the main pollen sum) for the MD04-2801 core, with related  
1143 ecological groups. For both a) and b), continental non-pollen palynomorphs (NPPs) and pre-  
1144 quaternary cysts are highlighted in concentrations (number of palynomorphs per  $\text{cm}^3$  of  
1145 sediment). (For interpretation of the references to color in this figure legend, the reader is  
1146 referred to the web version of this article.)

1147

1148 **Figure 6:** Oceanic proxies from the MD04-2801 core plotted in age (Cal years BP) with related  
1149 pollen zones, sedimentological, stratigraphical limits and remarkable periods (S1 = Sapropel  
1150 1). Modern values from KMDJ-23 core are plotted as colored stars in the left band of the figure

1151 (1 - 0 ka). a) Planktonic  $\delta^{18}\text{O}$  (‰), b) Alkenone derived annual Sea Surface Temperatures  
1152 (SST, shaded from low temperatures in blue to high temperatures in red, °C), c) Cold water  
1153 dinocyst taxa percentages (*N. labyrinthus*, *B. tepikiense* and *S. lazus*, cf. Figure 5) in reversed  
1154 logarithmic scale, d) Dinocysts-derived Winter (blue) and Summer (red) SST (°C) with shaded  
1155 reconstructed minima and maxima and alkenone annual SST as a dotted blue line. e) Dinocyst-  
1156 derived Winter (blue) and Summer (red) Sea Surface Salinity (SSS, psu) with shaded  
1157 reconstructed minima and maxima, f) Heterotrophic (orange) and Phototrophic (green) dinocyst  
1158 concentration in logarithmic scale, g) Planktonic (*G. bulloides*; in green) and endobenthic (*G.*  
1159 *affinis*; in orange)  $\delta^{13}\text{C}$  (‰ VPDB), h) XRF Ti/Ca ratio, i) *Brigantedinium* spp. percentages  
1160 (%), j) *Brigantedinium* spp. concentration (red line), k) *Impagidinium* spp. percentages (%), l)  
1161 *Impagidinium* spp. concentration (brown).

1162

1163 **Figure 7:** Continental proxies from the MD04-2801 core plotted in age (Cal years BP) with  
1164 related pollen zones, sedimentological, stratigraphical limits and exceptional periods (S1 =  
1165 Sapropel 1, Megadrought Algeria = MDA). Modern values from KMDJ-23 core are plotted as  
1166 colored stars in the left band of the figure (1 - 0 ka). a) Kaolinite/Illite percentages of the clayey  
1167 phase ratio with higher Illite values in green and higher values in Kaolinite in red, b) freshwater  
1168 algae concentration (green), c) *Glomus* (HDV-207) concentration (grey), d) superior plant leaf  
1169 wax produced TERR-alkane (shaded green silhouette) and major represented n-C29 + n-C-31  
1170 (green dotted line) fluxes ( $\text{ng}\cdot\text{g}^{-1}\cdot\text{yrs}^{-1}$ ), e) Siliciclastic coarse grain inputs schematized by  
1171 magnetic susceptibility (SI), f) Mediterranean and Eurosiberian forest (cf. Figure 5)  
1172 percentages, g) Coastal-steppic and Semi-arid vegetation (cf. Figure 5) percentages, h)  
1173 Temperature seasonality index calculated with pollen-derived Mean Temperature of the  
1174 Warmest Month (MTWA) and Mean Temperature of the Coldest Month (MTCO) as (MTWA-  
1175 MTCO). i) Pollen-derived annual precipitation reconstructions (mm, blue line), j) Altitudinal  
1176 forest (cf. Figure 5), k) Human impact taxa (cf. Figure 5) percentages.

1177

1178 **Figure 8:** West to east transect of sequences from the Gulf of Cadiz (MD99-2339), Alboran  
1179 sea (ODP site 976 and MD95-2043), Algerian Margin (MD04-2801, this study) and Sicilian  
1180 strait (MD04-2797) with paleoenvironmental data plotted in age (Cal years BP) both on their  
1181 published chronology and their geographical situation on the map versus Orbital parameters (a)  
1182 NGRIP  $\delta^{18}\text{O}$  (‰, Vinther et al., 2006) in black, b) 65°N insolation in yellow ( $\text{W}/\text{m}^2$ ) from  
1183 Berger and Loutre (1991), c) Precession in blue and e) Hematite-stained quartz % in red (Bond

1184 et al., 2001). For both represented cores, (d,h,k,n,q) Alkenone SST are represented (black line,  
1185 °C), (f,l,i,o,r) OCEN/LMAC log ratio representing oceanic dinocyst taxa *O. centrocarpum*  
1186 versus estuarine dinocyst taxa *L. machaerophorum* log ratio (blue shaded silhouette, higher  
1187 ratios represent lower river discharge conditions), (g,j,m,p) Summed Mediterranean and  
1188 Eurosiberian forest (%) with total sum as a green silhouette and eurosiberian proportion as a  
1189 brown dotted line. Spotted forest retreat events are shown as dotted horizontal lines with  
1190 corresponding ages. The regional map figures all cited sequences, geographical coordinates and  
1191 zonal correlations with negative NAO conditions (modified after Perşoiu et al. (2019) in Bini  
1192 et al. (2019). Green zones show positive correlations with NAO- conditions indicating stronger  
1193 precipitations than average during NAO- and orange zones figure negative correlations with  
1194 NAO- conditions indicating lower precipitations than average during NAO-.

1195

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2013 **Table**

2014 Table 1

Code	Spectrometer	Depth (cm)	Dated material	<sup>14</sup> C age	Error	<sup>14</sup> C age – reservoir age	IntCal20 Cal BP Min-Max	Error $\sigma$
<b>SacA43123</b>	ECHOMICADAS	3	<i>G. bulloides</i>	170	30	-230	<b>0</b> 0-0	1 $\sigma$
<b>SacA55619*</b>	ARTEMIS	31 <sup>a</sup>	<i>G. bulloides</i>	820	30	420	<b>491,5</b> 472-511	1 $\sigma$
<b>SacA55620</b>	ARTEMIS	231	<i>G. bulloides</i>	1400	30	1000	<b>928,5</b> 900-957	2 $\sigma$
<b>GifA20376</b>	ECHOMICADAS	311	<i>G. bulloides</i>	1290	60	890	<b>817</b> 716-918	2 $\sigma$
<b>SacA55621</b>	ARTEMIS	431	<i>G. bulloides</i>	2165	30	1765	<b>1644,5</b> 1571-1718	2 $\sigma$
<b>GifA21150</b>	ECHOMICADAS	522	<i>G. bulloides</i>	3610	70	3210	<b>3424</b> 3357-3723	1 $\sigma$
<b>GifA18283</b>	ECHOMICADAS	531	<i>G. bulloides</i>	3870	80	3470	<b>3737,5</b> 3634-3841	1 $\sigma$
<b>SacA54337</b>	ARTEMIS	531	<i>G. bulloides</i>	3820	30	3420	<b>3647,5</b> 4229-4522	2 $\sigma$
<b>GifA20378</b>	ECHOMICADAS	550	<i>G. bulloides</i>	4330	60	3930	<b>4375,5</b> 4229-4522	2 $\sigma$
<b>GifA21151</b>	ECHOMICADAS	559	<i>G. bulloides</i>	4390	60	3990	<b>4432</b> 4245-4619	2 $\sigma$
<b>GifA20380</b>	ECHOMICADAS	579	<i>G. bulloides</i>	5000	60	4600	<b>5342,5</b> 5214-5471	2 $\sigma$
<b>GifA21152</b>	ECHOMICADAS	581	<i>G. bulloides</i>	5060	70	4660	<b>5392</b> 5315-5469	1 $\sigma$
<b>SacA55622</b>	ARTEMIS	631	<i>G. bulloides</i>	6200	30	5800	<b>6584</b> 6499-6669	2 $\sigma$
<b>GifA18282</b>	ECHOMICADAS	731	<i>G. bulloides</i>	8470	70	8070	<b>8917,5</b> 8696-9139	2 $\sigma$
<b>SacA54338</b>	ARTEMIS	731	<i>G. bulloides</i>	7990	35	7590	<b>8392</b> 8374-8410	1 $\sigma$
<b>GifA18256*</b>	ECHOMICADAS	931 <sup>b</sup>	<i>G. bulloides</i>	11110	270	10710	<b>12488,5</b> 11808-13169	2 $\sigma$
<b>SacA54339</b>	ARTEMIS	931	<i>G. bulloides</i>	10600	40	10200	<b>11867,5</b> 11739-11996	2 $\sigma$
<b>SacA54335</b>	ARTEMIS	978	Gastéropode	11000	40	10600	<b>12653</b> 12616-12690	1 $\sigma$
<b>SacA54336</b>	ARTEMIS	978	Gastéropode	11015	40	10615	<b>12659</b> 12621-12697	1 $\sigma$
<b>SacA55623</b>	ARTEMIS	1031	<i>G. bulloides</i>	12445	40	12045	<b>13920,5</b> 13804-14037	2 $\sigma$

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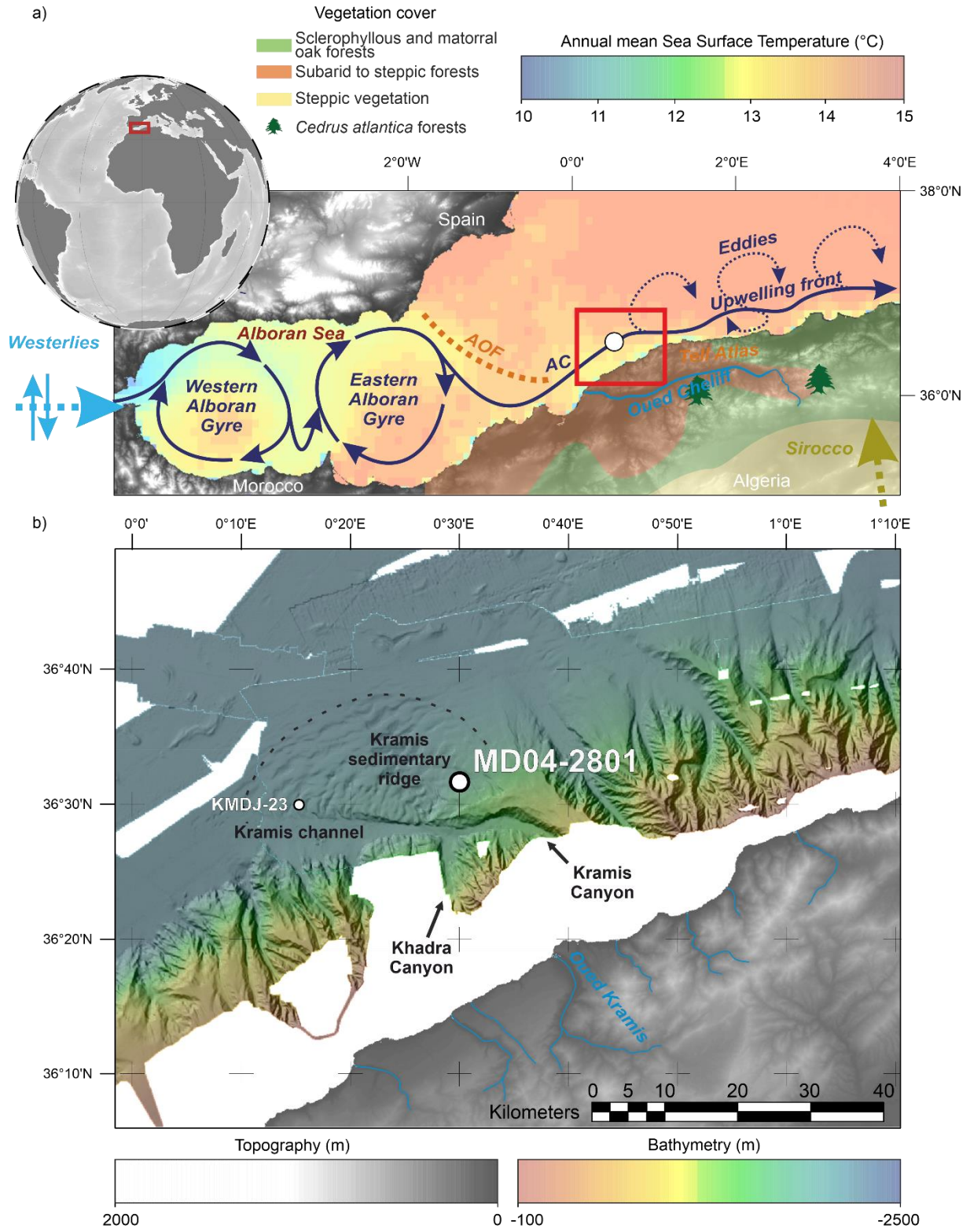
Pollen zones	Limits	Interval (cm)	Age (cal BP)	Description of Dinocyst zones	Pollen zones	Inferred hydrological changes	Description of pollen zone	Vegetation changes	Inferred climatic changes	Non-pollen palynomorphs remarks
MD04-5	Top - f	0 - 370	0 - 1 400	High values of <i>Brigantedinium</i> spp. (60% mainly), <i>S. mirabilis</i> and <i>O. centrocarpum</i> . Increasing values of estuarine-stratified taxa and thermophilous full-oceanic taxa. Diverse coastal productivity and upwelling heterotrophic assemblage. Occurrences of <i>Lejeunecysta</i> spp.	Highest heterotrophic taxa representations. Mixed upwelling and coastal productivity.	Upwelling driven productivity mixed with river discharge induced coastal productivity. Increasing oligotrophic conditions signal	Strongest representation of <i>Cichorioideae</i> (up to 35% mainly), <i>Asterioideae</i> . Stable percentages of <i>Poaceae</i> , <i>Quercus ilex</i> , deciduous <i>Quercus</i> , <i>Olea</i> , <i>Pistacia</i> , <i>Juniperus</i> , <i>Cupressus</i> , <i>Cedrus</i> . Increasing percentages of <i>Ephedra</i> and <i>Artemisia</i> . Increasing occurrences and representations of human impact taxa.	Open shrubs and steppe vegetation combined with open mediterranean forest forming matorrals and maquis. Potential human activity expansion.	Increasing aridity	Freshwater algae stable representation. Glomus high abundances, ascospores stable abundances. Occasional coprophilous abundances.
	f - e	370 - 485	1 400 - 2 700	High values of <i>Brigantedinium</i> spp. (60% mainly) followed by stable represented <i>S. mirabilis</i> and <i>O. centrocarpum</i> . Diverse coastal productivity and upwelling heterotrophic assemblage. High representation of <i>T. applanatum</i> .	Highest heterotrophic taxa representations. High upwelling and coastal productivity.	Upwelling driven productivity under relatively stable Atlantic influence.	Strong increase of <i>Cichorioideae</i> (30% mainly), <i>Asterioideae</i> . Stable percentages of <i>Poaceae</i> , <i>Quercus ilex</i> , deciduous <i>Quercus</i> , <i>Olea</i> , <i>Pistacia</i> , <i>Juniperus</i> , <i>Cupressus</i> , <i>Cedrus</i> , <i>Ephedra</i> and <i>Artemisia</i> .	Open shrubs and steppe vegetation combined with open mediterranean forest forming matorrals and maquis.	Increasing aridity	Freshwater algae stable representation. Glomus high abundances, ascospores stable abundances.
MD04-4	e - d	485 - 575	2 700 - 5 120	High values of <i>S. mirabilis</i> (30% mainly) and <i>I. aculeatum</i> . High representations of <i>L. machaerophorum</i> . Increasing percentages of <i>S. bentorii</i> , <i>N. labyrinthus</i> and <i>T. applanatum</i> .	High representation of phototrophic taxa. Upwelling cortege strong representation.	Intense upwelling activity. Intense oceanic influence. Seasonal oligotrophic stratified warm surface waters persistent signal.	Increasing of <i>Chenopodiaceae</i> , <i>Cichorioideae</i> , <i>Artemisia</i> and <i>Ephedra</i> . Small decrease of <i>Quercus ilex</i> and decrease of <i>Pistacia</i> , <i>Quercus suber</i> and <i>Cedrus</i> .	Open mediterranean forest with extended underbrush and maquis of <i>Cichorioideae</i> , <i>Asteraceae</i> and <i>Poaceae</i> steppe	Decreasing rainfalls with centennial oscillations	Lower freshwater algae and Glomus abundances. Peak of ascospores around 540 cm.
MD04-3	d - c	575 - 740	5 120 - 8 600	High values of <i>Brigantedinium</i> spp. increasing percentages of <i>I. aculeatum</i> (15-20% mainly) and <i>S. mirabilis</i> . Rare occurrences of <i>Lejeunecysta</i> spp. And <i>T. applanatum</i> .	Stable strong heterotrophic representation. Highest percentages of the Thermophilous full-oceanic taxa majorly represented by <i>Impagidinium aculeatum</i> .	Strongest oligotrophic surface conditions, increasing stratification and sea surface temperature. Persistent upwelling productivity signal.	Highest trees percentages. Increasing percentages of <i>Cupressaceae</i> , <i>Pistacia</i> and <i>Olea</i> , <i>Quercus ilex</i> and <i>Poaceae</i> . Decrease of <i>Chenopodiaceae</i> and small decrease of <i>Cichorioideae</i> which peaks from 650 to 600 cm.	Open mediterranean oak forest combined with underbrush and maquis of <i>Cichorioideae</i> , <i>Asteraceae</i> and <i>Poaceae</i>	Increased humidity and temperature marked with centennial oscillations	Highest representations of freshwater algae. Stable high representation of Glomus and ascospores.

	c - b	740 - 910	8600 - 11500	High percentages of <i>Brigantedinium</i> spp. (40 % mainly). Diverse coastal productivity and upwelling heterotrophic assemblage. Highest percentages of <i>O. centrocarpum</i> (10-20% mainly).	Increasing of the heterotrophic taxa representations. Increasing representation of thermophilous full-oceanic taxa.	Oligotrophic surface conditions, stratification and sea surface temperature. Persistent upwelling driven productivity.	Strong increase of <i>Quercus ilex</i> , deciduous <i>Quercus</i> , <i>Pistacia</i> , <i>Olea</i> , <i>Asterioideae</i> , <i>Cichorioideae</i> and <i>Poaceae</i> . Decrease of <i>Cedrus</i> , <i>Chenopodiaceae</i> , <i>Artemisia</i> and <i>Ephedra</i> . Increasing representation of monocotyledonae and pteridophyte spores.	Open mediterranean forest and underbush or maquis	Warmer conditions and gradual increased humidity	Stable high representation of Glomus and ascospores.
MD04-2	b - a	910 - 1025	11500 - 13700	Increase of the <i>N. labyrinthus</i> percentages (30 - 35% mainly). Cold water taxa <i>S. lazus</i> and <i>B. tepikiense</i> are also represented in high values. <i>O. centrocarpum</i> shows stronger representations around 910-950 cm. Highest representation of the intern neritic taxa <i>S. ramosus</i> , <i>S. bentorii</i> and <i>S. membranaceus</i> .	Decrease of the heterotrophic taxa representation with the persistence of upwelling cortège taxa. Increasing percentages of cold water taxa and external neritic photrophic taxa. Diversified assemblage.	Cold surface temperature. Strong oceanic influence. Highest productivity period in this sequence.	Highest representations of <i>Cedrus</i> (30% mainly) with two major peaks at 970 and 1000 cm (reaching more than 40%). Increase of <i>Chenopodiaceae</i> , <i>Artemisia</i> and <i>Ephedra</i> with a decrease of all <i>Quercus ilex</i> , <i>Quercus suber</i> and <i>Cupressaceae</i> .	Steppe with semi-desert plants. Sparse Pine and coniferous woodlands and <i>Cedrus</i> forests uplands.	Dry and cold conditions	Weak or lacking freshwater algae and fungal spores signal
MD04-1	a - Bottom	1025 - 1042	13700 - 14000	Dominance of <i>Brigantedinium</i> spp.	Dominance of the heterotrophic taxon <i>Brigantedinium</i> spp.	Apparent productive conditions, active upwelling.	Dominance of <i>Chenopodiaceae</i> , <i>Cichorioideae</i> and <i>Poaceae</i> associated to <i>Artemisia</i> and <i>Ephedra</i> . Low representation of <i>Quercus ilex</i> (less than 10%) and <i>Cupressaceae</i> .	Dominating steppe with sparse mediterranean woodlands.	Dry conditions	Weak or lacking freshwater algae and fungal spores signal

