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1 **Connection between South Mediterranean climate and North African atmospheric**
2 **circulation during the last 50,000 yr BP North Atlantic cold events**

3
4 V. Bout-Roumzeilles^{a,*}, N. Combourieu Nebout^b, O. Peyron^c, E. Cortijo^b, A. Landais^d, V.
5 Masson-Delmotte^d

6 ^aUMR CNRS 8110, Processus et Bilans des Domaines Sédimentaires, Université de Lille 1, 59655
7 Villeneuve d'Ascq Cedex, France

8 ^bUMR CEA-CNRS 1572, Laboratoire des Sciences du Climat et de l'Environnement, Domaine du
9 CNRS, 91198 Gif-sur-Yvette, France

10 ^cUMR CNRS 6565, Laboratoire de Chrono-écologie, Université de Franche-Comté, 16 Route de Gray,
11 25030 Besançon, France

12 ^dIPSL/CEA-CNRS-UVSQ, Laboratoire des Sciences du Climat et de l'Environnement, CEA Saclay,
13 l'Orme des Merisiers, 91191 Gif-sur-Yvette Cedex, France

14 *Corresponding author. Tel.: +33320434395; fax: +33320434910.

15 E-mail address: viviane.bout@univ-lille1.fr (V. Bout-Roumzeilles).

16
17 **Abstract**

18 High-resolution clay mineralogical analyses were performed on sediment deposited
19 during the last 50,000 yr in the Alboran sea (ODP Site 976). The clay mineral record is
20 compared with pollen assemblages and with annual precipitation (Pann) and mean
21 temperatures of the coldest month (MTCO) reconstructed with the modern analog technique
22 (MAT). Enhanced contribution of palygorskite, a typical wind-blown clay mineral,
23 characterizes the North Atlantic cold climatic events. Coeval development of the semi-arid
24 vegetation (*Artemisia* rich) associated with a drastic fall of reconstructed precipitations and
25 temperatures, suggest cold and arid continental conditions in the West Mediterranean area
26 during North Atlantic cold events. The clay mineral association, especially the palygorskite
27 content and the illite-to-kaolinite ratio, indicate western Morocco as one of the major source
28 of the clay-size fraction during the North Atlantic cold events. The maximum abundance of
29 *Artemisia* associated with the presence of *Argania* pollen both indicate Morocco as the main
30 origin for pollen during these cold periods. The comparison of these pollen and clay mineral-
31 specific features allows us to pinpoint western Morocco as the dominant source of wind-

32 blown particles during North Atlantic cold events. These specific mineralogical composition
33 and palynological assemblages reveal enhanced aridity over North Africa and intensification
34 of winds favouring dust erosion and transport from North Africa toward the Alboran Sea
35 during the North Atlantic cold events. According to atmospheric models, such a meridian
36 transport (1) likely results from the development of strong and stable anticyclonic conditions
37 over the tropical Atlantic and North Africa, similar to today's summer meteorological
38 configuration and (2) implies a northward position of the westerly winds during North
39 Atlantic cold events. Finally the synoptic situation over the West Mediterranean during the
40 North Atlantic cold events is compared with the North Atlantic Oscillation (NAO), suggesting
41 that during the cold Atlantic events, weather regimes over Europe and North Africa may have
42 been systematically shifted towards a positive NAO situation.

43

44 **1. Introduction**

45 The Alboran Sea is a semi-enclosed basin situated in a climatic transitional area
46 between the Atlantic Ocean and the Mediterranean Sea (Fig. 1). In the Mediterranean Sea, the
47 formation of deep-water is mainly driven by seasonal climatic conditions: summer
48 anticyclonic conditions favor evaporation over precipitation and dense water mass formation
49 (Béthoux, 1980). Moreover, the displacement of European depressions over the
50 Mediterranean creates high climatic instability and allows frequent incursions of the westerly
51 winds. These climatic changes strongly influence the Alboran sea sedimentation: several
52 high-resolution records reveal a millennial climate variability similar to the Dansgaard–
53 Oeschger events defined in Greenland ice cores (Cacho et al., 2000; Moreno et al., 2002,
54 2005; Sánchez-Goñi et al., 2002; Combourieu Nebout et al., 2002). The more intense cold
55 stadials favored the northern continental ice-sheet growth, which provoked ice-calving and
56 major iceberg discharges in the North Atlantic ocean. These so-called Heinrich events (HE)
57 are recorded in sediments by the abundance of coarse-grain detritus associated with a typical
58 fresh meltwater supply. Isotopic records indicate that deep convection was more efficient
59 during cold stadials and HE than during warm interstadials suggesting an intensification of
60 the northwesterlies during North Atlantic cold climatic events (Cacho et al., 2000). Pollen
61 analyses reveal that arid and cold conditions develop on the surrounding continents during the
62 HE and some cold stadials (Combourieu Nebout et al., 2002; Sánchez-Goñi et al., 2002).
63 Moreover, grain-size and elemental analyses also suggest enhanced eolian contribution to the
64 Alboran sedimentation during North Atlantic cold events (Moreno et al., 2002, 2005). The