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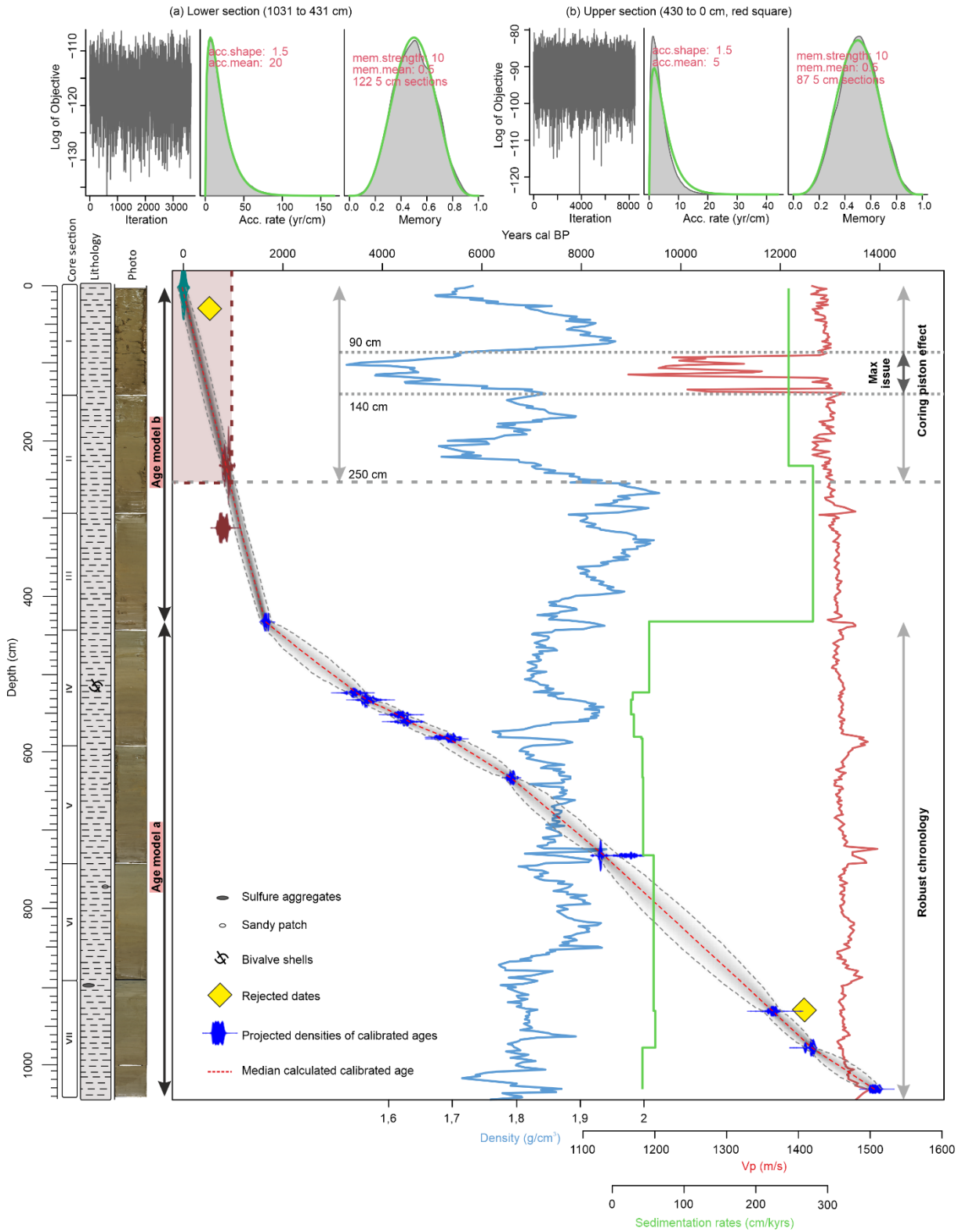
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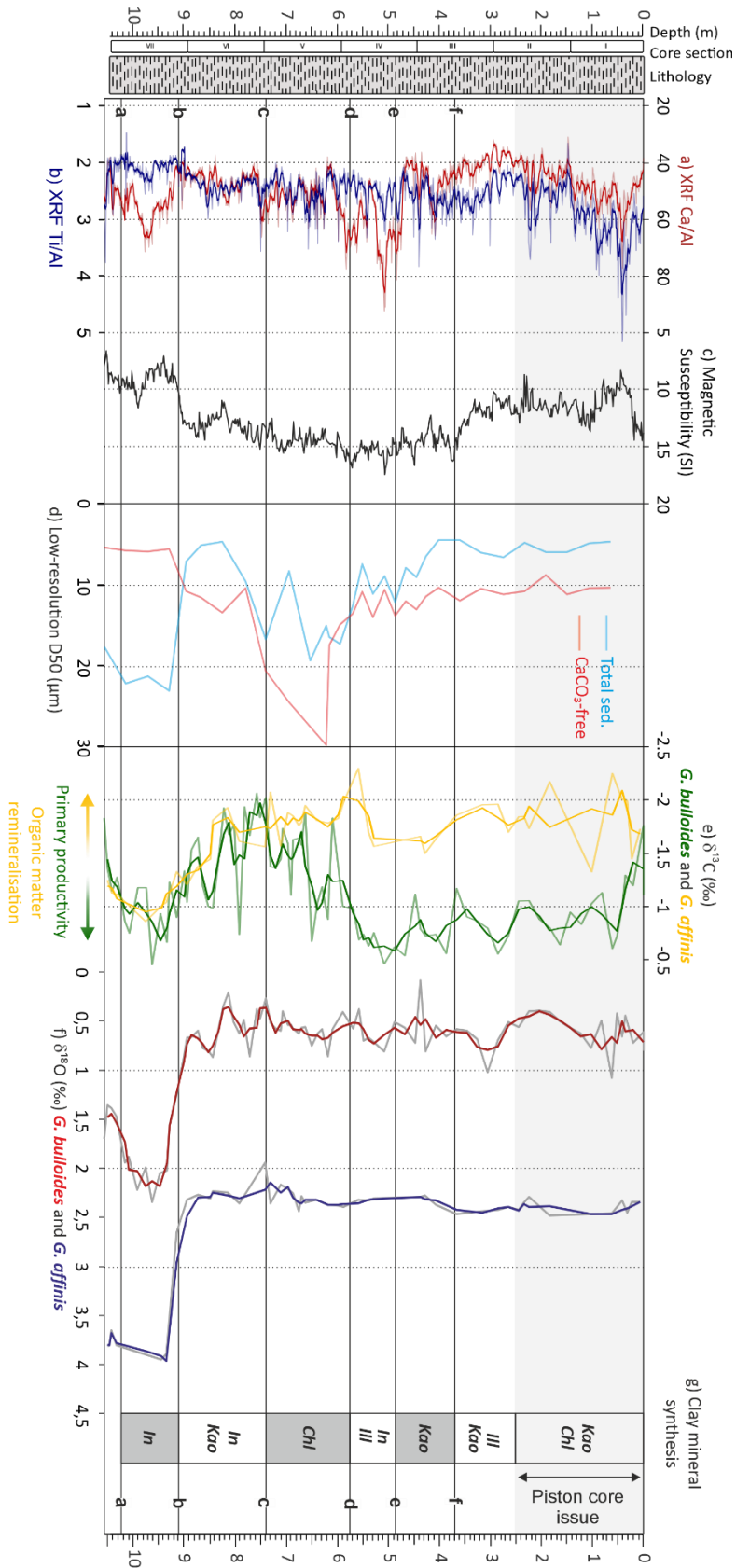
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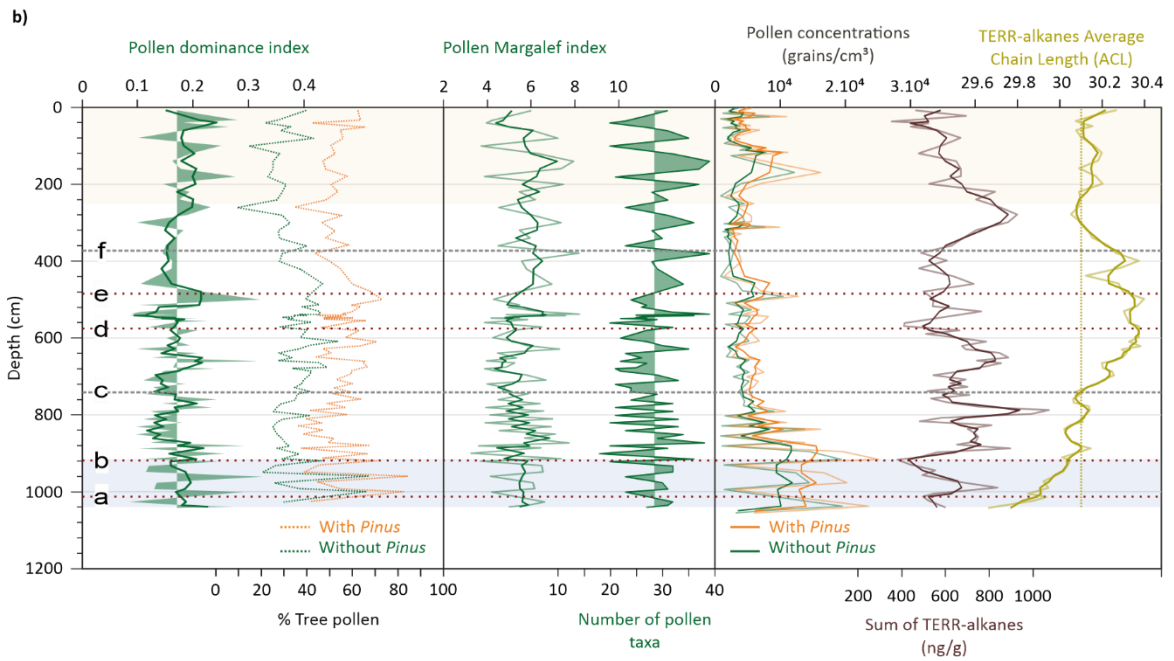
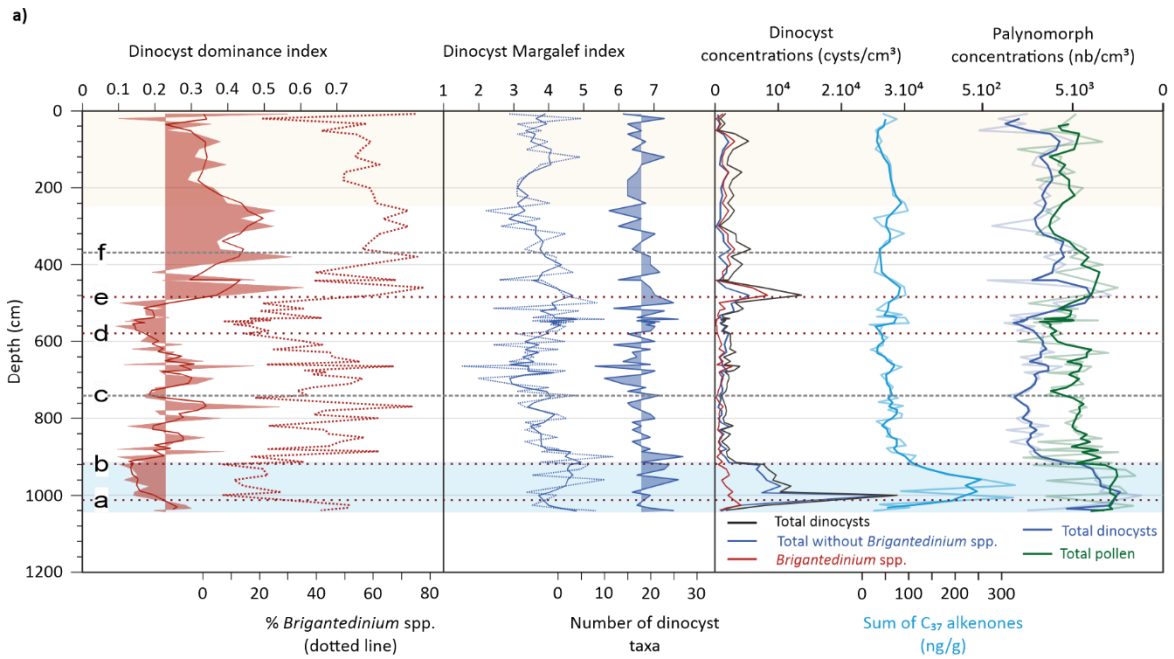


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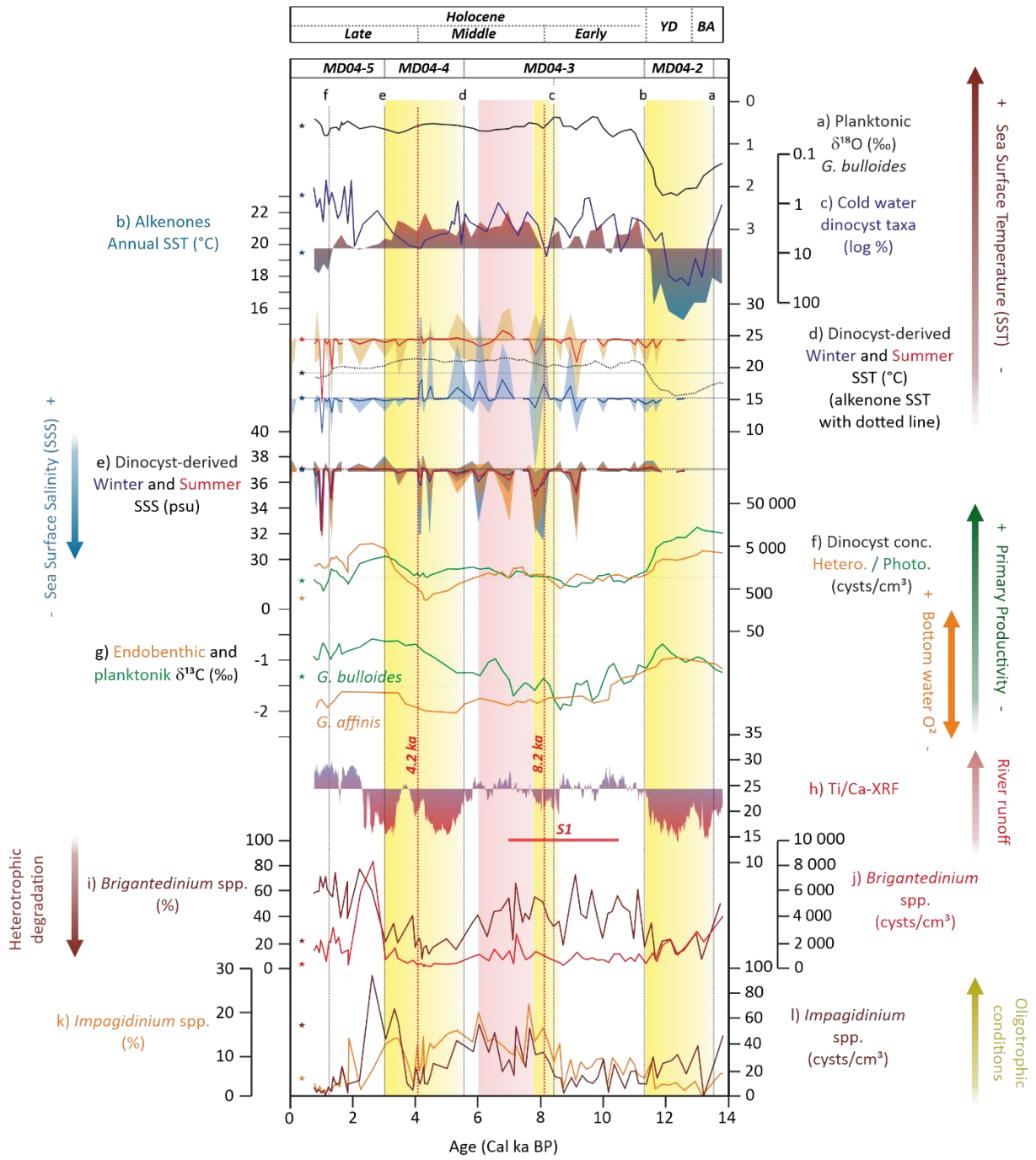
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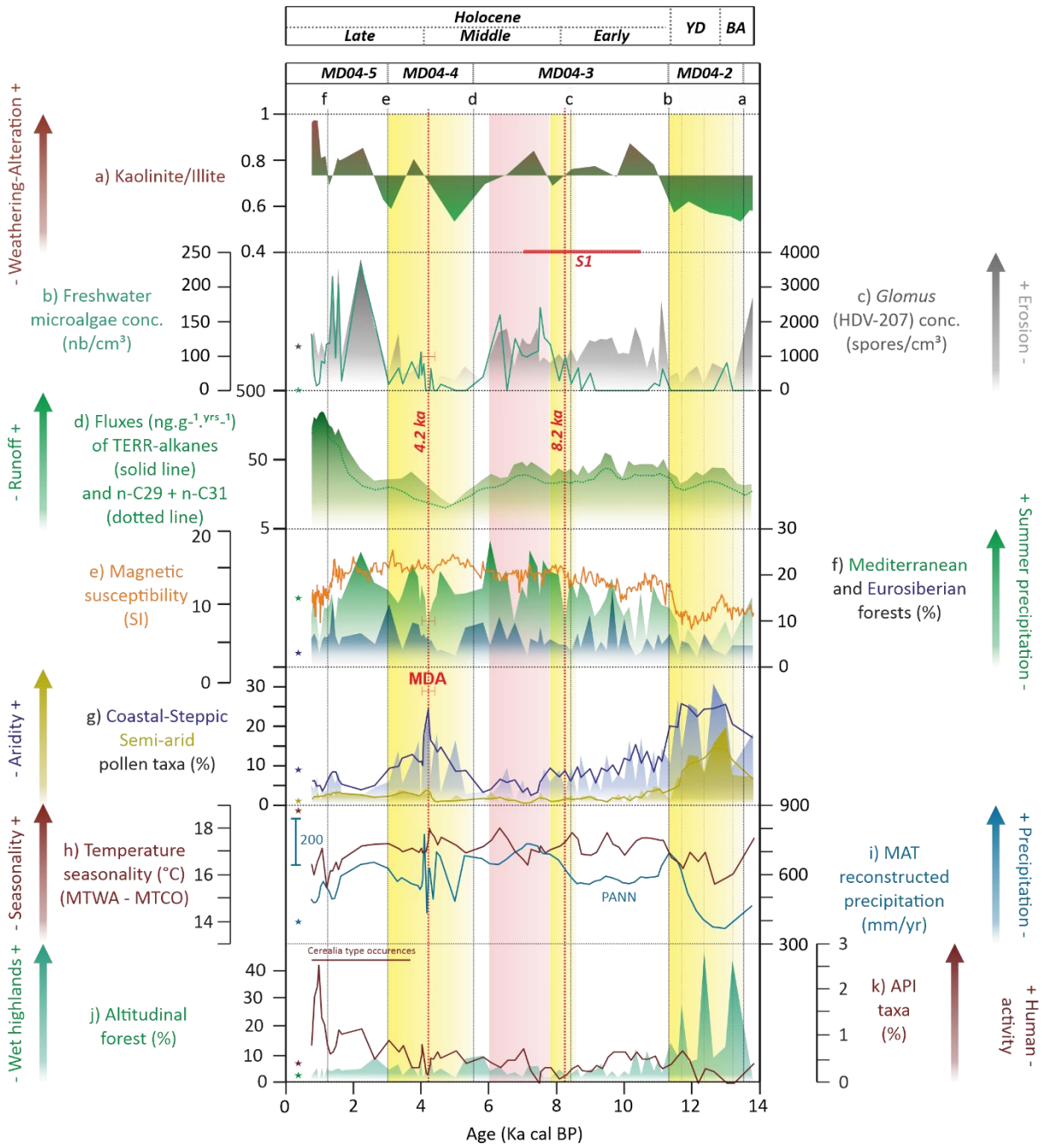


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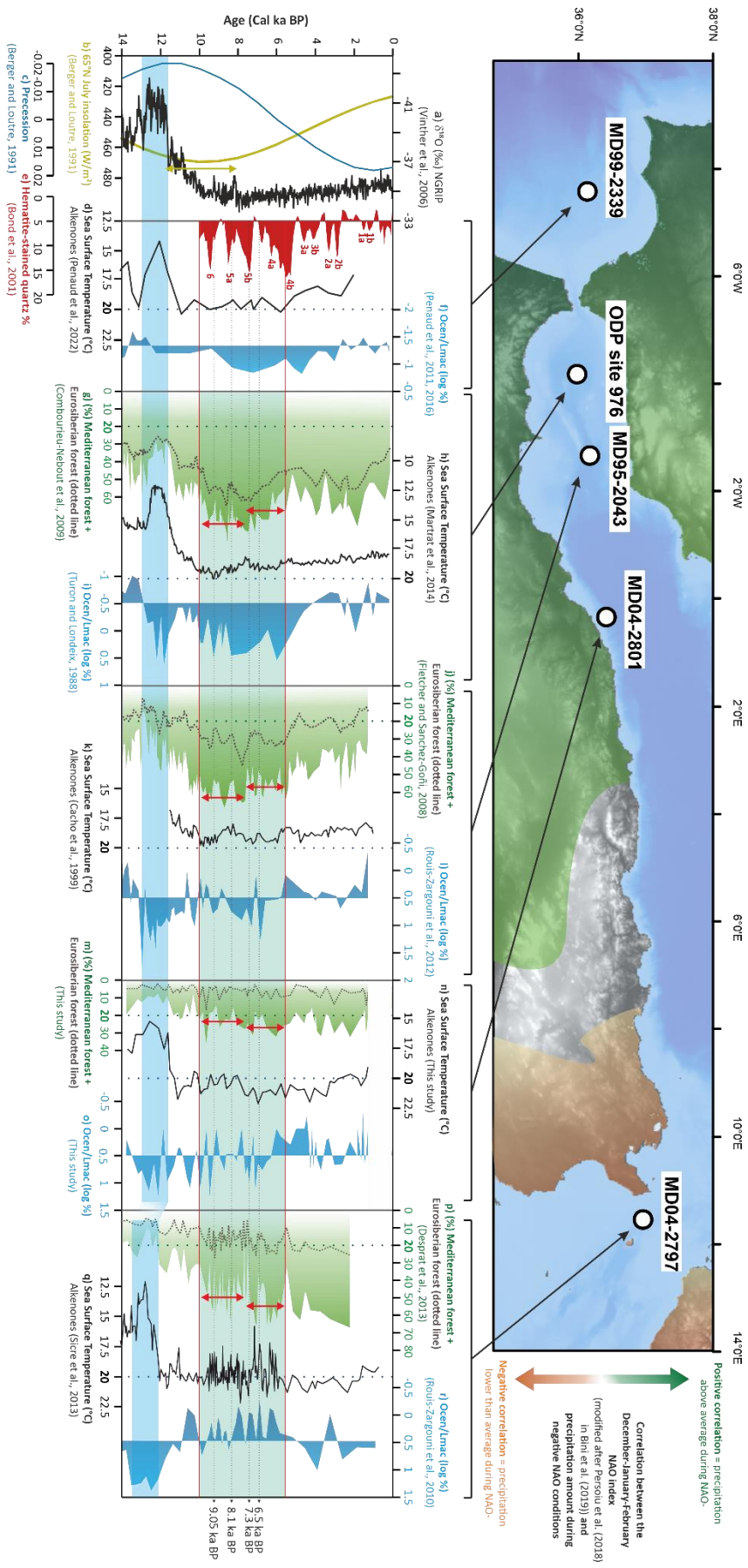


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2068 Figure 7



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**Date:** Apr 05, 2023  
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Land-sea linkages on the Algerian Margin over the last 14 kyrs BP: climate variability at orbital to centennial timescales

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I have completed my evaluation of your manuscript. I am happy with the responses to the reviewers however I have made corrections and suggestions for improvement of the abstract and one minor change to the introduction. These are mostly stylistic to simplify the writing and make the concrete results evident. Please see the PDF.

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## **Highlights**

- Land-sea multiproxy approach on the Algerian Margin over the last 14 kyrs
- Productivity regimes closely **associated** with the vigour of the Algerian Current
- Settlement of modern production conditions since 3 ka BP
- First record of the Algerian Mega Drought event between 4.3 and 3.9 ka BP
- NPP fingerprint in marine sediments related to erosion and river runoff

**" *Palaeogeography, Palaeoclimatology, Palaeoecology* "**

Declaration of competing interest

Date : 24th of March, 2023

Your Name: Vincent Coussin

Manuscript Title: Land-sea linkages on the Algerian Margin over the last 14 kyrs BP: climate variability at orbital and multi-centennial timescales

We disclose any financial and personal relationships with other people or organizations that could inappropriately influence (bias) our work. We don't have any interests to declare.

We, the authors, declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

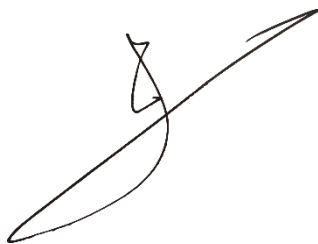
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Sincerely,

On behalf of all authors

A handwritten signature in black ink, consisting of a stylized, cursive script that is difficult to decipher but appears to be a personal name.