65 occurrence of such climatic conditions over the Mediterranean seems to be linked to the
66 westerly regime over Europe and very similar to weather regime variations which characterize
67 the North Atlantic Oscillation (NAO) (Rohling et al., 1998; Cacho et al., 2000; Combourieu
68 Nebout et al., 2002; Sánchez-Goñi et al., 2002; Moreno et al., 2005). Mechanisms, however,
69 are still unclear. In order to understand the links between the cold climatic events recorded in
70 Greenland ice core (Johnsen et al., 1992) and the climatic changes over the Mediterranean
71 area and North Africa, high-resolution mineralogical analyses of sediments from the ODP
72 Site 976 (36112N, 4118W) were performed on the 0–50 ka interval. Indeed previous studies
73 in the tropical Atlantic Ocean demonstrated that mineralogy could successfully be used to
74 trace the source and transport of wind-blown particles (Caquineau et al., 1998). Our main
75 objective is then to trace the variations of dust emission and transport over North Africa and
76 South-West Mediterranean related to the North Atlantic Marine Isotopic Stage 3 cold events
77 (Dansgaard–Oeschger stadials and HE). The composition of the clay mineral fraction is also
78 compared to pollen assemblages in order to reconstruct the western Mediterranean oceanic
79 and continental paleoenvironments and climate changes during the last 50,000 yr BP.

80

81 **2. Eolian input, atmospheric scenario and clay mineral transport**

82 The eolian supply contributes significantly to the terrigenous marine sedimentation
83 and can then be used to trace the climatic evolution of continental areas (Sarnthein et al.,
84 1982; Ruddiman et al., 1989). But the dust transport shows strong seasonal variability in
85 occurrence, origin, trajectories and composition (Prospero et al., 1981; Pye, 1987; Chiapello
86 et al., 1997; Moulin et al., 1997; Grousset et al., 1998; Ratmeyer et al., 1999).

87

88 *2.1. Eolian and riverine contribution to deep-sea sediments*

89 Sedimentation in the Mediterranean Sea is mainly terrigenous due to the vicinity of the
90 surrounding continents associated with important riverine and eolian supplies. At present-day
91 a major part of detrital clays is supplied via rivers (Milliman and Meade, 1983; Stanley et al.,
92 1992). In the eastern Mediterranean, most particles (120.106 t/yr) are provided by the Nile
93 River. The Rhone River with an annual discharge of 31.106 t/yr is the main contributor to
94 sedimentation in the northwestern Mediterranean whereas the Po River (13.106 t/yr) and the
95 Ebro River (18.106 t/yr) are of minor influence.

96 The eolian contribution to deep-sea sediments has been demonstrated in several
97 studies (Prospero, 1981a, b; Pye, 1987) especially in Mediterranean fine-grained fraction
98 (Tomadin and Lenaz, 1989; Matthewson et al., 1995; Guerzoni and Chester, 1996). Because
99 mineral aerosols can be long-range transported (Rea et al., 1985; Guerzoni and Chester,
100 1996), massive plumes of desert dust are exported to the Atlantic Ocean and to the
101 Mediterranean all year long. There is still a debate about the atmospheric contribution to
102 deep-sea sediments with estimations ranging from 10% to 50% (Loye-Pilot et al., 1986;
103 Guerzoni et al., 1997). In fact, the eolian supply is generally estimated to be one order of
104 magnitude lower than fluvial supply at the scale of the whole Mediterranean basin (3.9.106
105 t/yr) (Bergametti et al., 1989c). This value probably underestimates the real contribution of
106 eolian supply since an important part of river material may be trapped on the continental shelf
107 on the West Mediterranean (Sarnthein et al., 1982; Ratmeyer et al., 1999). Previous studies
108 based on radionuclides (Gascó et al., 2002) and trace metal budget (Elbaz-Poulichet et al.,
109 2001) concluded that sedimentation in the western Mediterranean and in the Alboran Sea is
110 significantly fed by eolian particles compared to riverine inputs. This characteristic results
111 both from a rather low fluvial discharge from the Ebro River compared to other peri-
112 Mediterranean rivers and from extended desert areas (Sahara and Sahel) seasonally exposed
113 to strong winds, which provide huge amounts of dust particles to the atmosphere (Prospero,
114 1981a; Coudé-Gaussen, 1982; Middleton, 1985; Pye, 1987).