1 **Land-sea linkages on the Algerian Margin over the last 14 kyrs BP: climate**  
2 **variability at orbital to centennial timescales**

3  
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21 **Highlights**

- 22 • Land-sea multiproxy approach on the Algerian Margin over the last 14 kyrs
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- 24 • Settlement of modern production conditions since 3 ka BP
- 25 • First record of the Algerian Mega Drought event between 4.3 and 3.9 ka BP
- 26 • NPP fingerprint in marine sediments related to erosion and river runoff

27

28

## 29 **Abstract**

30 Past and present environmental conditions over the Holocene along the Algerian coast involve  
31 complex atmosphere-hydrosphere-biosphere interactions and anthropogenic activities on  
32 adjacent watersheds. Atlantic Ocean surface waters entering the western Mediterranean Sea at  
33 the Gibraltar Strait create the Algerian Current, which flows along the North African coast in a  
34 succession of strong and large-scale eddies. Deep-water upwelling plumes are other recurrent  
35 hydrological features of the Algerian margin affecting regional environmental features.  
36 However, vegetation and paleohydrological changes that have occurred over the Holocene have  
37 not yet been described. To bridge this gap, a suite of paleoclimate proxies was analysed in  
38 marine core MD04-2801 (2,067 m water depth) at a secular-scale resolution over the last 14  
39 kyrs BP. Terrestrial (pollen grains) and marine (dinoflagellate cysts or dinocysts) palynological  
40 assemblages, as well as sedimentological (grain-size analysis and XRD-based quantitative  
41 analysis of clay minerals) and biomarkers (alkenones and n-alkanes), were determined to  
42 explore the links between past sea surface hydrological conditions and regional environmental  
43 changes on nearby watersheds.

44 The over-representation of heterotrophic dinocyst taxa (*Brigantedinium* spp.) indicates strong  
45 planktonic productivity in the study area. Results shows that the links between dryness on land  
46 and surface hydrological conditions are expressed by : (i) recurrent upwelling cells during the  
47 relatively dry climate conditions of the Younger Dryas (12.7 to 11.7 ka BP), the Early Holocene  
48 (11.7 to 8.2 ka BP) and from 6 ka BP onwards, (ii) enhanced fluvial discharges between 8.2  
49 and 6 ka BP during the African Humid Period concomitant with the colonization of coastal  
50 lands by Mediterranean forest. Middle to Late Holocene transition around 4.2 ka BP  
51 characterizes by the intense event referred to here as the Algerian Mega Drought (4.3 to 3.9 ka  
52 BP).

53

54 *Keywords: Holocene; Dinocysts; Pollen; Biomarkers; Clay analysis; Algerian Current*

55

56 *Abbreviations: AM: Algerian Margin; AC: Algerian Current; WMB: Western Mediterranean*  
57 *Basin; WMDW: Western Mediterranean Deep Waters; LIW: Ligurian Intermediate Waters;*  
58 *MOW: Mediterranean Outflow Waters; YD: Younger Dryas; B/A: Bölling-Alleröd.*

59

## 60 **1. Introduction**

61 Interactions between low- and mid-latitude atmospheric circulations and local-scale  
62 configurations such as orography and coastal geomorphology, have created the specificities of  
63 the Mediterranean climate (Brayshaw et al., 2011). Furthermore, the summer season length  
64 depending on the vigor of the Hadley cell directly impacts summer droughts in the  
65 Mediterranean Basin (Lionello et al., 2006). In contrast, Mediterranean storm activity driving  
66 the main seasonal precipitation is strongly associated with the position and strength of the  
67 North-Atlantic mid-latitude storm tracks (Brayshaw et al., 2010). Consequently, the  
68 interactions between tropical convection and North-Atlantic storm tracks constitute a complex  
69 but essential element in understanding the long-term, rapid climate change that took place in  
70 the WMB during the Holocene. Climate changes during the last climatic cycle (e.g.  
71 Combourieu-Nebout et al., 1999, 2002; Sánchez-Goñi et al., 2002; Beaudouin et al., 2007;  
72 Bout-Roumazeilles et al., 2007; Brauer et al., 2007; Fletcher and Sánchez-Goñi, 2008; Kotthoff  
73 et al., 2008) have driven rapid paleoenvironmental changes in the Mediterranean basin.

74 Global warming, together with the generally high climatic and environmental sensitivity of this  
75 region raises questions concerning future environmental and human trajectories in the  
76 Mediterranean Basin, in particular due to subtropical aridification (IPCC report, 2019).

77 In this context, the Algerian Margin (AM) appears ideal to investigate both terrestrial (i.e.  
78 landscape changes) and marine (i.e. hydrological changes) ecosystems inherited from climate  
79 change and land-use practices over the Holocene. The AM, and mostly its westernmost part, is  
80 a highly productive area contrasting with the predominantly oligotrophic waters of the Western  
81 Mediterranean Basin (Sournia, 1973; Lohrenz et al., 1988). Strong riverine inputs (i.e. flash-  
82 flood episodes) to coastal waters and upwelling cells result in nutrient-enriched surface waters  
83 (Raimbault et al., 1993). These hydrological patterns provide understanding of the distribution  
84 of planktonic organisms as recently discussed for fossilized dinocysts at the scale of the Western  
85 Mediterranean Basin (WMB) (Coussin *et al.*, 2022).

86 Numerous studies have shown the rapid response of Mediterranean environments to Holocene  
87 climate variability (e.g. Rohling et al., 2002; Fletcher et al., 2013; Chabaud et al., 2014; Sicre  
88 et al., 2016; Jalali et al., 2016; 2017, 2018; Di Rita et al., 2018; Bini et al., 2021), including  
89 research on remote short-term events of the North Atlantic Basin (e.g. Bond et al., 1997, 2001;  
90 Mayewski et al., 2004; Sicre et al., 2021). However, Holocene paleoenvironmental changes  
91 along the northern African margin, between the Alboran Sea (e.g. Combourieu-Nebout et al.,

92 1999, 2009 ; Fletcher et al., 2013) and the Sicilian Strait (e.g. Rouis-Zargouni et al., 2010, 2012;  
93 Desprat et al., 2013 ; Di Rita et al., 2018), remain poorly documented.  
94 Here, we present new results for the AM based on the multi-proxy analysis of the marine core  
95 MD04-2801 (36°30.99'N; 0°30.03'E) over the last 14 kyrs BP, with a focus on the Holocene  
96 interval. This study benefited from a detailed sedimentological description (including X-ray  
97 fluorescence-XRF and grain-size analyses, clay mineral identification and conventional stable  
98 isotopes of O and C), centennial-scale resolution reconstructions of palynological proxies  
99 (pollen grains, dinocysts and other non-pollen palynomorphs or NPP), and molecular  
100 biomarkers (alkenones and n-alkanes). Our main objectives are i) to characterize upwelling  
101 variations through dinocyst assemblages and North-Atlantic atmospheric and hydrological  
102 influences on ecosystem variability, ii) to explore dryness and moisture conditions on land in  
103 relation with river discharge, iii) to assess the non-pollen palynomorphs (NPP) fingerprint in  
104 marine sediments and their relationship with erosion and river runoff on adjacent watersheds,  
105 iv) to evaluate the first pollen- and dinocyst-based quantifications of climate and hydrological  
106 parameters, respectively, in the study area. This dataset finally contributes to improve  
107 knowledge on north to south and west to east climatic and environmental gradients across the  
108 WMB.  
109

## 110 **2. Environmental context**

### 111 **2.1. Geographical and geomorphological background**

112 The marine sediment core MD04-2801 was retrieved on the AM, 24 km from the coast, on the  
113 eastern side of the Kramis deep-sea fan (Babonneau et al., 2012; Figure 1b). From a  
114 geomorphological point of view, the Algerian coast is limited to the south by the Dahra  
115 Mountains (Cretaceous schist clay substratum) that reach an altitude of 1550 m and is bordered  
116 by the Tellian Atlas chain. The study area is surrounded by Tortonian (blue marls and  
117 sandstones), Messinian (gypsum, gypsy marls, diatomites and diatomitic marls), Pliocene  
118 (marine blue marls, sandstones and limestones), and Quaternary (calcareous sandstones, sands  
119 and alluvial deposits) geological land formations (e.g. Perrodon, 1957; Meghraoui et al., 1996;  
120 Belkebir et al., 2008; Osman et al., 2021). The proximity of the AM to high relief means that  
121 its environment includes small coastal watersheds and small, fluctuating river flows (i.e. oueds).  
122 The oued Cheliff, whose mouth is located around 60 km to the west of the MD04-2801 core  
123 site (Figure 1b), is the largest oued of the region and is characterized by an average weak flow  
124 of  $15 \text{ m}^3 \cdot \text{s}^{-1}$ , varying from  $1.5 \text{ m}^3 \cdot \text{s}^{-1}$  during the driest episodes to  $1,500 \text{ m}^3 \cdot \text{s}^{-1}$  during flash-  
125 flood events (Gautier et al., 1998). The source of the oued Kramis (Figure 1b) is located in the  
126 Saharian Atlas and flows to the sea through the Dahra Mountains, distally feeding the Kramis  
127 deep-sea fan (Babonneau et al., 2012).

128 Two major climate features characterize the study area: i) mild conditions under the strong  
129 influence of mid-latitude westerly atmospheric circulation over the North Atlantic (i.e.  
130 westerlies), especially during winter, and ii) dry conditions (about 3 to 5 months per year) due  
131 to the strengthened Azores High, especially during summer (Lionello et al., 2006). The  
132 meteorological station at Mostaganem (near the Cheliff mouth) reports an average annual  
133 temperature of  $18.7^\circ\text{C}$  (minimum of  $5^\circ\text{C}$  and maximum of  $25^\circ\text{C}$ ) between 1981 and 2010. Over  
134 this period, seasonal flash floods of nearby oueds, mainly during the “humid” season (fall to  
135 spring), represent the largest part of annual precipitation (i.e. average amount of 383 mm/yr,  
136 minimum of 1 mm/month and maximum of 71 mm/month). Flash floods drive huge amounts  
137 of terrigenous sediments (i.e. organic and inorganic particles and nutrients) to coastal waters  
138 due to their high erosive capacity (e.g. Pouquet, 1967; Guizien et al., 2007; Tzoraki and  
139 Nikolaidis, 2007).

140

### 141 **2.2. Landscape**

142 The Mediterranean landscapes shaping the study area are characterized by an altitudinal belt  
143 type organization split into three major subdivisions (Barbero et al., 1981; Polunin and Walters,  
144 1985; Quezel and Medail, 2003). The thermo-Mediterranean belt covers lowlands and areas up  
145 from the coast to a 1,000 m altitude and is composed of *Olea*, *Pistacia*, sclerophyllous  
146 shrublands and xerophytous taxa, associated with steppe and semi-desert representative taxa  
147 (e.g. *Artemisia*, *Amaranthaceae*, *Ephedra*). From 1,000 to 1,500 m, the meso-Mediterranean  
148 belt is composed of the sclerophyllous oak forest (e.g. *Quercus ilex*, *Quercus suber*, *Buxus* and  
149 *Myrtus*) and the humid-temperate oak forest (dominated by deciduous *Quercus* and Ericaceae,  
150 in association with *Juniperus* and *Cupressus*). At higher altitudes, from 1500 to 2300 m, the  
151 supra-Mediterranean belt is characterized by a specific coniferous forest (i.e. North African  
152 species of *Pinus*, *Abies* and *Cedrus*). The oro-Mediterranean belt extends up to 2800 m in the  
153 high Atlas with a high rate of representation of *Juniperus* (open forest taxon or arborescent  
154 mattorals). Finally, the alti-Mediterranean belt (i.e. mountainous regions) is composed of  
155 scattered Chamaephytae taxa (e.g. *Erica*, *Romarinus* and other Lamiaceae, *Ilex* or *Artemisia*)  
156 and represents the highest vegetation belt in the area. It corresponds to the grassland belt of  
157 European mountains (Quezel and Medail, 2003).

158

### 159 **2.3. Hydrological context**

160 The semi-enclosed Mediterranean Sea undergoes excess evaporation over freshwater input,  
161 resulting in a deficient water balance (Béthoux, 1979, 1984). The western Mediterranean Sea  
162 is strongly influenced by the Modified Atlantic Waters (MAW) entering through the Gibraltar  
163 strait, flowing along the Spanish coast and forming two anticyclonic gyres (i.e. the Western  
164 Alboran Gyre-WAG and the Eastern Alboran Gyre-EAG; Figure 1a). The Almeria-Oran front  
165 (35 km wide; 200 m deep; Figure 1a) position and intensity depends on the degree of  
166 development of the EAG (Tintoré et al., 1988; Rohling et al, 1995; Viúdez and Tintoré, 1995;  
167 Rohling et al., 2009). The MAW follow the Almeria-Oran front, which marks a deflection along  
168 the AM, forming the Algerian Current (AC, Figure 1; Millot, 1987; Millot, 1999, Millot and  
169 Taupier-Letage, 2005). The AC undulates eastward up to 30–40 km from the coast to 3°E  
170 (Millot, 1985, 1987; Arnone and La Violette, 1986; Arnone et al., 1990; Perkins and Pistek,  
171 1990) where North African coast irregularities generate wind-driven eddies (cf. dotted arrows  
172 in Figure 1a). These eddies are responsible for northward coastal current extensions as well as  
173 the associated offshore propagation of low-salinity surface waters (Millot, 1999; Millot and  
174 Taupier-Letage, 2005).

175 The AC shows a salinity gradient from the Alboran Sea ( $< 37$  psu; Arnone and La Violette,  
176 1986) to the east and the internal zones of the WMB (psu  $> 37.5$ ). In its coherent form, the AC  
177 marks a haline density front (Arnone et al., 1990; Perkins and Pistek, 1990) responsible for  
178 vertical mixing (i.e. upwelling; Sournia, 1973; Lohrenz et al., 1988; Raimbault et al., 1993),  
179 while the Alboran Sea is characterized by a general oligotrophic regime. On the coastal side of  
180 the density front, isopycnal mixing brings nutrient-enriched waters from the nutricline to the  
181 photic zone while, on the offshore side, diapycnal mixing brings deeper nutrients to the surface  
182 (i.e. nutrient export crossing the haline front; Raimbault et al., 1993), promoting enhanced  
183 productivity (Raimbault et al., 1993; Coussin et al., 2022). Additionally, seasonal offshore  
184 winds induce coastal upwelling, probably supported by low barometric pressure cells due to  
185 solar heating (Bakun and Agostini, 2001).

186 Finally, the regional climate (cf. section 2.1) is responsible for weak and irregular fluvial  
187 discharge especially during the driest season (i.e. April to September) while strong oued  
188 discharge (i.e. flash floods) occasionally occurs during autumn and winter, transporting  
189 terrigenous material and nutrients to the sea (Guizien et al., 2007; Tzoraki and Nikolaidis,  
190 2007).

### 191 **2.3. Sedimentological context**

192 Core MD04-2801 (36°30.99'N; 00°30.03'E; 24.82 m long; 2,063 m water depth) is located  
193 about 6 km north of the Kramis Canyon, which has an east to west orientation in the lower slope  
194 (Figure 1b). The core is located at the base of the slope and is separated from the canyon by a  
195 canyon terrace. Turbidity current overflow from the canyon to the core site is currently assumed  
196 to be very low (Babonneau et al., 2012). However, a contribution of diluted mud plumes at the  
197 top of the turbidity currents could explain the high sedimentation rates in the area. Finally, a  
198 large sediment wave field develops downslope along the right side of the Kramis Canyon. These  
199 sedimentary features mark the overflow zone of turbidity currents of the Kramis and Khadra  
200 canyons on the Kramis sedimentary ridge. Core MD04-2801 is located at the top of this field  
201 and was affected by intense overflow currents in the early phase of the formation of the Kramis  
202 sedimentary ridge (Babonneau et al., 2012).

203 The uppermost 10 m of MD04-2801 are not affected by gravity-driven sediment instability  
204 processes (i.e. turbidity currents and resulting turbidites; Babonneau et al., 2012). From 1045  
205 cm upward (From section VII to section I; Figure 2), sediment generally consists of hemipelagic  
206 clays. Below 1,045 cm, section VIII consists of fine-grained turbidite beds (of approximately 1  
207 cm thick) within a silty-clay matrix representing repeated destabilization of the shelf sediments  
208 via turbiditic plumes. Silty to sandy deposits lie on the slopes of the fan with a wide dispersal  
209 of turbiditic overflows across the abyssal plain (Babonneau et al., 2012). Around the Kramis  
210 fan, a canyon levee crest, 200 m higher than the channel bottom, only releases overflow of the  
211 largest turbidity currents, resulting in interfingered turbiditic levee deposits of the Kramis  
212 system with hemipelagic sediment (Babonneau et al., 2012). The absence of turbidites in the  
213 upper sections of core MD04-2801 (above 1,045 cm, Sections I to VII; Figure 2) reflects the  
214 isolation of the core site from the turbiditic channel due to aggradation of the levees.

215

## 216 **3. Methodology**

### 217 **3.1. Sediment cores and stable isotope analyses**

218 The log of core MD04-2801 was established through visual description of the sedimentary  
219 facies (Figure 2). The physical properties of the core (i.e. P-wave velocity, magnetic  
220 susceptibility and gamma-ray attenuation density) were measured using a 'Geotek Multi Sensor  
221 Core Logger' (MSCL) with a 2-cm-step (average 30 yrs) resolution at the Ifremer Marine  
222 Geosciences laboratory (Plouzané, France). X-ray fluorescence (XRF) profiles, for the semi-  
223 quantitative chemical composition analysis of the study core, were acquired with an "Avaatech



224 core-scanning XRF” with a 1-cm-step (average 15 yrs) resolution (Ifremer Marine Geosciences  
225 laboratory, Plouzané, France). In sediments, the Ti element is commonly interpreted as a  
226 terrigenous-siliclastic signature while the Ca element is related to carbonate materials of detritic  
227 and/or biogenic sources (Richter et al., 2006). Based on this assumption, the XRF-Ti/Ca ratio  
228 has been commonly used on silico-clastic margins (where Ca mainly originates from biogenic  
229 carbonates) to estimate varying terrigenous inputs to the marine realm. In this study, even if  
230 geological formations on land are mainly composed of carbonates, we will use this ratio  
231 combined with other proxies to track fluvial input to the marine realm.

232 Grain-size analyses were first performed at high resolution on total sediments (Master thesis of  
233 Si Bachir Roza, IUEM) and, in a second step, at a lower resolution on both total and  
234 decarbonated sediments (after HCl 30% treatment) at the IUEM (*Institut Universitaire*  
235 *Européen de la Mer*, Plouzané, France) using a Malvern MASTERSIZER 2000. The software  
236 GRADISTAT was used to produce particle grain-size distribution and size statistics from the  
237 laser granulometer data, including median grain size (D50) as well as sediment volumetric  
238 phase percentages (i.e. clays:  $0 < \varnothing < 10 \mu\text{m}$ , silts:  $10 < \varnothing < 63 \mu\text{m}$ , and sands:  $\varnothing > 63 \mu\text{m}$ ).

239 Semi-quantitative mineralogical composition of the clay fraction was measured by X-ray  
240 diffraction (XRD) at the Ifremer Marine Geosciences laboratory (Plouzané, France) with a  
241 Bruker D2 PHASER set (with a Lynxeye fast detector; Cu X-ray tube; 30 kV voltage; 10 mA  
242 intensity). After decarbonation and decantation to retain only the  $< 2\mu\text{m}$  fraction, the sample  
243 was deposited on oriented glass. Each sample was routinely analyzed from 2 to  $30^\circ$  with a  
244 resolution of  $0.02^\circ$  lasting 1 s, with three XRD runs: i) air-dried, ii) ethylene-glycol saturated  
245 and iii) after calcination at  $490^\circ\text{C}$ . The characterization of each clayey mineral followed the  
246 description of Bout-Roumazeilles et al. (1999). Semi-quantitative estimation of clay mineral  
247 abundances (%) was performed using the Macintosh MacDiff® 4.2.5 software (R. Petschick,  
248 <http://www.geologie.uni-frankfurt.de/Staff/Homepages/Petschick/RainerE.html>).

249 Finally, stable isotopes were performed on planktonic *Globigerinoides bulloides* as well as  
250 endobenthic *Globobulimina affinis* foraminifera, hand-picked in the  $>150 \mu\text{m}$  sediment  
251 fraction. Isotopic analyses were conducted at the “*Pôle Spectrométrie Océan*” (IUEM,  
252 University of Brest, France) on a Finnigan MAT253 equipped with a Kiel-device automated  
253 introduction line. Analytical precisions for this spectrometer are  $<0.05\text{‰}$  for the  $\delta^{18}\text{O}$  and  
254  $<0.03\text{‰}$  for the  $\delta^{13}\text{C}$  using, respectively, the certified NBS-19 and NBS-18 standards.

255 Core KMDJ-23 ( $36^\circ30.006'\text{N}$ ;  $0^\circ15.422'\text{E}$ ; 7.52 m long; 2542 m water depth) was collected  
256 close to core MD04-2801 (Figure 1b). In this study, modern palynological assemblages related  
257 to current hydrological conditions are considered thanks to the top sediments of core KMDJ-

258 23 with radionuclide dating that confirmed the contemporaneous deposits at the study site  
259 (Coussin et al., 2022). We compare dinocyst data (i.e. *O. centrocarpum* for the North Atlantic  
260 influence (i.e. AC strengthening) versus *L. machaerophorum* for the estuarine influence (i.e.  
261 surface stratification) or Ocen/Lmac ratio), pollen data (sum of Mediterranean and Eurosiberian  
262 forest taxa), and alkenone SST, with coeval records of the Gulf of Cadiz (core MD99-2339),  
263 the Alboran Sea (ODP site 976 and core MD95-2043), the Algerian Margin-AM (MD04-2801,  
264 this study) and the Siculo-Tunisian strait (core MD04-2797).

265

266

## 267 **3.2. Palynological analyses**

### 268 3.3.1. Palynological treatments and palynomorph identifications

269 About 1 to 2 cm<sup>3</sup> of sediments were sampled every 20 cm in the upper MD04-2801 core (0 to  
270 500 cm) at about 100 yrs resolution and every 10 cm in the lower part (500 to 1042 cm) at about  
271 150 yrs resolution. Eighty-six samples were processed using the same palynological protocol  
272 as for palynomorph extraction, allowing direct comparison between terrestrial (pollen, spores,  
273 freshwater microalgae, and other continental non-pollen palynomorphs-NPPs) and marine  
274 (dinocysts and other marine NPPs such as marine microalgae or foraminiferal linings)  
275 microfossils on the same palynological slides. The preparation technique (Geo-Ocean  
276 laboratory, IUEM, France) was performed on the <150 µm fraction following the standardized  
277 palynological protocol of de Vernal et al. (1999), slightly adapted at the EPOC laboratory  
278 (University of Bordeaux, [http://www.epoc.u-](http://www.epoc.u-bordeaux.fr/index.php?lang=fr&page=eq_paleo_pollens)  
279 [bordeaux.fr/index.php?lang=fr&page=eq\\_paleo\\_pollens](http://www.epoc.u-bordeaux.fr/index.php?lang=fr&page=eq_paleo_pollens)). It includes chemical treatments  
280 (cold HCl: 10, 25 and 50%; cold HF: 45 and 70%, to remove carbonates and silicates,  
281 respectively) and sieving through single-use 10 µm nylon mesh screens. To avoid selective  
282 dinocyst degradation during sample treatment, no oxidative agent or heavy liquid technique  
283 was applied. Microscopic identification was performed with a Zeiss (Axio Scope.A1)  
284 microscope at x630 magnification. Absolute concentrations of palynomorphs were calculated  
285 using the marker grain method (Stockmarr, 1971; de Vernal et al., 1999; Mertens et al., 2009).  
286 Accordingly, aliquot volumes of *Lycopodium* spores were added to each sample before  
287 chemical treatment to allow the calculation of palynomorph concentrations as a number of  
288 palynomorphs/cm<sup>3</sup> of dry sediments (i.e. these exotic spores are counted simultaneously with  
289 studied palynomorphs for each sample).

290 A threshold of 100 individuals (> 5% in the total assemblage) is required to identify major  
291 species (Fatela and Taborda, 2002). In this study, 88 samples were analysed, with a minimum

292 count of 100 dinocysts (taxonomy following Fensome et al., 1993) and 150 pollen grains except  
293 for the over-represented taxon *Pinus* (Turon, 1984; Heusser and Balsam, 1985; taxonomy  
294 following Reille, 1992). Minimal counts were not reached for two dinocyst (40-41 and 541-542  
295 cm) and three pollen (20-21, 440-441, 441-442 cm) assemblages. Their corresponding levels  
296 were therefore excluded from the discussion. Among dinocysts, *Brigantedinium* spp. includes  
297 all round-brown cysts, *Echinidinium* spp. includes all brown cysts with typical *Echinidinium*  
298 spine-like processes not determined on a species level, and *Spiniferites* spp. includes all  
299 *Spiniferites* taxa not determined on a species level. In addition, heterotrophic dinocysts (i.e.  
300 derived from dinoflagellates with a strict heterotrophic nutritional strategy) are indirectly related  
301 to food resources, especially diatoms, as commonly shown in upwelling areas (Wall et al., 1977;  
302 Lewis et al., 1990; Marret, 1994; Biebow, 1996; Zonneveld et al., 1997, 2001; Targarona et al.,  
303 1999; Bouimetarhan et al., 2009; Penaud et al., 2016). Therefore, the sum of heterotrophic taxa  
304 was made to account for “strict” heterotrophic dinocysts. Among continental palynomorphs,  
305 “undetermined fungal spores” include all fungal spores that cannot be determined on type-code,  
306 genus or species levels. Regarding relative abundance of pollen assemblages, percentages of  
307 *Pinus* were based on the total pollen sum, while continental NPP relative abundances were  
308 calculated on a total sum that includes the pollen main sum (i.e. without *Pinus*) and the sum of  
309 spores and other continental NPPs (van Geel et al., 1972; Cugny et al., 2010; Miola, 2012).

310

### 311 3.3.2. Statistical analysis on palynological results

312 Palynological diagrams of pollen and dinocyst assemblages were performed with the Tilia  
313 software (Grimm, 1990), also defining the more parsimonious statistically homogeneous  
314 palynological zonation according to the CONNIS model (Grimm, 1987).

315 Taxonomical diversity indexes were calculated using the “PAST version 4.06b” software  
316 (Hammer et al., 2001), including the species richness (i.e. number of taxa per sample), the  
317 Margalef’s richness index (diversity index), and the dominance index (i.e. the value “0”  
318 indicates equal presence of all taxa while the value “1” indicates the dominance of one taxon  
319 in the assemblage). In addition, multivariate analyses (Detrended Correspondence Analysis,  
320 DCA) were performed with the PAST program for semi-quantitative geochemical XRF data  
321 (cf. Data Availability section).

322

### 323 3.3.3. Dinocyst-inferred environmental reconstructions

324 Dinocyst-based sea-surface environmental quantifications were performed using R version  
325 2.7.0 software (R Development Core Team, 2008; <http://www.r-project.org/>) and the Modern  
326 Analogue Technique (MAT; e.g. Guiot, 1990; Guiot and de Vernal, 2007). This method consists  
327 of selecting (based on a dissimilarity index) a limited number of analogue surface dinocyst  
328 assemblages and associated environmental values. A modern surface database is thus required.  
329 Dinocyst fossil assemblages were compared to the most recent standardized Northern  
330 Hemisphere “modern” database (n=1,968 sites; de Vernal et al., 2020), recently upgraded with  
331 new modern assemblages of the Western Mediterranean Basin (WMB; + n=23: 6 in the Gulf of  
332 Lion and 17 in the AM; Coussin et al., 2022). The dinocyst dataset includes 71 different taxa  
333 in relation with 17 modern environmental parameters (de Vernal et al., 2020). Five modern  
334 analogues were found by the MAT, which allowed to calculate environmental parameters  
335 considering an average of related parameter values, with the maximum weight attributed to the  
336 statistically closest analogue (e.g. Guiot and de Vernal, 2007). Considering the statistical  
337 threshold distance of the MAT ( $d_T = 1.2$ ), analogues are considered as i) remote when the  
338 distance  $d > d_T$ , acceptable when  $d_T/2 < d < d_T$ , and good when  $d < d_T/2$  (de Vernal et al., 2005).  
339 Root Mean Square Errors (RMSE) are used to discuss uncertainties in fossil quantifications,  
340 often caused by the lack of corresponding modern analogues of fossil assemblages (Guiot and  
341 de Vernal, 2007; de Vernal et al., 2020). In this study, we have estimated summer and winter  
342 sea surface temperature ( $SST_{winter}$  and  $SST_{summer}$ ; RMSE of 1.2°C and 1.8°C, respectively), sea  
343 surface salinity ( $SSS_{winter}$  and  $SSS_{summer}$ ; RMSE of 1.1 psu and 2.1 psu, respectively), and mean  
344 annual Primary Productivity ( $PP_{annual}$ ; RMSE of 436.1 gC m<sup>-2</sup> yr<sup>-1</sup>).  
345

### 346 3.3.4. Pollen-inferred climate reconstruction

347 Pollen reconstructions were also generated with the MAT applying the same general principles  
348 as for the dinocyst-based reconstructions. In this case, the method calculates a dissimilarity  
349 index between fossil pollen obtained on core MD04-2801 and modern pollen assemblages  
350 extracted from the database updated in Dugerdil et al. (2021). Modern climate parameters  
351 associated with the best analogues are then weighted (according to the similarity of the best  
352 four analogues) to provide values for fossil-pollen assemblages. Climate reconstructions were  
353 obtained with a leave-one-out approach. In this study, the climate variables are Mean  
354 Temperature of the Coldest Month (MTCO; RMSE of 4.7°C), Mean Temperature of the  
355 Warmest Month (MTWA; RMSE of 2.6°C), Annual Temperature (TANN; RMSE of 3.1°C),

356 Annual Precipitation (PANN; RMSE of 199 mm/yr), and Summer Precipitation (SUMMERPR;  
357 RMSE of 51.3 mm/summer). We also calculated a temperature seasonality index as the  
358 difference between MTWA and MTCO reconstructions using the Rioja package in R (Juggins,  
359 2012).

360

### 361 **3.4. Biomarker analyses**

362 Biomarker analyses were performed at a temporal resolution of about 150 years. Lipids were  
363 extracted from 1.5 to 2 g of freeze-dried sediments using a mixture of  
364 dichloromethane/methanol (2:1 v/v). Silica gel chromatography was used to isolate alkenones  
365 and n-alkanes from the total lipid extracts. They were then analysed by gas chromatography,  
366 following Sicre et al. (1990). We used the global calibration from Conte et al. (2006) to convert  
367 the unsaturation ratio of C<sub>37</sub> alkenones ( $U^{k'}_{37} = C_{37:2}/(C_{37:2} + C_{37:3})$ ) into sea surface temperature  
368 (SST) using the following equation ( $SST = -0.957 + 54.293(U^{k'}_{37}) - 52.894(U^{k'}_{37})^2 + 28.321$   
369  $(U^{k'}_{37})^3$ ).

370 Simultaneously, high molecular-weight terrestrial n-alkane concentrations were determined.  
371 The C<sub>29</sub>, C<sub>31</sub>, C<sub>33</sub> and C<sub>35</sub> homologues produced from higher plants were quantified. Their sum,  
372 thereafter named TERR-alkanes, was used to reflect terrestrial inputs to the studied site  
373 (Castañeda et al., 2009; Jalali et al., 2017). Vegetation types can be distinguished based on the  
374 relative homologue distribution of leaf wax n-alkanes. Deciduous trees and shrubs are thought  
375 to mainly produce n-alkanes with n-C<sub>27</sub> and n-C<sub>29</sub> while grasses and herbs mainly produce n-  
376 C<sub>31</sub> and n-C<sub>33</sub> (Vogts et al., 2009; Schäfer et al., 2016; Bliedtner et al., 2018). Average Chain  
377 Length (ACL) of n-alkanes was also calculated to produce information on water availability  
378 and compare this to vegetation-type indicators from pollen analyses (Jalali et al., 2017).

379

380

## 381 **4. Results**

### 382 **4.1. Age model of core MD04-2801**

383 The age model of core MD04-2801 was built by integrating 20 AMS  $^{14}\text{C}$  dates (11 from the  
384 ARTEMIS spectrometer of the Laboratoire de mesure du Carbone 14, CEA Paris-Saclay, and  
385 nine from the ECHoMICADAS spectrometer; Table 1): 18 samples consist of monospecific  
386 planktonic foraminifera (*G. bulloides*) and two samples consist of gastropods (Table 1). All  
387 radiocarbon dates were calibrated using the CALIB 8.2 software (Stuiver and Reimer, 1993)  
388 and the IntCal20 calibration curve (Reimer et al., 2020), first considering a reservoir age of -  
389 400 years (Siani et al., 2000). To establish the age model (Figure 2), the rbacon package  
390 (Blaauw and Christen, 2011) was used under R (version 4.1.0; R Development Core Team,  
391 2021; <http://www.r-project.org/>). Two dates were discarded at 931 cm (large analytical error of  
392 270 years; Table 1) and 31 cm (considered as an outlier regarding the first 4 m of the core;  
393 yellow diamonds in Figure 2).

394 It is worth noting that the stratigraphy of the upper section is suspected to be influenced by a  
395 core disturbance by piston effect. This is supported by decreasing values of the sediment density  
396 from 250 cm upward, with very low  $V_p$  values between 140 and 90 cm (Figure 2). For this  
397 reason, the age model was calculated independently for the upper (431 to 0 cm) and lower  
398 (1,031 to 431 cm) parts of the studied core, and then brought together (Figure 2). Considering  
399 the density as the artefact clue, abrupt change in sedimentation rates at 431 cm (Figure 2) is  
400 suggested while the artefact in the sampling appears from 250 cm upward. Furthermore,  
401 laminations are visible below 400 cm but less clear above this level (especially from 250 cm  
402 upward), where sediments appear to be more homogenous (Figure 2). At the MD04-2801 core  
403 site, situated beyond the crest of a turbidite channel-levee system, the expected sedimentary  
404 record could be composed of hemipelagites and fine-grained turbidites from turbidity currents  
405 overspilling the levee. These high accumulation rates (i.e. around 150 cm/kyr on the 431–0 cm  
406 section; Figure 2) cannot therefore be expected to reflect gravity-driven sedimentary processes.  
407 In light of these features, a coring artefact in MD04-2801 is probable (Figure 2). Overall, a  
408 robust chronology is assumed from 431 cm to the base of the core with average sedimentation  
409 rates of about 40 cm/kyr (stable  $V_p$  and density values with a two-step density trend at around  
410 870 cm; Figure 2), while a less robust chronology is assumed from 431 cm upward with a two-  
411 step trend in physical sediment properties. From 431 to 250 cm, well-layered sediments, as  
412 observed in the basal section, correspond to a strong increase in density values and still stable  
413  $V_p$  values and may be related to an acceleration in sedimentation rates (280 cm/kyr; Figure 2).

414 From 250 cm upward, the creep of sediments appears very likely affected by the piston effect  
415 (strong decrease in density values at 250 cm and unexpected low Vp values between 120 and  
416 70 cm). According to the age model (Figure 2), the base of the studied core is dated at 14 cal  
417 ka BP.

418

## 419 **4.2. Sedimentological signals**

420 The core MD04-2801 mainly consists of homogeneous silty sediments that can be separated by  
421 six limits (a to f in Figure 3) based on the trends in graphs of sedimentological parameters.

422 KMDJ23 is a core very close to the MD04-2801 coring site whose top sample (water-sediment  
423 interface) was analyzed and presented in Coussin et al., 2022 ([https://doi-org.scd-proxy.univ-  
424 brest.fr/10.1016/j.marmicro.2022.102157](https://doi-org.scd-proxy.univ-brest.fr/10.1016/j.marmicro.2022.102157) ). It constitutes a modern assemblage useful as a  
425 reference point.

426

### 427 4.2.1. X-ray Fluorescence

428 In order to investigate the co-occurrences of major elements of the XRF dataset, we performed  
429 a Detrended Component Analysis (DCA) on selected elements (Ca, Si, Al, K, S, Ti, Fe, Mn,  
430 Sr; cf. Data in brief). In the study area, the silico-clastic detrital signature is well expressed by  
431 Ti and Fe, while Si and Al are the main chemical components of aluminosilicates. Ti, Fe, Si  
432 and Al show similar trends suggesting that these elements potentially relate to the clayey  
433 fraction formed by the chemical alteration of soils. Conversely, common patterns of Sr and Ca  
434 point to biomineralized and/or detrital carbonates. The DCA statistical analysis (Data in Brief)  
435 led to the most relevant XRF ratios for the following discussion. Given the difficulty in  
436 deconvoluting terrigenous and marine sources in the Ca-XRF signature, we considered both  
437 Ca/Al-XRF (mixed detrital-biogenic signature, Figure 3a) and Ti/Al-XRF (detrital signature;  
438 Figure 3b) for the paleoenvironmental interpretation conducted in the AM sediments. Both  
439 ratios generally show similar fluctuations in temporal variations over time and amplitudes,  
440 suggesting a stronger detrital source in the Ca-XRF signature except for two intervals  
441 characterized by high Ca/Al-XRF and low Ti/Al-XRF ratios from the base of the core to 910  
442 cm (limit “b”) and between 575 and 485 cm (limits d and e). The Ti/Ca-XRF ratio is considered  
443 as primarily detrital and linked to silico-clastic *versus* carbonate sources to the AM.

444

### 445 4.2.2. Magnetic Susceptibility and grain size

446 The Magnetic Susceptibility (MS) signal shows distinct fluctuations between 3.8 and 17.5 SI.  
447 Three main phases are identified with average values of 9.2 SI from the base to 910 cm (limit

448 “b”), of 14.3 SI between 910 and 370 cm (limit “f”) and of 11.6 SI from 370 cm upward (Figure  
449 3c).

450 In addition, according to the high-resolution grain-size data of total sediments (Data In Brief),  
451 the 4–63  $\mu\text{m}$  fraction largely dominates (silt, average of 66%), followed by the fraction  $<4$   $\mu\text{m}$   
452 (clay, average of 23%) and the fraction  $>63$   $\mu\text{m}$  (sand, average of 11%). More specifically, from  
453 the base of the sequence to 910 cm (limit “b”), the high proportion of the  $>63$   $\mu\text{m}$  fraction  
454 (Figure 3d) is associated with low amounts of ferro-magnetic minerals (low MS values; Figure  
455 3c), high Ca/Al values *versus* low Ti/Al (Figure 3 a,b), and extremely low median (D50) grain  
456 size of CaCO<sub>3</sub>-free sediments *versus* high D50 grain size of total sediments (Figure 3d). This  
457 may indicate that coarser sediments are mainly inherited from the erosion of carbonate  
458 formations, with little advection of small-sized silico-clastic and ferro-magnetic sediments.

459 Then, from 910 cm (limit “b”) to 370 cm (limit “f”), higher MS values (Figure 3c) combined  
460 with D50 values of CaCO<sub>3</sub>-free sediments higher than D50 values of total sediments (Figure  
461 3d) indicate increasing advection of silico-clastic and ferro-magnetic silto-clayey material with  
462 a lower proportion of detritic carbonate particles. Across limits “b” to “f”, the coarsest detrital  
463 particles of the mix (silicates and carbonates) are particularly evident in the 740–575 cm interval  
464 (between limits “c” and “d” or interval “c-d”), and correspond to two remarkable peaks of sandy  
465 sediments at 580 and 600 cms (Data in Brief). It is worth noting that the 575 to 485 cm interval  
466 (“d-e”) coincides with the second interval of high Ca/Al-XRF values (as in zone “a-b”) and  
467 lower D50 grain-size values (Figure 3d), with coarser sediments corresponding to silty rather  
468 than sandy particles as in the interval “a-b”.

469 From 370 cm (limit “f”) to 250 cm, MS values as well as grain-size properties point to finer  
470 silto-clayey sediments (Figure 3c). Finally, from 250 cm upward, wide ranges of coarse *versus*  
471 fine-sediment fluctuations (Data in Brief), associated with low D50 grain-size values (Figure  
472 3d), can be reconciled by invoking a small proportion of very coarse sediments which would  
473 bias the mean but hardly alter the particle-size medians. A grey band in Figure 3 highlights this  
474 section, suspected to be affected by core disturbance through piston effect.

475

#### 476 4.2.3. Clay mineral composition

477 Clay mineral averages are about 8% of Illite-Smectite (Interstratified), 18% of Chlorite, 32%  
478 of Kaolinite and 43% of Illite (Data In Brief). Clay results are represented as anomalies relative  
479 to the mean of each dataset (Data In Brief). Due to high sedimentation rates (around 50 cm/kyr;  
480 Figure 2), palygorskite was not significantly detected. The boxes in Figure 3g highlight the  
481 Majorly different clay mineral phases (relative to their mean values). The two intervals of



482 enhanced Ca/Al-XRF values (“a-b” and “d-e”) are also characterized by the highest  
483 interstratified values and lowest kaolinite percentages. Conversely, kaolinite percentages  
484 increase during intervals of both increasing proportions of clays and finer grain-size sediments  
485 (“b-c” and “e”-250cm). This suggests that increasing kaolinite values could evidence  
486 strengthened chemical alteration on land. We consequently use the Kaolinite/Illite ratio as a  
487 proxy of chemical alteration throughout the sequence.

488

### 489 **4.3. Stable isotope signals**

#### 490 4.3.1. Carbon isotopes in foraminifera

491 The  $\delta^{13}\text{C}$  values of endobenthic *Globobulimina affinis* and planktonic *Globigerinoides*  
492 *bulloides* foraminifera range between -0.9 and -2.1‰ (mean of -1.6‰) and between -0.6 and -  
493 2‰ (mean of -1.1‰), respectively (Figure 3e). Planktonic and endobenthic  $\delta^{13}\text{C}$  signals show  
494 similar values until 740 cm (limit “c”), but exhibit a significant offset (average of 0.7 ‰) after  
495 575 cm (limit “d”).

496 Heavier planktonic  $\delta^{13}\text{C}$  values observed during the interval “a-b”, as well as after 575 cm (limit  
497 “d”) reveal strong primary productivity. Conversely, the  $\delta^{13}\text{C}$  of endobenthic foraminifera  
498 generally reflects the  $\delta^{13}\text{C}$  of pore waters, which depends on the export flux of organic matter  
499 and availability of dissolved oxygen in bottom waters (e.g. McCorkle et al., 1990; Mackensen  
500 & Licari, 2003; Fontanier et al., 2006). Lighter benthic  $\delta^{13}\text{C}$  values after limit “b” may be  
501 indicative of remineralization of enhanced organic matter in bottom sediments.

502

#### 503 4.3.2. Oxygen isotopes

504 Endobenthic (*G. affinis*) and planktonic (*G. bulloides*)  $\delta^{18}\text{O}$  values range between 2.1 and 4 ‰  
505 (mean of 2.6 ‰) and between 0.4 and 2.2 ‰ (mean of 0.8 ‰), respectively, and show similar  
506 patterns throughout the sequence (Figure 3f). Heavier  $\delta^{18}\text{O}$  values (colder sea surface  
507 temperatures) in the interval “a-b” are reflected by values of 1.9 and 3.8 ‰ for planktonic and  
508 endobenthic taxa, respectively. Lighter mean  $\delta^{18}\text{O}$  values after limit “b” are stable around 0.6  
509 ‰ (standard deviation of 0.2 ‰) and 2.4 ‰ (standard deviation of 0.1 ‰) for planktonic and  
510 endobenthic taxa, respectively. However, wider ranges of planktonic  $\delta^{18}\text{O}$  isotope value  
511 variations, with slightly lower values since interval “b-d”, may be indicative of either  
512 decreasing salinities and/or increasing temperatures.

513

### 514 **4.4. Palynological analyses**

#### 515 4.4.1. Dinoflagellate cysts

##### 516 • *Diversity and concentrations*

517 Thirty-nine different dinocyst taxa were identified over the whole sequence, with a mean  
518 species richness of 18 different taxa per slide (Figure 4a). Species richness is lower than average  
519 from the base of the sequence to limit “a” (1,025 cm), in the “b-d” interval (910–575cm), and  
520 after limit “e”. Conversely, species richness is higher than average in “a-b” (1,025–910 cm) and  
521 “d-e” (575–485 cm) intervals. Both intervals are also characterized by low kaolinite percentages  
522 and high Ca/Al-XRF values, as well as heavy planktonic  $\delta^{13}\text{C}$  values.

523 The dinocyst dominance index (Figure 4a) is systematically explained by the major taxa  
524 *Brigantedinium*. The dinocyst diversity (Figure 4a), as reflected by the Margalef index (similar  
525 to species richness), shows opposite trends compared to *Brigantedinium* spp.; the lowest  
526 diversity being synchronous with high *Brigantedinium* spp. percentages.

527 Total dinocyst concentrations, mainly explained by *Brigantedinium* spp. occurrences, range  
528 between 450 and 29,000 cysts/cm<sup>3</sup>, with mean values of around 3,300 cysts/cm<sup>3</sup> (Figure 4a).  
529 Dinocyst concentrations show higher values during intervals “a-b” (1,025 to 910 cm) and “d-  
530 e” (575 to 485 cm), both previously described by a stronger diversity. We thus plotted the  
531 concentrations of all dinocysts without *Brigantedinium* spp. against the concentrations of  
532 *Brigantedinium* spp. alone in order to evaluate the respective contribution of these heterotrophic  
533 taxa with regards to the rest of the dinocyst community (Figure 4a). Up to limit “b”, other  
534 dinocysts are higher than *Brigantedinium* spp. (around 10,000 *versus* 2,000 cysts/cm<sup>3</sup>). They  
535 follow similar patterns between limits “b” and “e” (around 1,500 cysts/cm<sup>3</sup>) and, after limit “e”,  
536 all other dinocyst concentrations are slightly lower than *Brigantedinium* spp. (1,000 vs. 1,500  
537 cysts/cm<sup>3</sup>). Dinocyst concentrations show lower values but similar evolution compared to  
538 pollen grain concentrations throughout the sequence, except for similar concentrations obtained  
539 from 1040 cm to limit “b” and during the interval “d-e” (575–485 cm).

540

##### 541 • *Dinocyst assemblages and dinocyst zones*

542 Dinocyst assemblages are dominated by eight autotrophic taxa: *Nematosphaeropsis*  
543 *labyrinthus*, *Impagidinium aculeatum*, *Spiniferites mirabilis*, *Operculodinium centrocarpum*,  
544 *Spiniferites bentorii*, *Spiniferites membranaceus*, cysts of *Pentapharsodinium dalei*,  
545 *Lingulodinium machaerophorum* and seven heterotrophic taxa including *Echinidinium* spp.,  
546 *Selenopemphix quanta*, cysts of *Protoperidinium nudum*, *Selenopemphix nephroides*,

547 *Lejeunecysta* spp. (grouping of *L. oliva* and *L. sabrina*), *Trinovantedinium* spp. and  
548 *Brigantedinium* spp. (Figure 5a).

549 The dinocyst assemblages led us to consider four main limits, thus five palynozones (MD04-1  
550 to MD04-5; Fig. 5). These boundaries/zones are based on the CONNISS cluster analysis  
551 performed on dinocyst assemblages (threshold used is 11; Figure 5a). These four limits also  
552 correspond to four sedimentological limits (a-b-d-e; Figs. 3 and 4). Zone MD04-1, from the  
553 base of the sequence to limit “a”, is characterized by the dominance of *Brigantedinium* spp., *S.*  
554 *mirabilis* and *O. centrocarpum*. The second zone MD04-2 (interval “a-b”) is marked by  
555 increasing values of *N. labyrinthus* reaching 20 to 40%, associated with the increase in *B.*  
556 *tepiense*, *S. lazus* and *O. centrocarpum*. Zone MD04-03 (interval “b-d”) is characterized by a  
557 high plateau of *Brigantedinium* spp. up to ca. 40%, associated with the increase in *I. aculeatum*  
558 (up to 15 %) and *S. mirabilis*, especially in the interval “c-d”, and a progressive decrease in *O.*  
559 *centrocarpum* percentages. Zone MD04-4 (interval “d-e”) shows a sharp drop in  
560 *Brigantedinium* spp. percentages reaching 20%, while *S. mirabilis* increases to 30%. Finally,  
561 zone MD04-5 (from limit “e” onward) is characterized by the highest values of *Brigantedinium*  
562 spp. (about half of the total assemblage) associated with *S. mirabilis* (around 15%). A full  
563 description of main dinocyst results is available in Data in Brief.

564

#### 565 4.4.2. Pollen grains

##### 566 • *Diversity and concentrations*

567 Seventy-one different pollen taxa were identified for the whole sequence, with a mean species  
568 richness of 28 different taxa per slide (Figure 4b). Species richness ranges between 18 and 29  
569 taxa per slide with lower values between limits “c” and “f” (740 to 370 cm) which also  
570 correspond to the strongest representation of forest taxa (cf. percentages of total trees and total  
571 trees with *Pinus*; Figure 4b). In contrast, increased diversity coincides with the diversification  
572 of herbaceous plants. Mean total pollen concentrations are approximately of 6200 grains/cm<sup>3</sup>  
573 (ranging between 1300 and 25,000 grains/cm<sup>3</sup>); the highest values are in intervals “a-b” (1,025  
574 to 910 cm) and “d-e” (575 to 485 cm), as for dinocysts, and above 250 cm (removed from the  
575 discussion).

576 *Pinus* concentrations follow the same trend as total pollen concentrations that are mainly driven  
577 by trees (especially *Quercus*). Strong pollen production, enhanced river transport, and finer  
578 grain-sized sediments, are crucial factors contributing to increase pollen-grain concentrations.  
579 However, the strong link between pollen (terrestrial compartment) and dinocyst (marine realm)

580 concentrations point to a common mechanism of organic matter export to the AM and  
581 sedimentation processes.

582

583 • *Pollen and Non-Pollen Palynomorph (NPP) assemblages and pollen zones*

584 The zones defined on the basis of dinocyst assemblages have also been used for pollen  
585 assemblages to facilitate land-sea comparison (Figure 5b). Zone MD04-1 is characterized by  
586 the dominance of herbaceous pollen taxa, mainly Cichorioideae and Poaceae. Zone MD04-2 is  
587 marked by the strong increase in the altitudinal taxa *Cedrus* (reaching maximum percentages  
588 above 40% at 1001 and 961 cm), associated with semi-desert, steppic pollen taxa (i.e. *Ephedra*  
589 and *Artemisia*) and coastal-steppic taxa (i.e. Amaranthaceae). Zone MD04-3 is characterized  
590 by the progressive increase in arboreal taxa (especially *Quercus ilex*), associated with strong  
591 occurrences of herbaceous taxa (Cichorioideae and Poaceae) until 740 cm (limit “c”). In zone  
592 MD04-3, limit “c” corresponds to the onset of the strongest forest representation, largely  
593 represented by *Quercus*, associated with Cupressaceae, as well as Mediterranean forest (*Olea*,  
594 *Pistacia*) and open vegetation (i.e. Cichorioideae and Poaceae) taxa. Interestingly, from limit  
595 “c”, freshwater algae occurrences also increase. Zone MD04-3 is also marked by increasing  
596 abundance of *Glomus* spores and Ascospores. Zone MD04-4 shows a strong representation of  
597 arboreal taxa (up to 40%) associated with a slight decrease in open-vegetation taxa  
598 (Cichorioideae, Poaceae). Coastal-steppic taxa (Amaranthaceae), with slight increases in  
599 *Ephedra* and *Artemisia*, also correspond to decreasing occurrences of *Glomus* spores. Finally,  
600 zone MD04-5 is characterized by the progressive decrease in arboreal taxa (especially *Quercus*)  
601 favoring the synchronous increase in open-vegetation taxa (Cichorioideae, Asteroideae,  
602 Poaceae). Additionally, percentages of semi-desert taxa (*Ephedra* and *Artemisia*) somewhat  
603 increase with those of *Olea*, and *Glomus* spore occurrences progressively increase. Modern  
604 climate-landscape relationships in Eurasia and northern Africa (Woodwards, 1987; Peyron et  
605 al., 1998) will be considered for pollen interpretation. A full description of main pollen results  
606 is available in Data in Brief.

607

608 **4.4. Palynological quantification**

609 For dinocyst-inferred sea-surface reconstructions, the maximum number of selected analogues  
610 is five (Figure 4) Also, a threshold of 1.35 is adopted by the MAT (Modern Analogue  
611 Technique) to exclude too dissimilar assemblages. In this study,  $D_{min}$  varies around an average  
612 value of 0.87: no analogue was selected for six levels (440, 664, 800, 948, 992, 1000 cm), only  
613 one analogue for four levels (60, 746, 860, 932 cm), two analogues for one level (976 cm), three

614 analogues for three levels (976 cm), four analogues for nine levels (340, 532, 696, 760, 872,  
615 880, 920, 1026, 1040 cm) and five analogues for the 63 other levels, testifying for statistical  
616 robustness of the reconstruction for about three quarters of the analysed samples.

617 For pollen-inferred climate reconstructions, the number of selected analogues is always four.  
618 Appropriate analogues are selected through cross-validation based on the leave-one-out  
619 approach. Stable Dmin values are about 0.39 from 1,040 cm to limit “e” and about 0.47 from  
620 limit “e” to the top of the sequence, testifying to the robustness of reconstructed climatic  
621 parameters.

622 Considering hydrological (cf. dinocyst-based quantifications) and climate (cf. pollen-based  
623 quantifications) parameters, SST and SSS are discussed in parallel with annual precipitation  
624 and temperature seasonality. The exhaustive dataset of reconstructed environmental parameters  
625 is available in Data in Brief.

626

#### 627 **4.5. Molecular biomarkers**

628 Concentrations of C<sub>37</sub> alkenones, plotted as the sum of C<sub>37:2</sub> + C<sub>37:3</sub>, range from 18 to 328.5  
629 ng.g<sup>-1</sup>, with a mean value of about 75.6 ng.g<sup>-1</sup> (Figure 4a). The  $\sum C_{37}$  follows the same trend as  
630 that of palynomorph (dinocyst and pollen) concentrations along the sequence, with higher  
631 values in the oldest interval “a-b” (1,025 to 910 cm), highlighting the common pattern in  
632 organic matter export and preservation through both biomarker and palynological approaches.

633 Concentrations of TERR-alkanes range between 354 and 1,071 ng.g<sup>-1</sup>, with a mean value of  
634 643 ng.g<sup>-1</sup> (Figure 4b). Up to limit “b” (910 cm), they decrease to the lowest values of the record  
635 (379 ng.g<sup>-1</sup>). From limits “b” to “d”, TERR-alkane concentrations are generally higher and  
636 highly variable with above average values. They broadly decrease during intervals “d” to “f”  
637 and increase again until 370 cm before decreasing up to the top of the studied core.

638 Finally, the ACL (Average Chain Length; Figure 4b) calculated from the n-alkane distribution  
639 shows increasing values from interval “a” to “d”, suggesting a gradual dryness (expressed by  
640 high ACL values), followed by stable values up to limit “f”, followed by decreasing values  
641 close to the mean of the dataset (30,1) up to the top of the studied sequence. Mean values of the  
642 ACL are generally consistent with our palynological data underlying a strong representation of  
643 open vegetation along the sequence.

## 644 **5. Discussion**

### 645 **5.1. Palynomorph preservation and the signature of *Brigantedinium* spp.**

646 Fine-grained (silty-clayey) sediments and high sedimentation rates (ca. 50 cm/kyr) recorded  
647 with core MD04-2801 may have favored conditions for the preservation of fossilized  
648 palynomorphs (dinocysts and pollen grains). A recent study of the modern distribution of pollen  
649 grains in the WMB suggested that modern pollen assemblages in our study area are  
650 representative of the adjacent vegetation (e.g. *Quercus ilex*, Amaranthaceae and Cichorioideae;  
651 Coussin et al., 2022). However, previous studies have investigated taxa sensibilities to  
652 oxidation effects (e.g. Havinga, 1967, 1971; Lebreton, 2009). It has for exemple been shown  
653 that *Quercus* and Cichorioideae pollen grains are not very sensitive to degradation and could  
654 be overrepresented in pollen assemblages at the expense of other taxa. The intact aspect of all  
655 pollen grains throughout the sequence leads us to hypothesize that pollen are mainly from the  
656 coastal Algerian catchments and that over-representation of the main taxa is unlikely.  
657 Regarding dinocyst taxa, *Brigantedinium* spp. are dominant and show large fluctuations (ca. 10  
658 to 80 %; Figure 4a, 6j) throughout core MD04-2801. *Brigantedinium* spp. are often interpreted  
659 as witnessing upwelling regimes (e.g. Marret, 1994; Zonneveld et al., 1997, 2001;  
660 Bouimetarhan et al., 2009; Penaud et al., 2016; Coussin et al., 2022). Moreover, modern  
661 occurrences of *Brigantedinium* spp. in surface sediments of the western Mediterranean Basin  
662 (around 20%; Coussin et al., 2022) in association with *T. applanatum*, *Lejeunecysta* spp.,  
663 *Echinidinium* spp., *S. nephroides* and grouped *Selenopemphix quanta* and *Protoperidinium*  
664 *nudum*, also allowed to assign these taxa to productive surface waters and were used to highlight  
665 the major haline-upwelling front associated with the AC, itself depending on the vigour of the  
666 Alboran gyres (Coussin et al., 2022). *Brigantedinium* spp. peaking values of ca. 80% over the  
667 Holocene (Figure 6i) were never reached in western Mediterranean modern surface sediments,  
668 even along the AC (Coussin et al., 2022). Since *Brigantedinium* spp., as well as *Echinidinium*  
669 spp., are well-known for their strongest sensitivity to oxic conditions (e.g. Zonneveld et al.,  
670 1997; Kodrans-Nsiah et al., 2008; Bogus et al., 2014), their percentages must be interpreted  
671 carefully as direct tracers of primary productivity. Indeed, it has been shown that their  
672 occurrences in sediments decrease logarithmically with increasing bottom water oxygen  
673 content (Zonneveld et al., 2001, 2007, 2008). Our reconstructions therefore raise questions  
674 about potential taphonomic biases that may have affected dinocyst assemblages.  
675 The MD04-2801 core retrieved at a water depth of 2,063 m is located in the water depth range  
676 of the Western Mediterranean Deep Waters (WMDW). The WMDW, as well as Ligurian

677 Intermediate Waters (LIW), contribute to the Mediterranean Outflow Water (MOW) export at  
678 the Gibraltar Strait (Stommel et al., 1973; Lionello et al., 2006) which varied through time (e.g.  
679 Voelker et al., 2006; Toucanne et al., 2007; Peliz et al., 2009; Rogerson et al., 2010; Bahr et al.,  
680 2014, 2015; Voelker and Aflidason, 2015; Hernández-Molina et al., 2014). Stronger LIW  
681 during cold climate events (Toucanne et al., 2012) such as the Younger Dryas (YD), implying  
682 a stronger WMB ventilation, is also supported by Alboran Sea records (Mc Culloch et al.,  
683 2010). In contrast, warmer Holocene conditions, and especially the Sapropel 1 event ( $10.8 \pm$   
684  $0.4$  to  $6.1 \pm 0.5$  ka BP) in the Eastern Mediterranean Basin (e.g. Kallel et al., 1997; Bar-  
685 Matthews et al., 2000, 2003; Mercone et al., 2000; Rohling et al., 2002; Tachikawa et al., 2015),  
686 are characterized by a weakened/cessation of the LIW formation (e.g. Toucanne et al., 2012).  
687 This shift from well-ventilated bottom waters during the YD to less-ventilated ones during the  
688 Holocene optimum (ca. 9.5-6.5 ka BP) may respectively correspond to low (around 20% such  
689 as today) or high ( $> 40\%$ ) percentages of *Brigantedinium* spp. (Figure 6i). There is therefore a  
690 risk that *Brigantedinium* spp. relative abundances may be modulated by oxygenation conditions  
691 despite the high sedimentation rates recorded at our studied site. In this context, Zonneveld et  
692 al. (2007) suggested to use absolute concentrations of phototrophic rather than heterotrophic  
693 taxa (or total dinocyst) ones, combined with dinocyst diversity (or species richness), to better  
694 assess productivity conditions. In the following discussion, these recommendations are  
695 considered to limit potential biases due to diagenesis or ventilation when discussion dinocyst  
696 assemblage reconstructions.

697

## 698 **5.2. From the Bölling-Alleröd to the Younger Dryas**

### 699 5.2.1. Hydrological conditions

700 Alkenone SSTs show a strong cooling from the Bölling-Alleröd (B/A: zone MD04-1) to the  
701 Younger Dryas (YD: zone MD04-2 or “a-b”; Figure 6) featuring the lowest SST values (i.e.  
702  $15.5^{\circ}\text{C}$ ;  $4.1^{\circ}\text{C}$  below modern annual SSTs), consistent with the heaviest planktonic  $\delta^{18}\text{O}$  values  
703 greater than 2‰ (Figure 6a,b). These low temperatures corresponds to the lowest reconstructed  
704 seasonality values (Figure 7h). This cold SST trend is synchronously observed in both the  
705 WMB sequences (Figure 8d,h,k,n,q). During the YD, cool-water dinocyst taxa (*N. labyrinthus*,  
706 *B. tepikiense* and *S. lazus* ; Figure 6c) dominating today polar to subpolar environments  
707 (Rochon et al., 1999; Van Nieuwenhove et al., 2020) show maximum percentages, while  
708 dinocyst-derived SSTs are not able to provide modern analogues representative of the  
709 environmental conditions of this cold climate event (Figure 6b). Indeed, all selected analogues

710 had statistical distances higher than the accepted threshold (cf. Data in Brief). SSTs lower by  
711 3.5 and 8.5°C with respect to present-day winter conditions were reconstructed using  
712 foraminifera and dinocysts in SW Portugal and Cadiz-NW Morocco, respectively (Penaud et  
713 al., 2011). At these northeastern Atlantic subtropical sites, the same YD assemblages (*N.*  
714 *labyrinthus*, *B. tepikiense* and *S. lazus*) were observed with slight differences in percentages: *B.*  
715 *tepikiense* hardly occurred in the Gulf of Cadiz and further south, while *S. lazus* was not found  
716 off Portugal (Penaud et al., 2011). These observations support the mixed northern and  
717 subtropical North Atlantic influences in the AM. Also, as observed in the Alboran Sea (Turon  
718 and Londeix, 1988), *N. labyrinthus*, a stratigraphical marker of the YD, testifies of the  
719 southward shift of the bioclimatic belts during this cold event of the last deglaciation. In the  
720 AM, percentages around or slightly higher than 30% are closer to those reconstructed off the  
721 Iberian margin (slightly higher than 20%) than in NW Morocco (about 5%), and point to an  
722 enhanced advection of cold Atlantic waters in the WMB. In addition, *O. centrocarpum* (i.e.  
723 North Atlantic taxon) shows four-time stronger representation than *L. machaerophorum*  
724 estuarine taxon, suggesting the prevailing oceanic influence in the AM and associated low  
725 fluvial input (Figure 5a). This is supported by the higher values of Ocen/Lmac dinocyst ratio  
726 for all the compared WMB sites (Fig. 8)

727 Heavy planktonic  $\delta^{13}\text{C}$  values (Figure 6g) and higher concentrations of alkenones (Figure 4a)  
728 and phototrophic dinocyst concentrations (Figure 6f) as well as a strong dinocyst diversity  
729 (Figure 4a) suggest enhanced primary productivity, despite lower percentages of  
730 *Brigantedinium* spp. (Figure 6i) that may result from a lower preservation of heterotrophic cysts  
731 under stronger bottom-water ventilation (cf. section 5.1). More productive conditions may be  
732 attributed to a stronger vigour of the AC resulting from the strengthening of the Alboran gyres  
733 during the YD (Combourieu-Nebout et al., 1999; Barcena et al., 2001; Penaud et al., 2011;  
734 Rouis-Zargouni et al., 2012; Ausín et al., 2015). This finding can also be explained by enhanced  
735 vertical mixing triggered by stronger winds replenishing surface waters with deep water  
736 nutrients.

### 737 5.2.2. Climate and continental context

738 Enhanced YD productivity could result from fertilization of the photic zone by Saharan dust  
739 deposition (Moreno et al., 2002; Bout-Roumazelles et al., 2007; Jimenez-Espejo et al., 2008;  
740 Rodrigo-Gamiz et al., 2011; Bout-Roumazelles et al., 2013). Unfortunately, the clayey fraction  
741 of core MD04-2801 only represents ca. 20% of the sediment lithology. The high sedimentation  
742 rates (ca. 50 cm/kyr), mainly characterized by silts, do not allow characterizing aeolian-



743 transported clayey minerals such as the typical palygorskite signature which is drowned in other  
744 clayey minerals amount signals.

745 During the YD, the strong representation of semi-arid (*Artemisia*, *Ephedra*) and steppic-coastal  
746 (Amaranthaceae) taxa, and the weak representation of Mediterranean forest taxa indicate  
747 extremely dry conditions characterized by an open and steppic landscape (Figure 7g). This open  
748 landscape is expressed by the lowest forest taxa representation in the WMB sequences (Figure  
749 8g,j,m,p). Previous studies in the Western Mediterranean Sea already showed this cold-dry  
750 event as characterized by a first dry phase followed by a more humid period (e.g. Combourieu  
751 Nebout et al., 1998, 2002; Turon et al., 2003; Naughton et al., 2007; Kotthoff et al., 2008;  
752 Fletcher and Sanchez-Goñi, 2008; Dormoy et al., 2009; Combourieu-Nebout et al., 2009;  
753 Desprat et al., 2013). This bipartite structure is not obvious at the resolution of our study, except  
754 for a slight decreasing trend of *Artemisia* from the start to the end of the YD (Figure 5b).  
755 Additionally, increasing ACL values from 29.8 to 30.2 (Figure 4b) are consistent with a higher  
756 plant adaptation to water stress.

757 The YD sedimentary facies of core MD04-2801 highlights coarse carbonate sediments with  
758 minor advection of small-sized silico-clastic and ferro-magnetic sediments (Figure 3d).  
759 Consequently, arid conditions during the YD, as revealed by pollen grains, may have favored  
760 erosion of sedimentary formations onland and aeolian transport of carbonate particles amplified  
761 by strengthened atmospheric circulation. Indeed, low Kaolinite values (cf. Data in Brief)  
762 suggest reduced chemical alteration, while low concentrations of *Glomus* spores evidence weak  
763 runoff due to low precipitations (Figure 7c). Sporadic but intense erosive runoff events may be  
764 linked to peaks of reworked cysts originating from the alteration of Tertiary carbonate  
765 formations (Figure 5a). Indeed, Algerian oued discharge intensifies during intense rainfalls  
766 events responsible for flash floods with strong erosive effects. However, the scarce occurrences  
767 of continental NPPs and generally low concentrations of reworked dinocysts rather attest low  
768 alteration and low fluvial delivery to the AM.

769 Finally, unusual occurrences of *Cedrus* (about 20 %, peaking at 40 % ; Figure 7j) are recorded.  
770 Considering the modern distribution of *Cedrus atlantica* in Northern Africa (Bell et al., 2019),  
771 in the highest altitudinal vegetation belts (Ben Tiba and Reille, 1982; Stambouli-Essassi et al.,  
772 2007), and the modern distribution of *Cedrus* percentages (around 0.5%) in KMDJ-23 core  
773 (Coussin et al., 2022), we suggest that a wider altitudinal *Cedrus-Pinus* forest developed in the  
774 high reliefs of the Tell Atlas. Even if stronger aeolian transport of coniferous pollen grains  
775 better dispersed by winds than other pollen grains is possible under stronger atmospheric  
776 circulation, synchronous peaks of *Cedrus* and reworked cyst concentrations (Figure 4), rather

777 suggest remaining mild conditions in altitudinal zones enhancing fluvial transport (i.e. strong  
778 seasonal erosive runoff) of *Cedrus*, even under the prevailing arid conditions of the YD.

779

### 780 **5.3. The Early Holocene (11.7–8.2 ka BP)**

#### 781 5.3.1. Delayed Mediterranean forest expansion

782 The Early Holocene is characterized by a strong decrease of the semi-arid and coastal-steppic  
783 vegetation (Figure 7g), replaced by typical matorrals (xerophytous open vegetation) mainly  
784 represented by Cichorioideae (Figure 5b). At the same time, the altitudinal forest represented  
785 by *Cedrus* is no longer recorded along the Holocene with high percentages (i.e. values close to  
786 modern ones; Figure 7j), due to reduced extent of these altitudinal vegetation belts in the Atlas  
787 Mountains in a context of increasing temperatures allowing other taxa to colonise altitudinal  
788 belts. Previous studies also discussed the limited altitudinal area where *Cedrus* retracted at the  
789 YD-Holocene transition, while warmer Holocene conditions favors the evergreen *Quercus*  
790 forest expansion (Marret and Turon, 1994; Cheddadi et al., 1998, 2009; Zielhofer et al., 2017).  
791 Until 8 ka BP, the progressive increase of Mediterranean forest taxa, combined with the  
792 persistent signature of the open vegetation (e.g. Cichorioideae, Poaceae; Figure 7 f,g), suggest  
793 a progressive increase of moisture, which is a critical limiting factor for the forest expansion in  
794 the southern Mediterranean area (Quezel, 1999). Increasing moisture is also supported by  
795 sedimentological, bioindicator, and biochemical runoff tracers (i.e. higher magnetic  
796 susceptibility (Figure 7e) and Ti/Ca-XRF values (Figure 6h), higher concentrations of *Glomus*  
797 spores (Figure 7c) and of pre-quaternary cysts (Figure 4a), higher TERR-alkane fluxes (Figure  
798 7d)). In the AM, *Quercus* maximal values thus appear delayed, while Mediterranean matorrals  
799 (mainly represented by Cichorioideae, Poaceae and Asteraceae) associated with typical  
800 sclerophytous trees (*Olea* and *Pistacia*), are still observed.

801 The delayed expansion of forest appears consistent with current Mediterranean observations  
802 suggesting that, following moisture deficiency, three millennia are necessary for a full  
803 Mediterranean forest recovery (e.g. Combourieu-Nebout et al., 1998, 2002; Allen et al., 2002;;  
804 Turon et al., 2003; Naughton et al., 2006; Fletcher and Sanchez-Goñi, 2008; Jalut et al., 2009;  
805 Tzedakis, 2007; Fletcher et al., 2010; Zielhofer et al., 2017). The Early Holocene corresponds  
806 to the highest values of boreal summer insolation (Berger and Loutre, 1991; Figure 8b),  
807 responsible for high summer temperatures that may have enhanced summer Mediterranean  
808 droughts, therefore slowing down the development of trees, especially evident in the more  
809 sensitive eastern part of the basin (Figure 8m,p). Previous studies conducted in northwestern

810 Africa also discussed the maximal forest development at around 8.5 ka BP (Ballouche, 1986;  
811 Brun 1989; Lamb et al., 1989), consistently with the maximal values reached at the end of the  
812 Early Holocene in our study core (ca. 8 ka BP). Climate quantifications also suggest relatively  
813 low precipitation before 8.5 ka BP while the temperature seasonality indicates a strong thermal  
814 amplitude explained by high summer temperatures (Figure 7h). The Alboran Sea and by  
815 extension the AM are extremely sensitive to the Atlantic moisture through the influence of  
816 westerlies (i.e. for Mediterranean cyclogenesis). From 11.7 to 10 ka BP, the extended dry period  
817 post-YD has also been reported across the SW and NE Mediterranean basin (Dormoy et al.,  
818 2009) and is probably linked to a still weak influence of westerly cyclones (Kotthoff et al.,  
819 2008). Indeed, the North Atlantic storm tracks may have been maintained in a southern position  
820 under the influence of the Fennoscandian Ice Sheet still persistent until 9 ka BP (Magny et al.,  
821 2003). There, the forest expansion is directly in phase with the climate change of northern  
822 Atlantic latitudes (cf. NGRIP oxygen isotopes *versus* Alboran Sea forest signal in Figure 8a,g,j),  
823 in agreement with numeric simulations (Carlson et al., 2008). The Atlantic influence, and  
824 associated moisture transport, follows a decreasing gradient from west to east (Figure 8h,j,m,p)  
825 between the Alboran Sea to Algeria, whatever the climate interval considered over the last 14  
826 kyrs.

827

### 828 5.3.2. Warmer oligotrophic conditions

829 In parallel with the Mediterranean forest expansion (Combourieu-Nebout et al., 1998, 1999,  
830 2002, 2009), alkenone, dinocyst and planktonic  $\delta^{18}\text{O}$  data (Figure 6a,b,c) point to a strong  
831 increase of SSTs at the start of the Holocene, with a 4.5°C increase of alkenone-based annual  
832 SST (i.e. from 16°C during the YD to ca. 20.5°C during the Holocene). It is worth noting that  
833 alkenone-based SSTs exhibit mean annual values consistent with the dinocyst-based SST  
834 seasonal variability range (Figure 6b). Furthermore, both alkenone- and dinocyst-derived SST,  
835 as well as percentages of cold water dinocyst taxa, point to slightly cooler SST conditions  
836 during the Early Holocene regarding the following conditions of the Middle Holocene. The  
837 warmest conditions are therefore not reached yet during the Early Holocene, and the prevalence  
838 of runoff signatures (significant peaks of *Glomus* and pre-Quaternary cysts; Figure 4a, 7a) may  
839 result from increasing moisture combined with a still high erodability of soils in a continental  
840 context of persistent opened landscape.

841 The Holocene transition is also characterized by a pronounced drop of dinocyst and alkenone  
842  $\text{C}_{37}$  concentrations (Figure 4a), as well as lighter planktonic  $\delta^{13}\text{C}$  values (Figure 7f), likely

843 accounting for less productive conditions. Interestingly, heterotrophic cyst percentages (Figure  
844 7j) increase with a plateau of high values (about 50 %) persistent until 6.5 ka BP. However, the  
845 Early Holocene also corresponds to the maximum of the boreal summer insolation and the  
846 related northward migration of the intertropical convergence zone. This configuration drives  
847 the formation of Sapropel S1 (cf. Figure 6; Rohling, 1994; Rohling et al., 2004, 2015) added to  
848 the enhanced river discharge in the Eastern Mediterranean Basin, as observed eastward in the  
849 Siculo-Tunisian strait between ca. 9.5–6 ka BP (Bout-Roumazeille et al., 2013). We suggest  
850 that enhanced African monsoons (e.g. Emeis et al., 2000 ; Kallel et al., 1997 ; De Menocal et  
851 al., 2000 ; Tachikawa et al., 2015 ; Siani et al., 2013), associated with the cessation of deep and  
852 intermediate water formation (Frigola et al., 2007; Toucanne et al., 2012), may have favored  
853 organic matter and therefore heterotrophic cyst preservation, and especially that of the most  
854 sensitive taxa *Brigantedinium* spp., under anoxic bottom waters in the Mediterranean Sea. Low  
855 productive conditions in the AM, as also confirmed by significant co-occurrences of *I.*  
856 *aculeatum* and *S. mirabilis* (Coussin et al., 2022), resonate with the oligotrophic conditions  
857 recorded in the Gulf of Cadiz (Penaud et al., 2016) that may have propagated in the WMB  
858 through advection of nutrient-poor subtropical North Atlantic Central Waters.

859

#### 860 **5.4. Middle Holocene (8.2–4.2 ka BP)**

861 After an increasing trend across the Early Holocene, the Mediterranean forest reaches maximal  
862 values higher than 20% during the Mid-Holocene, while the Eurosiberian taxa do not show a  
863 significant increase (Figure 7f). These latter arboreal taxa require high moisture conditions and  
864 a reduced seasonality in the precipitation regime, therefore suggesting still moderate  
865 precipitation in the southern Mediterranean Basin as also confirmed by sclerophyllous and  
866 matorral observations (Figure 7g). The best coincidence interval for high-forest percentages in  
867 the three western Mediterranean sequences is recorded between 10 and 5.5 ka BP (green colored  
868 band in Figure 8). More specifically, the Mid-Holocene can be subdivided into three main  
869 phases.

##### 870 5.4.1. The “8.2 ka BP” event

871 The first event, centered around 8.2 ka BP, lasting for about 100 to 200 years, is characterized  
872 by a significant drop in forest distribution (Figure 7f). This is reminiscent of the so-called “8.2  
873 ka event” (Alley et al., 1997) that led to cold climate and hydrological conditions in the  
874 Northern Hemisphere and also affected the WMB (Combourieu Nebout et al., 1998, 2002;  
875 Magny et al., 2003; Zanchetta et al., 2007; Fletcher and Sanchez-Goñi, 2008; Pross et al., 2009;

876 Depreux et al., 2021) by limiting the precipitation pattern (Berger and Guilaine, 2009; Morrill  
877 et al., 2013). During this arid event, anomalously low fluvial discharge may be responsible for  
878 lower concentrations of pre-Quaternary cysts, *Glomus* spores, and freshwater microalgae in the  
879 AM (Figure 5a, 7b,c). This drought interval is also obvious with low values of the ratios Ti/Ca-  
880 XRF ratio (Figure 6h) and Kaolinite/Illite (Figure 7a) thus respectively suggesting both lower  
881 river runoff and chemical alteration. The 8.2 ka BP event is also known as a cold event with  
882 lowered SSTs, as recorded by alkenone SST (Figure 6b).

#### 883 5.4.2. The African Humid Period

884 Between 8 and 6 ka BP, evergreen oaks largely dominated the Mediterranean forest (Figure 5b,  
885 7f), with the maxima recorded at that time, associated with the highest representation of *Pistacia*  
886 and *Olea*, and the lowest representation of coastal-steppic and semi-arid taxa (Figure 7g),  
887 suggesting decreasing summer aridity and mild winters. From 8 to 6 ka BP, this important  
888 increase in moisture is consistent with previous studies conducted in the southwestern  
889 Mediterranean lowland areas (Fletcher et al., 2013; Jaouadi et al., 2016).

890 In addition, high river discharges are highlighted by increasing pre-Quaternary cyst and *Glomus*  
891 spore concentrations, as well as by the first significant increases in freshwater microalgae  
892 concentrations (Figure 7b) and significant low excursions of dinocyst-based SSS estimates  
893 (salinity drops of around 1.5 psu; Figure 6d). Simultaneously, higher Kaolinite (Figure 7a) and  
894 Ti/Ca-XRF (Figure 6h) values attest to increasing chemical alteration and river runoff, in a  
895 context of warmer SSTs suggested by dinocyst-derived and alkenone reconstructions (1.5°C  
896 higher than present; Figure 6b,c). This interval of increased precipitation in the Algerian  
897 highlands is synchronously recorded by several studies in the Maghreb region (Jaouadi et al.,  
898 2016; Lebreton et al., 2019; Depreux et al., 2021) and by Mediterranean simulations (Brayshaw  
899 et al., 2011; Peyron et al., 2017). At this time, rains grew stronger and spread northward into  
900 the Sahara with enhanced summer rainfall in Africa and other parts of the tropics (e.g. de  
901 Menocal et al., 2000; McGee et al., 2013). No monsoon precipitations are recorded in the  
902 studied Western Mediterranean area (Tzedakis, 2007; Brayshaw et al., 2011), but increasing  
903 moisture attests to the strongest phase of summer rainfall (average annual precipitation of 650  
904 mm; 270 mm higher than the present) in a context of enhanced temperature seasonality (Figure  
905 7h).

906 After the oligotrophic cooler conditions of the Early Holocene, higher nutrient-enriched fluvial  
907 discharge may explain a slight increase in productivity, as suggested by increasingly heavy  
908 values of planktonic  $\delta^{13}\text{C}$  and a slight increase in phototrophic cyst concentrations (Figure 6f,g).

909 However, the Middle Holocene also records the strongest representation of the subtropical  
910 taxon *I. aculeatum*, concomitantly with Alboran Sea and Gulf of Cadiz sequences (Penaud et  
911 al., 2011, 2016; Rouis-Zargouni et al., 2012), this taxon signing for warmer-oligotrophic sea  
912 surface conditions. We therefore suggest that the high mid-Holocene SSTs may have prolonged  
913 the seasonal length of water column stratification and thus the deepening of the thermocline.  
914 We hypothesize that the subsequent deepening of the nutricline mitigated the productive  
915 conditions, explaining the low contrast between early and Middle Holocene productivity  
916 regimes.

917 At ca 8 ka BP, the shift between the Early and Middle-Holocene is marked by the onset of the  
918 Western Alboran Gyre circulation (Rohling et al., 1995; Pérez-Folgado et al., 2003; Ausín et  
919 al., 2015), promoting enhanced Atlantic water inflow into the Mediterranean Basin and the  
920 onset of the AC flow through the east, consistently with the increased Ocen/Lmac ratio from  
921 Cadiz to Algeria (Figure 8f,i,l,o). Interestingly, from 8 ka BP, the easternmost Ocen/Lmac  
922 signature shows an inverse trend to that of all western Mediterranean sequences, suggesting a  
923 strong depletion of the Atlantic influence from the Middle-Holocene at the Siculo-Tunisian  
924 strait, while increasing Ocen/Lmac ratios were synchronously recorded for the cold YD from  
925 west to east in the five sediment cores (Figure 8f,i,l,o,r).

926

#### 927 5.4.3. Mediterranean forest retreat onset

928 From 6 ka BP, the progressive decline in forest taxa and the increase in coastal-steppic taxa  
929 percentages, associated with decreasing fluxes of TERR-alkanes as well as decreasing  
930 concentrations of pollen, *Glomus* spores, freshwater microalga and pre-Quaternary cysts  
931 (Figure 7b,c,d,f,g) suggest decreasing precipitation rates and runoff in the AM. Summer  
932 precipitation therefore gradually declined (Figure 7i), due to the decrease in summer solar  
933 radiation in the tropics (Berger and Loutre, 1991), and climate conditions became too dry for  
934 plants. The sharp drops in Ti/Ca-XRF (Figure 6h) and Kaolinite values (Figure 7a) also suggest  
935 dusty-desert conditions, in agreement with previous western Mediterranean aridification signals  
936 (e.g. Fletcher and Zielhofer, 2013; Depreux et al., 2021), therefore characterizing the end of the  
937 AHP (Shanahan et al., 2015). The aridity trend, that started after 6 ka BP, ranged from about  
938 5.5 to 3 ka BP (yellow band identified between limits “d” and “e” in Figures 6 and 7),  
939 consistently with an extremely dry interval described in western Mediterranean studies at the  
940 end of the African Humid Period (Cacho et al., 2001; Combourieu-Nebout et al., 2009), and  
941 also corresponding to increasing flash floods in Tunisia and Morocco due to erodible soils in

942 open landscape (Zielhofer and Faust, 2008; Depreux et al., 2021). During this interval,  
943 phototrophic productivity and higher dinocyst diversity (Figure 4a) coincide with ever-  
944 increasing heavy values of planktonic  $\delta^{13}\text{C}$  (Figure 6g). Productive conditions are related to  
945 decreasing percentages of *I. aculeatum* (i.e. SST cooling) and increasing percentages of *S.*  
946 *mirabilis* (i.e. Atlantic water influence), suggesting, as for the YD (section 5.2.a.), a stronger  
947 vigour of the AC resulting from the strengthening of the Alboran gyres. Lower *Brigantedinium*  
948 spp. values may result from a lower preservation under stronger ventilation of Mediterranean  
949 bottom waters at that time.

950

## 951 **5.5. Late Holocene (4.2 ka BP to present)**

### 952 5.5.1. The “4.2 ka BP” event

953 Peak values of coastal-steppic and semi-arid taxa percentages culminated between 4.3 and 3.9  
954 ka BP, coupled with the lowest *Glomus* spore concentrations recorded in the sequence, and may  
955 correspond to a phase of megadrought in Algeria (MDA in Figure 7) that lasted for about 400  
956 years (Figure 7g), consistent with a regional speleothem study from Ruan et al. (2016). The  
957 highest summer droughts recorded in the study area therefore appear synchronous with the well-  
958 known 4.2 ka BP event (e.g. Jalali et al., 2016; Bini et al., 2019, Kaniewski et al., 2019; Di Rita  
959 and Magri, 2019), within the 5.5–3 ka BP interval. This also coincides with the development of  
960 the plateau of the heaviest planktonic  $\delta^{13}\text{C}$  values (i.e. strongest productivity from 4.2 ka BP  
961 onward) in a context where the lowest percentages of *Brigantedinium* spp. were recorded, likely  
962 due to a strengthening of deep-water circulation at 4.2 ka BP (Figure 6g,i).

963

### 964 5.5.2. Settling of Modern conditions

965 The Late Holocene is characterized by the end of the 5.5–3 ka BP most arid Holocene interval  
966 followed by the last 3 kyrs BP occurring in a context of orbitally-driven climate aridity. From  
967 the Middle to Late Holocene, Mediterranean landscapes are strongly influenced by human  
968 impacts and fire activity (Pausas and Vallejo 1999, Vanni re et al., 2008; Mercuri et al., 2019).  
969 Over the last 3 kyrs BP, two phases are identifiable in this study. First, from 3 to 1.5 ka BP,  
970 strong river discharge to the AM and associated runoff are recognized through increasing Ti/Ca-  
971 XRF (Figure 6h) and Kaolinite/Illite (Figure 7a) values. Pre-Quaternary cyst (Figure 5a),  
972 *Glomus* spore and freshwater microalgae (Figure 7b,c) concentrations, even reached their  
973 highest values over this period. Stronger signals of alteration-erosion and river runoff to the

974 AM directly follow the 5.5–3 ka BP interval, as observed during the Early Holocene right after  
975 the YD. Only the freshwater algae remain stable with low values during the Early Holocene  
976 compared with the 3–1.5 ka BP interval. The 3 to 1.5 ka BP interval also corresponds to  
977 increasing advection of Anthropogenic Pollen Indicators (*Rumex*, *Cerealia*-type and *Plantago*  
978 *lanceolata*) as well as Amaranthaceae and *Artemisia* (Figure 5b), likely resulting from pastures,  
979 as previously suggested in arid climates (Jaouadi et al., 2010; Florenzano et al., 2012;  
980 Florenzano et al., 2015). Two factors may have amplified the signature of river erosion-runoff:  
981 i) the arid conditions prevailing that favored strong erodability of soils, and ii) the superimposed  
982 growing anthropic impacts opening the landscapes in adjacent watersheds (e.g. Pastoralism,  
983 culture parcels and land clearing).

984 The second phase, from 1.5 ka BP to the top of the sequence, presents a sharp drop in  
985 Mediterranean forest taxa percentages in parallel with the highest Kaolinite/Illite (strongest  
986 chemical alteration ; Figure 7a) and Ti/Ca-XRF values (strongest erosional-runoff processes;  
987 Figure 6h). The antagonist pattern between “*Glomus* spore - freshwater microalgae”  
988 concentrations and Kaolinite/Illite values (i.e. opposite their general covariation during the  
989 whole sequence) lead to interpret this interval as driven by anthropogenic forcing.

990 Regarding surface waters, the plateau of heavy planktonic  $\delta^{13}\text{C}$  values, starting at 3 ka BP  
991 coincides with decreasing *Impagidinium* spp. percentages and concentrations. At this period,  
992 *Brigantedinium* spp. percentages and concentrations maintain their highest values, with  
993 concentrations of heterotrophic cysts (Figure 6f) even significantly exceeding those of  
994 autotrophic cysts for the first time of the whole study sequence. From 3 ka BP, the upwelling  
995 taxon *T. applanatum* reaches its highest percentages and concentrations (Figure 5a). We  
996 therefore argue for the development of the current hydrographic conditions (cf. Figure 1a),  
997 where productivity is sustained by both vertical mixing due to the AC in the AM (wind-driven  
998 eddies) and nutrient-enriched fluvial discharge intensified by anthropic-driven land-use.  
999 Interestingly, the threshold previously highlighted at 1.5 ka BP (limit “f” in Figure 6)  
1000 corresponds to a marked drop in alkenone and dinocyst-derived SST estimates, that also  
1001 corresponds to reduced dinocyst-derived SSS estimates. From 1.5 ka BP to present, this SST  
1002 and SSS decrease would confirm that strong advection of continental waters, accelerated by  
1003 anthropic-driven erosional processes, can be superimposed on the post-3 ka BP setup of modern  
1004 sea surface conditions, participating in the present-day primary productivity in the AM.

1005

## 1006 **5.6. West to East Mediterranean Basin transect**

### 1007 5.6.1. Regional disparities in hydrological-climatic trends along the Holocene



1008 Pollen records from north-eastern Algeria, and more specifically marine records from the  
1009 Siculo-Tunisian Strait, show a progressive Late Holocene evolution characterized by higher  
1010 precipitation rates (Figure 8g, j, m, p). This may be due to the Mediterranean storm track  
1011 carrying increased moisture from the Atlantic through the Gulf of Lion to the north-eastern  
1012 Algeria, northern Tunisian and Sicilian areas (Desprat et al., 2013; Lionello et al., 2016). During  
1013 the Late Holocene, the northward storm track, affecting less frequently the westernmost  
1014 Mediterranean regions (i.e. Alboran Sea for instance characterized by increasing aridity despite  
1015 lower summer temperatures), would be responsible for stronger Mediterranean storms from the  
1016 Gulf of Lion to the Central Mediterranean Sea as presently observed (Lionello et al., 2006).  
1017 This dichotomy between climate trends recorded in the Alboran Sea and AM is furthermore  
1018 reflected by highest alkenone SST reached between 10–8 ka BP westward (and decreasing  
1019 afterwards following NGRIP temperatures; cf. ODP 976 data in Figure 8a, h). These  
1020 temperature ranges are reached from 8 ka BP eastward (particularly obvious with core MD04-  
1021 2801 data in Figure 8n). The increasing SST gradient from west to east is also evident whatever  
1022 the interval considered over the last 14 kyrs.

1023

#### 1024 5.6.2. Rapid Holocene climate changes

1025 Rapid decline of forest at the infra-millennial timescale suggests events of enhanced continental  
1026 aridity, synchronously with alkenone SST coolings at 9, 8.2, 7.3 and 6.5 ka BP (horizontal  
1027 dotted lines in Figure 8). These cold, arid events have already been described in marine and  
1028 continental studies from SW Iberia to the WMB (Cacho et al., 2001; Frigola et al., 2007; Jalut  
1029 et al., 2000, 2009; Fletcher and Sanchez-Goñi, 2008; Combourieu-Nebout et al., 2009; Chabaud  
1030 et al., 2014; Jalali et al., 2016; Azuara et al., 2020) and are associated with the North Atlantic  
1031 Bond events (Bond et al., 2001; Figure 8e). Several studies suggest that changes in North  
1032 Atlantic thermohaline circulation could have triggered the multi-centennial scale climate  
1033 variability of the WMB (Bianchi and McCave, 1999; Bond et al., 2001; Oppo et al., 2006;  
1034 Fletcher and Sanchez-Goñi, 2008; Combourieu-Nebout et al., 2009, Chabaud et al., 2014).

1035 From the Early Holocene, the AM forest decline events are generally synchronous with lower  
1036 alkenone SST and higher *O. centrocarpum* occurrences figured out by positive values of the  
1037 Ocen/Lmac ratio (Figure 8n,o). This suggests enhanced inflow of Atlantic waters in the WMB  
1038 and stronger moisture transport by the westerlies track directed northward and affecting to a  
1039 lesser extent the westernmost part of the Mediterranean Sea. By analogy, this would correspond  
1040 to recurrent positive modes of the North Atlantic Oscillation (NAO). Interestingly, these

1041 positive “NAO-like” events are expressed in contrast in the Siculo-Tunisian strait with lower  
1042 *O. centrocarpum* and higher values of *L. machaerophorum* occurrences, suggesting stronger  
1043 river discharge eastward. This pattern could illustrate the west-east modeled dipole response to  
1044 NAO-like changes in the SW Mediterranean Basin according to Bini et al. (2019) and Perşoiu  
1045 et al. (2019).

1046 Drier conditions, under enhanced wind strength in northern Atlantic latitudes (i.e. Bond event  
1047 under recurrent phases of positive “NAO-like” conditions), may therefore explain lower tree  
1048 percentages (Fletcher et al., 2010, 2013), and reversely higher tree percentages during recurrent  
1049 phases of negative “NAO-like” conditions (Figure 8). Our study reveals the rapid response of  
1050 Mediterranean vegetation and hydrological dynamics and the strong influence of the North  
1051 Atlantic climate through atmosphere-ocean interactions and ocean circulation at a multi-  
1052 centennial time scale.

1053

## 1054 **6. Conclusion**

1055 Multiproxy investigation of dinoflagellate cysts, pollen, non-pollen palynomorphs, stable  
1056 isotopes, clay mineral assemblages, grain-size analyses, marine and continental biomarkers,  
1057 and climate and hydrological quantitative reconstructions were conducted on the marine core  
1058 MD04-2801 on the Algerian Margin (AM). This study reveals the strong influence of orbital,  
1059 multi-centennial and centennial forcing on hydrological conditions and vegetation dynamics  
1060 over the last 14 kyrs BP. We show that dry and cold conditions prevailed during the Younger  
1061 Dryas as well as strong marine productivity. Warmer conditions of the Early to Middle  
1062 Holocene allowed for Mediterranean forest expansion, while the AM became oligotrophic until  
1063 6 ka BP. At an orbital timescale, the end of the African Humid Period led to aridification of the  
1064 western Mediterranean at the Middle to Late Holocene transition, with a dramatic forest retreat,  
1065 particularly pronounced between 4.3 and 3.9 ka BP. This event is referred to here as the  
1066 Algerian Mega Drought event, that appeared synchronously with the « 4.2 ka BP » event.  
1067 Sensitivity of the western Mediterranean to Northern Atlantic climate is also evidenced at an  
1068 infra-orbital timescale through several cold-dry events around 9, 8.1, 7.3 and 6.5 ka BP. The  
1069 forest decline from the Alboran Sea to the AM may result from the coupling of the North  
1070 Atlantic Bond events with prevailing positive modes of the North Atlantic Oscillation (NAO)  
1071 with a marked west to east dipole highlighted between the northern African coast up to Algeria  
1072 and Tunisia. Finally, over the last 3 kyrs BP, we have underlined the development of modern  
1073 productive conditions on the AM due to both vertical mixing (haline front and wind-driven  
1074 eddies of the Algerian Current) and nutrient-enriched fluvial discharge intensified by anthropic-  
1075 driven land-use.

1076

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1084 and discussions on their ecological signature. Thanks also to ISEM for their contribution.

1085

## 1086 **8. Data availability**

1087 MD04-2801 data discussed in the manuscript are available in the SEANOE repository:  
1088 <https://doi.org/10.17882/89514>

1089

## 1090 **9. Table captions**

1091 **Table 1:** MD04-2801 AMS-<sup>14</sup>C dates. Grey cells represent levels averaged for the final age  
1092 model. Dates in italic (with the annotation « \* ») were rejected for the final age model (Figure  
1093 2).

1094

1095 **Table 2:** This table presents MD04-2801 palynological data discussed in this study and  
1096 describes each pollen zone for dinocyst and pollen grains assemblages.

1097

## 1098 **10. Figure captions**

1099 **Figure 1:** a) Map presenting studied part of the Western Mediterranean Basin (WMB) on the  
1100 globe (red square on global scale map) , sea-surface temperature, as well as major sea-surface  
1101 and atmospheric currents (a simplified vegetation model according to Tassin (2012). b) Map  
1102 presenting the local scale map (red square on regional scale map) figure topography and  
1103 hydrographic network, high-resolution bathymetric data from the Algerian Margin (Babonneau  
1104 et al., 2012), morphological entities of the Kramis deep-sea fan and location of the study core  
1105 and selected corresponding modern sediments (Coussin et al., in prep.).

1106

1107 **Figure 2:** Age model for core MD04-280 based on the combination of age model a (lower  
1108 section (1031 to 431 cm)) and age model b (upper section (431 to 0 cm)) from rbacon package  
1109 calculation (Blaauw and Christen, 2011) performed under the R interface (version 4.1.0; R  
1110 Development Core Team, 2021; <http://www.r-project.org/>) and rejected dates. Stratigraphic  
1111 data includes the corresponding section number and photography, lithology, sediments density  
1112 ( $\text{g/cm}^3$ ), sedimentation rates (cm/kyrs) and Vp (m/s) values. Core disturbance by potential  
1113 piston effect is represented as a red square on the age model.

1114

1115 **Figure 3:** Sedimentological data of core MD04-2801 in function of depth, core section and  
1116 lithology. a) XRF Ca/Al ratio, b) XRF Ti/Al ratio, c) Magnetic susceptibility (SI). d) Low

1117 resolution total sediment D50 ( $\mu\text{m}$ ) in blue reported in faded blue on high-resolution total grain-  
1118 size (d) and  $\text{CaCO}_3$ -free D50 in red. e) Planktonic (*G. bulloides*; in green) and endobenthic (*G.*  
1119 *affinis*; in yellow)  $\delta^{13}\text{C}$  (‰ VPDB), higher planktonic signal suggests stronger primary  
1120 productivity while lower endobenthic signal suggests stronger organic matter remineralisation.  
1121 f) Planktonic (*G. bulloides*; in red) and endobenthic (*G. affinis*; in violet)  $\delta^{18}\text{O}$  (‰). g) Clay  
1122 mineral fractions of Interstratified Illite-Smectite (In), Chlorite (Ch), Kaolinite (Kao) and Illite  
1123 (II).

1124

1125 **Figure 4:** MD04-2801 a) marine and b) continental palynological, biomarkers and MAT  
1126 reconstruction data against depth (cm). a) Dinocyst diversity indexes are shown in red and blue,  
1127 in parallel with percentages of the major species *Brigantedinium* spp. (red dotted line).  
1128 Concentration of the total sum of dinocysts is shown in black, total sum of dinocysts without  
1129 *Brigantedinium* spp. is represented in blue and *Brigantedinium* spp. concentration is  
1130 represented in red. Concentration of  $\text{C}_{37}$  alkenones is represented in light blue (sum of  $\text{C}_{37}$ ,  
1131 ng/g). Total dinocyst (blue) and pollen with *Pinus* (orange) concentrations are represented in  
1132 the logarithmic scale. b) Pollen diversity indexes are in green, in parallel with percentages of  
1133 total trees (green) and total trees with *Pinus* (orange). Concentration of the total sum of pollen  
1134 is shown in orange, total sum of dinocysts without *Pinus* in green. Concentration of TERR-  
1135 alkanes in brown (sum of TERR-alkanes, ng/g) and Average Chain Length (ACL) in yellow  
1136 with average sequence value as a dotted line.

1137

1138 **Figure 5:** a) Dinocyst diagram (percentages of selected taxa exceeding at least once 1% in all  
1139 studied samples) of the MD04-2801 core, with related ecological groups (cf. Coussin et al.,  
1140 2022). Dinocyst zones are based on a CONISS statistical analysis on the Tilia program. b)  
1141 Pollen diagram (percentages of selected taxa when exceeding at least once 1% in all studied  
1142 samples, *Pinus* excluded from the main pollen sum) for the MD04-2801 core, with related  
1143 ecological groups. For both a) and b), continental non-pollen palynomorphs (NPPs) and pre-  
1144 quaternary cysts are highlighted in concentrations (number of palynomorphs per  $\text{cm}^3$  of  
1145 sediment). (For interpretation of the references to color in this figure legend, the reader is  
1146 referred to the web version of this article.)

1147

1148 **Figure 6:** Oceanic proxies from the MD04-2801 core plotted in age (Cal years BP) with related  
1149 pollen zones, sedimentological, stratigraphical limits and remarkable periods (S1 = Sapropel  
1150 1). Modern values from KMDJ-23 core are plotted as colored stars in the left band of the figure

1151 (1 - 0 ka). a) Planktonic  $\delta^{18}\text{O}$  (‰), b) Alkenone derived annual Sea Surface Temperatures  
1152 (SST, shaded from low temperatures in blue to high temperatures in red, °C), c) Cold water  
1153 dinocyst taxa percentages (*N. labyrinthus*, *B. tepikiense* and *S. lazus*, cf. Figure 5) in reversed  
1154 logarithmic scale, d) Dinocysts-derived Winter (blue) and Summer (red) SST (°C) with shaded  
1155 reconstructed minima and maxima and alkenone annual SST as a dotted blue line. e) Dinocyst-  
1156 derived Winter (blue) and Summer (red) Sea Surface Salinity (SSS, psu) with shaded  
1157 reconstructed minima and maxima, f) Heterotrophic (orange) and Phototrophic (green) dinocyst  
1158 concentration in logarithmic scale, g) Planktonic (*G. bulloides*; in green) and endobenthic (*G.*  
1159 *affinis*; in orange)  $\delta^{13}\text{C}$  (‰ VPDB), h) XRF Ti/Ca ratio, i) *Brigantedinium* spp. percentages  
1160 (%), j) *Brigantedinium* spp. concentration (red line), k) *Impagidinium* spp. percentages (%), l)  
1161 *Impagidinium* spp. concentration (brown).

1162

1163 **Figure 7:** Continental proxies from the MD04-2801 core plotted in age (Cal years BP) with  
1164 related pollen zones, sedimentological, stratigraphical limits and exceptional periods (S1 =  
1165 Sapropel 1, Megadrought Algeria = MDA). Modern values from KMDJ-23 core are plotted as  
1166 colored stars in the left band of the figure (1 - 0 ka). a) Kaolinite/Illite percentages of the clayey  
1167 phase ratio with higher Illite values in green and higher values in Kaolinite in red, b) freshwater  
1168 algae concentration (green), c) *Glomus* (HDV-207) concentration (grey), d) superior plant leaf  
1169 wax produced TERR-alkane (shaded green silhouette) and major represented n-C29 + n-C-31  
1170 (green dotted line) fluxes ( $\text{ng.g}^{-1}.\text{yrs}^{-1}$ ), e) Siliciclastic coarse grain inputs schematized by  
1171 magnetic susceptibility (SI), f) Mediterranean and Eurosiberian forest (cf. Figure 5)  
1172 percentages, g) Coastal-steppic and Semi-arid vegetation (cf. Figure 5) percentages, h)  
1173 Temperature seasonality index calculated with pollen-derived Mean Temperature of the  
1174 Warmest Month (MTWA) and Mean Temperature of the Coldest Month (MTCO) as (MTWA-  
1175 MTCO). i) Pollen-derived annual precipitation reconstructions (mm, blue line), j) Altitudinal  
1176 forest (cf. Figure 5), k) Human impact taxa (cf. Figure 5) percentages.

1177

1178 **Figure 8:** West to east transect of sequences from the Gulf of Cadiz (MD99-2339), Alboran  
1179 sea (ODP site 976 and MD95-2043), Algerian Margin (MD04-2801, this study) and Sicilian  
1180 strait (MD04-2797) with paleoenvironmental data plotted in age (Cal years BP) both on their  
1181 published chronology and their geographical situation on the map versus Orbital parameters (a)  
1182 NGRIP  $\delta^{18}\text{O}$  (‰, Vinther et al., 2006) in black, b) 65°N insolation in yellow ( $\text{W/m}^2$ ) from  
1183 Berger and Loutre (1991), c) Precession in blue and e) Hematite-stained quartz % in red (Bond

1184 et al., 2001). For both represented cores, (d,h,k,n,q) Alkenone SST are represented (black line,  
1185 °C), (f,l,i,o,r) OCEN/LMAC log ratio representing oceanic dinocyst taxa *O. centrocarpum*  
1186 versus estuarine dinocyst taxa *L. machaerophorum* log ratio (blue shaded silhouette, higher  
1187 ratios represent lower river discharge conditions), (g,j,m,p) Summed Mediterranean and  
1188 Eurosiberian forest (%) with total sum as a green silhouette and eurosiberian proportion as a  
1189 brown dotted line. Spotted forest retreat events are shown as dotted horizontal lines with  
1190 corresponding ages. The regional map figures all cited sequences, geographical coordinates and  
1191 zonal correlations with negative NAO conditions (modified after Perşoiu et al. (2019) in Bini  
1192 et al. (2019). Green zones show positive correlations with NAO- conditions indicating stronger  
1193 precipitations than average during NAO- and orange zones figure negative correlations with  
1194 NAO- conditions indicating lower precipitations than average during NAO-.

1195

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2013 **Table**

2014 Table 1

Code	Spectrometer	Depth (cm)	Dated material	<sup>14</sup> C age	Error	<sup>14</sup> C age – reservoir age	IntCal20 Cal BP Min-Max	Error $\sigma$
<b>SacA43123</b>	ECHOMICADAS	3	<i>G. bulloides</i>	170	30	-230	<b>0</b> 0-0	1 $\sigma$
<b>SacA55619*</b>	ARTEMIS	31 <sup>a</sup>	<i>G. bulloides</i>	820	30	420	<b>491,5</b> 472-511	1 $\sigma$
<b>SacA55620</b>	ARTEMIS	231	<i>G. bulloides</i>	1400	30	1000	<b>928,5</b> 900-957	2 $\sigma$
<b>GifA20376</b>	ECHOMICADAS	311	<i>G. bulloides</i>	1290	60	890	<b>817</b> 716-918	2 $\sigma$
<b>SacA55621</b>	ARTEMIS	431	<i>G. bulloides</i>	2165	30	1765	<b>1644,5</b> 1571-1718	2 $\sigma$
<b>GifA21150</b>	ECHOMICADAS	522	<i>G. bulloides</i>	3610	70	3210	<b>3424</b> 3357-3723	1 $\sigma$
<b>GifA18283</b>	ECHOMICADAS	531	<i>G. bulloides</i>	3870	80	3470	<b>3737,5</b> 3634-3841	1 $\sigma$
<b>SacA54337</b>	ARTEMIS	531	<i>G. bulloides</i>	3820	30	3420	<b>3647,5</b> 4229-4522	2 $\sigma$
<b>GifA20378</b>	ECHOMICADAS	550	<i>G. bulloides</i>	4330	60	3930	<b>4375,5</b> 4229-4522	2 $\sigma$
<b>GifA21151</b>	ECHOMICADAS	559	<i>G. bulloides</i>	4390	60	3990	<b>4432</b> 4245-4619	2 $\sigma$
<b>GifA20380</b>	ECHOMICADAS	579	<i>G. bulloides</i>	5000	60	4600	<b>5342,5</b> 5214-5471	2 $\sigma$
<b>GifA21152</b>	ECHOMICADAS	581	<i>G. bulloides</i>	5060	70	4660	<b>5392</b> 5315-5469	1 $\sigma$
<b>SacA55622</b>	ARTEMIS	631	<i>G. bulloides</i>	6200	30	5800	<b>6584</b> 6499-6669	2 $\sigma$
<b>GifA18282</b>	ECHOMICADAS	731	<i>G. bulloides</i>	8470	70	8070	<b>8917,5</b> 8696-9139	2 $\sigma$
<b>SacA54338</b>	ARTEMIS	731	<i>G. bulloides</i>	7990	35	7590	<b>8392</b> 8374-8410	1 $\sigma$
<b>GifA18256*</b>	ECHOMICADAS	931 <sup>b</sup>	<i>G. bulloides</i>	11110	270	10710	<b>12488,5</b> 11808-13169	2 $\sigma$
<b>SacA54339</b>	ARTEMIS	931	<i>G. bulloides</i>	10600	40	10200	<b>11867,5</b> 11739-11996	2 $\sigma$
<b>SacA54335</b>	ARTEMIS	978	Gastéropode	11000	40	10600	<b>12653</b> 12616-12690	1 $\sigma$
<b>SacA54336</b>	ARTEMIS	978	Gastéropode	11015	40	10615	<b>12659</b> 12621-12697	1 $\sigma$
<b>SacA55623</b>	ARTEMIS	1031	<i>G. bulloides</i>	12445	40	12045	<b>13920,5</b> 13804-14037	2 $\sigma$

2015

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2023 Table 2

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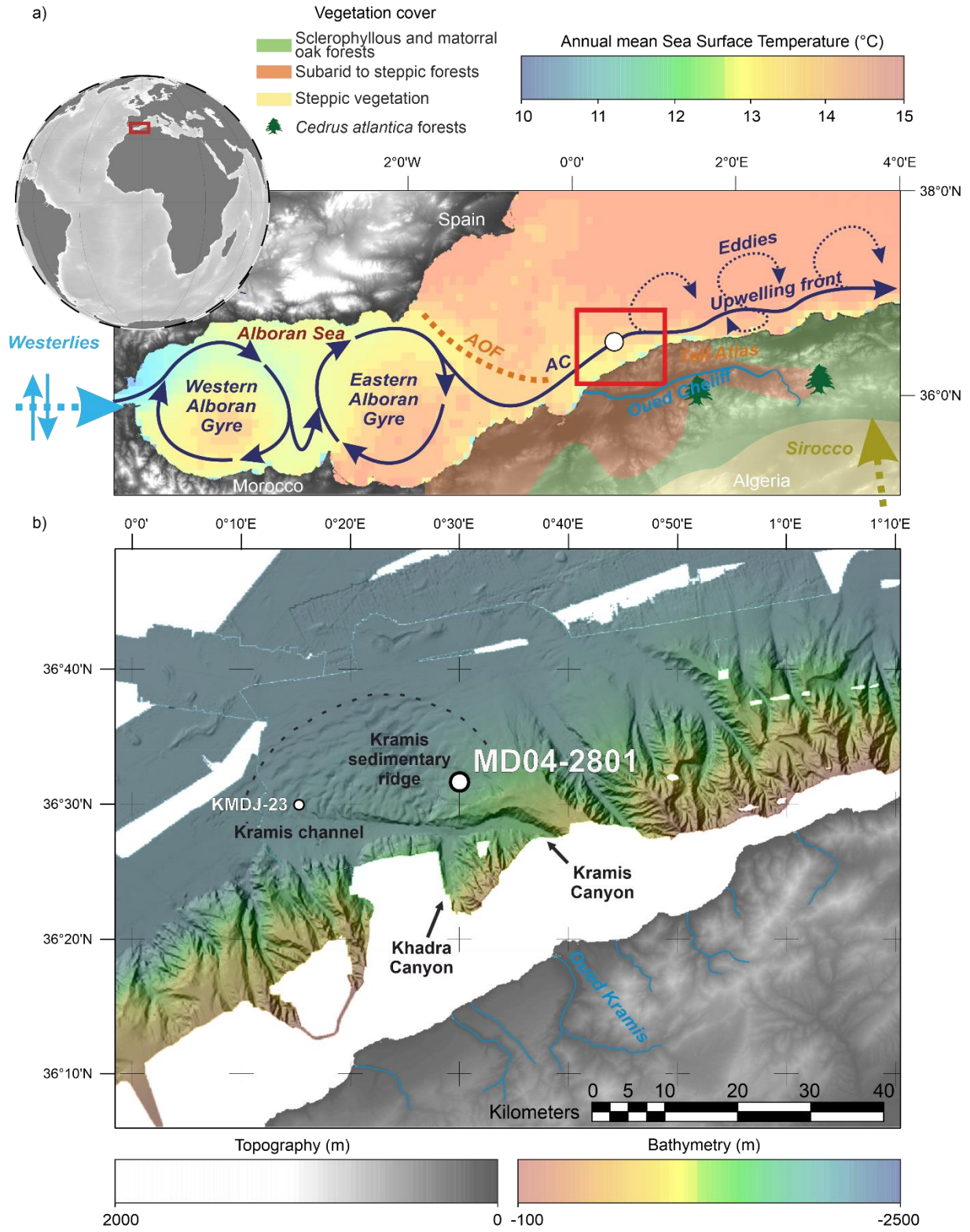
Pollen zones	Limits	Interval (cm)	Age (cal BP)	Description of Dinocyst zones	Pollen zones	Inferred hydrological changes	Description of pollen zone	Vegetation changes	Inferred climatic changes	Non-pollen palynomorphs remarks
MD04-5	Top - f	0 - 370	0 - 1 400	High values of <i>Brigantedinium</i> spp. (60% mainly), <i>S. mirabilis</i> and <i>O. centrocarpum</i> . Increasing values of estuarine-stratified taxa and thermophilous full-oceanic taxa. Diverse coastal productivity and upwelling heterotrophic assemblage. Occurrences of <i>Lejeunecysta</i> spp.	Highest heterotrophic taxa representations. Mixed upwelling and coastal productivity.	Upwelling driven productivity mixed with river discharge induced coastal productivity. Increasing oligotrophic conditions signal	Strongest representation of <i>Cichorioideae</i> (up to 35% mainly), <i>Asterioideae</i> . Stable percentages of <i>Poaceae</i> , <i>Quercus ilex</i> , deciduous <i>Quercus</i> , <i>Olea</i> , <i>Pistacia</i> , <i>Juniperus</i> , <i>Cupressus</i> , <i>Cedrus</i> . Increasing percentages of <i>Ephedra</i> and <i>Artemisia</i> . Increasing occurrences and representations of human impact taxa.	Open shrubs and steppe vegetation combined with open mediterranean forest forming matorrals and maquis. Potential human activity expansion.	Increasing aridity	Freshwater algae stable representation. Glomus high abundances, ascospores stable abundances. Occasional coprophilous abundances.
	f - e	370 - 485	1 400 - 2 700	High values of <i>Brigantedinium</i> spp. (60% mainly) followed by stable represented <i>S. mirabilis</i> and <i>O. centrocarpum</i> . Diverse coastal productivity and upwelling heterotrophic assemblage. High representation of <i>T. applanatum</i> .	Highest heterotrophic taxa representations. High upwelling and coastal productivity.	Upwelling driven productivity under relatively stable Atlantic influence.	Strong increase of <i>Cichorioideae</i> (30% mainly), <i>Asterioideae</i> . Stable percentages of <i>Poaceae</i> , <i>Quercus ilex</i> , deciduous <i>Quercus</i> , <i>Olea</i> , <i>Pistacia</i> , <i>Juniperus</i> , <i>Cupressus</i> , <i>Cedrus</i> , <i>Ephedra</i> and <i>Artemisia</i> .	Open shrubs and steppe vegetation combined with open mediterranean forest forming matorrals and maquis.	Increasing aridity	Freshwater algae stable representation. Glomus high abundances, ascospores stable abundances.
MD04-4	e - d	485 - 575	2 700 - 5 120	High values of <i>S. mirabilis</i> (30% mainly) and <i>I. aculeatum</i> . High representations of <i>L. machaerophorum</i> . Increasing percentages of <i>S. bentonii</i> , <i>N. labyrinthus</i> and <i>T. applanatum</i> .	High representation of phototrophic taxa. Upwelling cortege strong representation.	Intense upwelling activity. Intense oceanic influence. Seasonal oligotrophic stratified warm surface waters persistent signal.	Increasing of <i>Chenopodiaceae</i> , <i>Cichorioideae</i> , <i>Artemisia</i> and <i>Ephedra</i> . Small decrease of <i>Quercus ilex</i> and decrease of <i>Pistacia</i> , <i>Quercus suber</i> and <i>Cedrus</i> .	Open mediterranean forest with extended underbrush and maquis of <i>Cichorioideae</i> , <i>Asteraceae</i> and <i>Poaceae</i> steppe	Decreasing rainfalls with centennial oscillations	Lower freshwater algae and Glomus abundances. Peak of ascospores around 540 cm.
MD04-3	d - c	575 - 740	5 120 - 8 600	High values of <i>Brigantedinium</i> spp. increasing percentages of <i>I. aculeatum</i> (15-20% mainly) and <i>S. mirabilis</i> . Rare occurrences of <i>Lejeunecysta</i> spp. And <i>T. applanatum</i> .	Stable strong heterotrophic representation. Highest percentages of the Thermophilous full-oceanic taxa majorly represented by <i>Impagidinium aculeatum</i> .	Strongest oligotrophic surface conditions, increasing stratification and sea surface temperature. Persistent upwelling productivity signal.	Highest trees percentages. Increasing percentages of <i>Cupressaceae</i> , <i>Pistacia</i> and <i>Olea</i> , <i>Quercus ilex</i> and <i>Poaceae</i> . Decrease of <i>Chenopodiaceae</i> and small decrease of <i>Cichorioideae</i> which peaks from 650 to 600 cm.	Open mediterranean oak forest combined with underbrush and maquis of <i>Cichorioideae</i> , <i>Asteraceae</i> and <i>Poaceae</i>	Increased humidity and temperature marked with centennial oscillations	Highest representations of freshwater algae. Stable high representation of Glomus and ascospores.

	c - b	740 - 910	8600 - 11500	High percentages of <i>Brigantedinium</i> spp. (40 % mainly). Diverse coastal productivity and upwelling heterotrophic assemblage. Highest percentages of <i>O. centrocarpum</i> (10-20% mainly).	Increasing of the heterotrophic taxa representations. Increasing representation of thermophilous full-oceanic taxa.	Oligotrophic surface conditions, stratification and sea surface temperature. Persistent upwelling driven productivity.	Strong increase of <i>Quercus ilex</i> , deciduous <i>Quercus</i> , <i>Pistacia</i> , <i>Olea</i> , <i>Asterioideae</i> , <i>Cichorioideae</i> and <i>Poaceae</i> . Decrease of <i>Cedrus</i> , <i>Chenopodiaceae</i> , <i>Artemisia</i> and <i>Ephedra</i> . Increasing representation of monocotyledonae and pteridophyte spores.	Open mediterranean forest and underbush or maquis	Warmer conditions and gradual increased humidity	Stable high representation of Glomus and ascospores.
MD04-2	b - a	910 - 1025	11500 - 13700	Increase of the <i>N. labyrinthus</i> percentages (30 - 35% mainly). Cold water taxa <i>S. lazus</i> and <i>B. tepikiense</i> are also represented in high values. <i>O. centrocarpum</i> shows stronger representations around 910-950 cm. Highest representation of the intern neritic taxa <i>S. ramosus</i> , <i>S. bentorii</i> and <i>S. membranaceus</i> .	Decrease of the heterotrophic taxa representation with the persistence of upwelling cortège taxa. Increasing percentages of cold water taxa and external neritic photrophic taxa. Diversified assemblage.	Cold surface temperature. Strong oceanic influence. Highest productivity period in this sequence.	Highest representations of <i>Cedrus</i> (30% mainly) with two major peaks at 970 and 1000 cm (reaching more than 40%). Increase of <i>Chenopodiaceae</i> , <i>Artemisia</i> and <i>Ephedra</i> with a decrease of all <i>Quercus ilex</i> , <i>Quercus suber</i> and <i>Cupressaceae</i> .	Steppe with semi-desert plants. Sparse Pine and coniferous woodlands and <i>Cedrus</i> forests uplands.	Dry and cold conditions	Weak or lacking freshwater algae and fungal spores signal
MD04-1	a - Bottom	1025 - 1042	13700 - 14000	Dominance of <i>Brigantedinium</i> spp.	Dominance of the heterotrophic taxon <i>Brigantedinium</i> spp.	Apparent productive conditions, active upwelling.	Dominance of <i>Chenopodiaceae</i> , <i>Cichorioideae</i> and <i>Poaceae</i> associated to <i>Artemisia</i> and <i>Ephedra</i> . Low representation of <i>Quercus ilex</i> (less than 10%) and <i>Cupressaceae</i> .	Dominating steppe with sparse mediterranean woodlands.	Dry conditions	Weak or lacking freshwater algae and fungal spores signal

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2026 Table 2

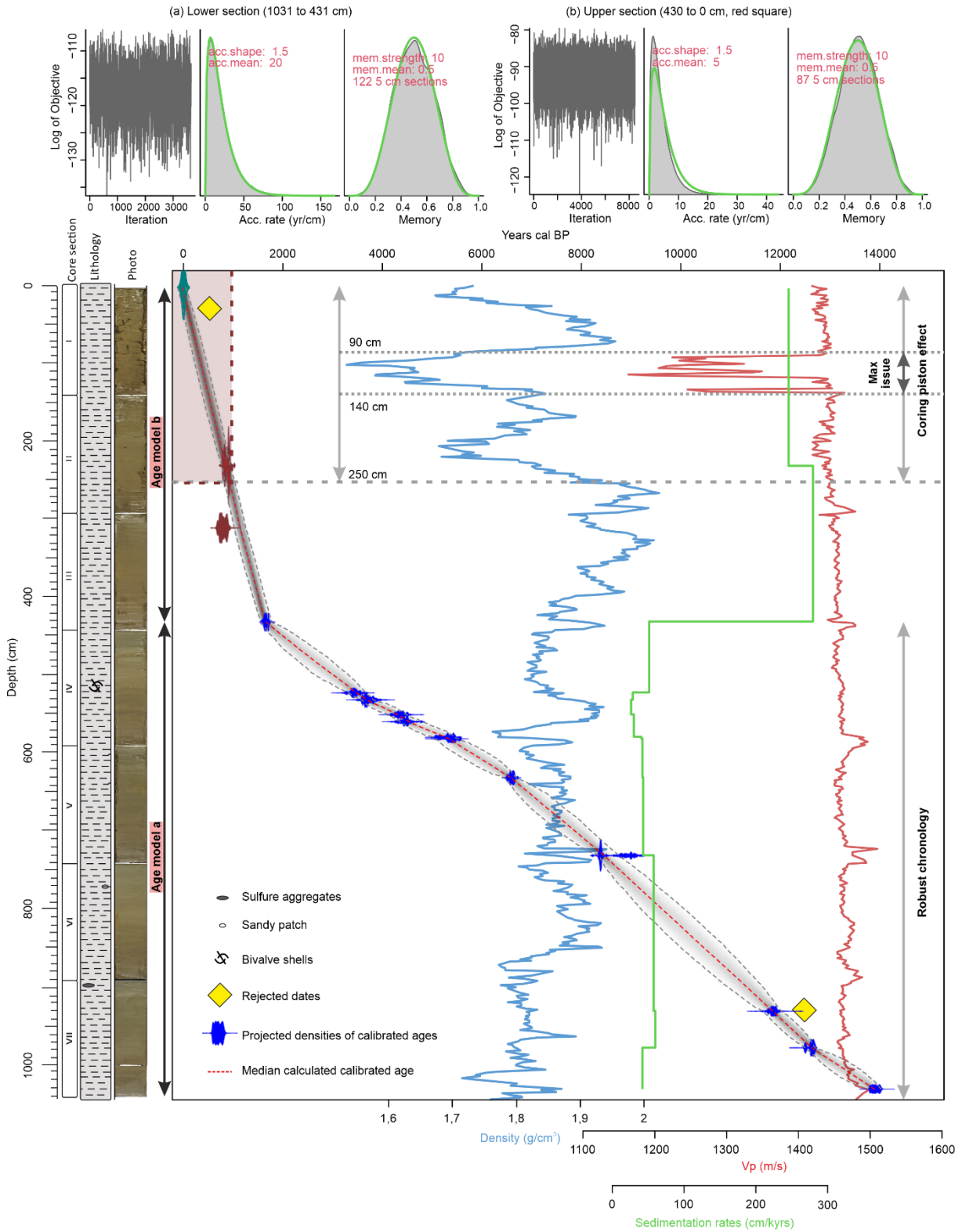
2027 **Figures**  
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 2029 **Figure 1**



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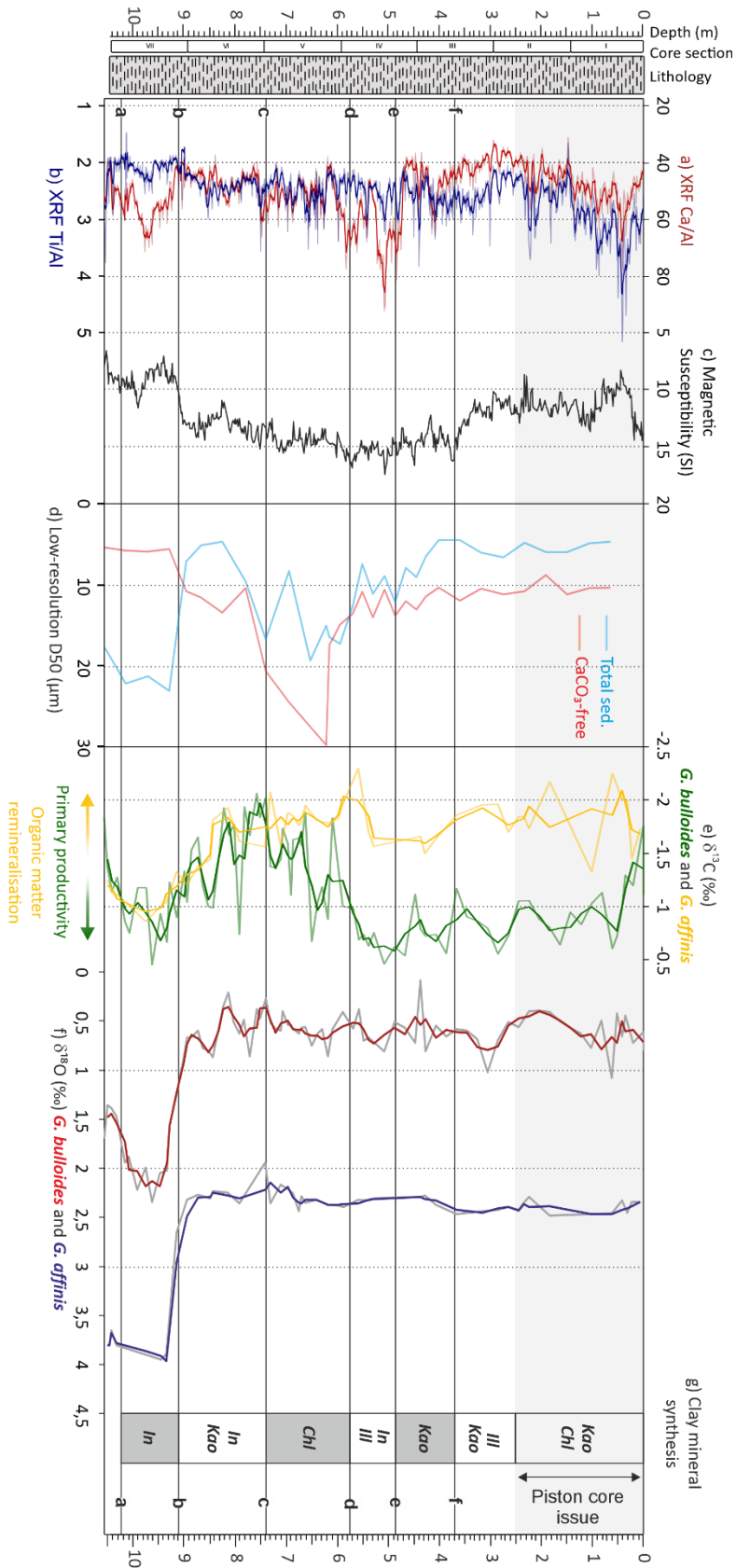
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2041 Figure 3

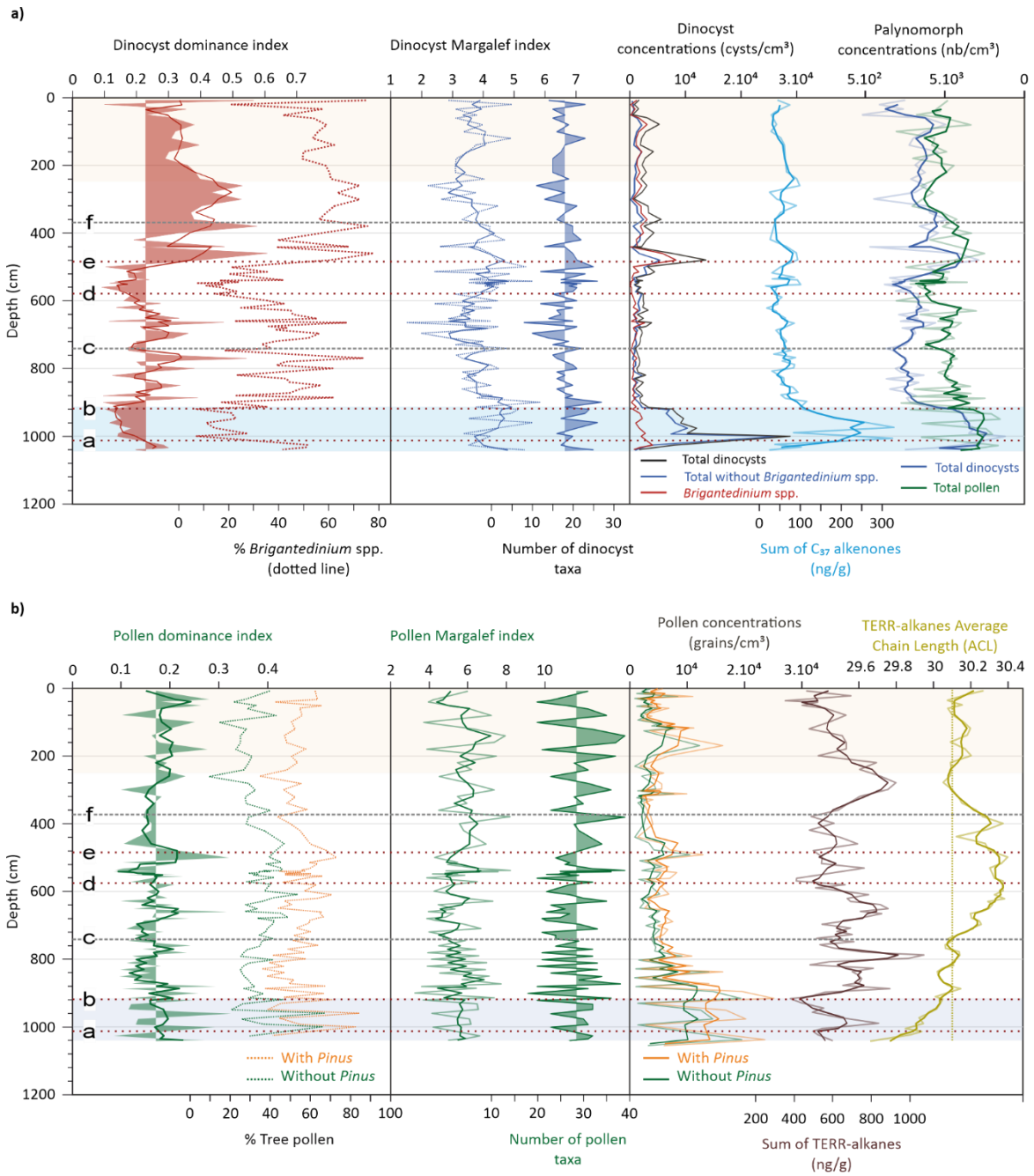


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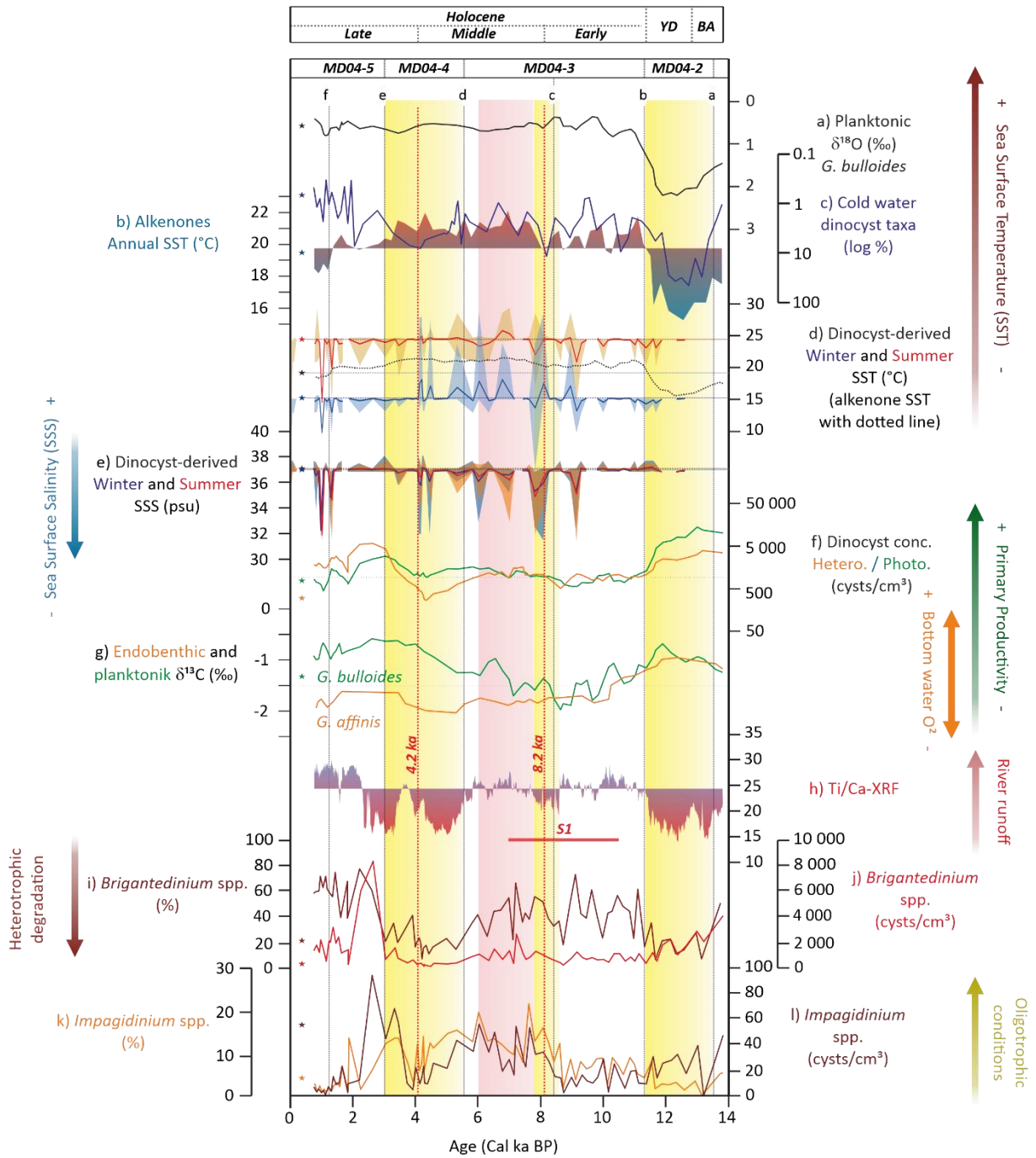
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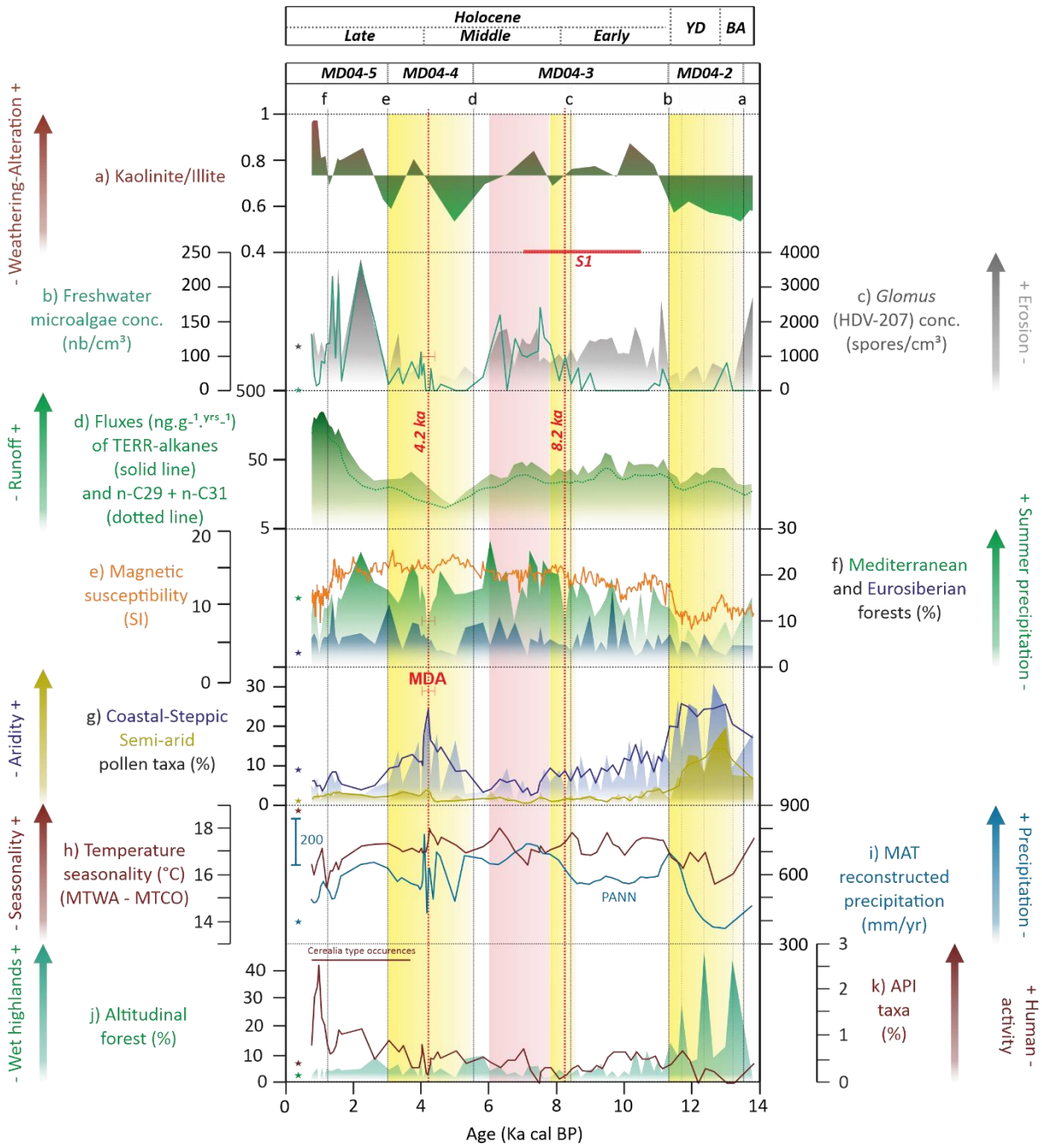


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2068 Figure 7



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