115

116 *2.2. Dust origin*

117 Arid regions such as the Sahara and semi-arid regions such as northern North Africa
118 or Sahel provide dust particles to the Atlantic Ocean and the Mediterranean Sea (Prospero et
119 al., 1981; Coudé-Gaussen, 1982; Matthewson et al., 1995). Grain-size analyses of wind-
120 blown dust reveal two populations characterizing different source areas and transport
121 mechanisms. Although major dust emission are generally situated in the subtropical desert
122 belt and in semiarid regions (Pye, 1987; Chamley, 1989 and references therein), grain-size
123 distribution reveals that the coarsest fraction is remobilized from Saharan dunes whereas the
124 finer size fraction originates from paleosols and little consolidated formations located on the
125 southern and northern borders of the desert (Rognon et al., 1996). The largest particles are
126 typical of dust storm and are generally transported by trade winds below 100km of altitude,
127 being restricted to continental and adjacent marine areas (Torres- Padrón et al., 2002). By
128 contrast, the fine-grained particles (< 2 mm) move over long distances as high-altitude

129 aerosols (Schütz, 1980). Finally satellite-derived data as Infrared Dust Differencing Index
130 (IDDI) and Total Ozone Mapping Spectrometer (TOMS) suggest that the Bodélédepression in
131 Chad (Brooks and Legrand, 2000; Washington and Todd, 2005) and West Sahara and more
132 generally topographic lows are among the most present-day dust productive areas.

133

134 2.3. *Wind systems*

135 The modern atmospheric circulation (Fig. 1) over North Africa is mainly controlled by
136 the northeast trade winds (TW) and by the mid-tropospheric Saharan Air Layer (SAL)
137 (Grousset et al., 1992; Matthewson et al., 1995). The resulting southern Saharan winds are
138 mono-directional with a general westward transport. The dust plume extension is seasonally
139 modulated by the migration of the Inter-Tropical Convergence Zone (ITCZ) (Prospero et al.,
140 1981; Pye, 1987; Torres-Padrón et al., 2002). In winter, when the ITCZ occupies its
141 southernmost position at 81N (Prospero et al., 1981; Pye, 1987), Saharan dust originates from
142 southern Sahara and Sahelian regions and is transported toward the tropical Atlantic Ocean by
143 the northeast trade winds (Schütz, 1980; Coudé-Gaussen et al., 1987; Bergametti et al.,
144 1989b; Grousset et al., 1992, 1998; Matthewson et al., 1995; Chiapello et al., 1995, 1997;
145 Moulin et al., 1997). In summer, trade winds are geographically restricted due to the northern
146 migration of the ITCZ (201N). Intensive insolation over Sahara creates strong surface winds
147 and large-scale convection which lifts particles to the high atmosphere (5 km). Particles
148 originating from western and central part of the Sahara (e.g. Torres-Padrón et al., 2002) are
149 transported at high-altitude by the SAL (Fig. 1), above the trade wind inversion toward the
150 tropical Atlantic (Schütz, 1980; Coudé-Gaussen et al., 1987). A north-turning part of the SAL
151 moves (NSAL) into an anticyclonic gyre along the African coast (Fig. 1) and reaches the
152 Mediterranean (Prospero et al., 1981; Bergametti et al., 1989b).

153 By contrast, winds (Fig. 1) are pluri-directionnal in northern Sahara (Coudé-Gaussen
154 et al., 1982). Their trajectories depend on the relative position of both high and low-pressure
155 systems over the Atlantic Ocean, the Mediterranean and on the westerly wind regime over
156 Europe (Coudé-Gaussen et al., 1982; Bergametti et al., 1989c; Moulin et al., 1997; Rodríguez
157 et al., 2001). Dust transport is sporadic in nature but a single event can account for more than
158 50% of the annual eolian flux (Guerzoni et al., 1997). Such meridian transports occur when
159 the westerly regime is weak or disrupted and are more frequent during summer (Coudé-
160 Gaussen et al., 1982; Guerzoni et al., 1997; Rodríguez et al., 2001; Torres- Padrón et al.,
161 2002; Ginoux et al., 2004). Three main atmospheric configurations (Fig. 2) favor the transport

162 of dust from North Africa toward the Mediterranean (Coudé- Gausсен, 1982; Coudé-Gausсен
163 et al., 1987; Bergametti et al., 1989c; Rodríguez et al., 2001): (1) a SW–NE transport (Fig. 2a)
164 toward the northern part of the Mediterranean occurs mostly in winter when a large
165 depression system develops between Canary Islands and the Iberian Peninsula; (2) during
166 interseason, a SE–NW transport (Fig. 2b) is initiated by the simultaneous occurrence of a
167 strong central European anticyclone and of a depression off Portugal; (3) summer dust
168 transport (Fig. 2c) mainly results from the westward shift of the North African anticyclone
169 associated with the remoteness of the Azores high, which provides a SW–NE depression
170 trench along the African coasts toward the Iberian Peninsula and western part of the
171 Mediterranean.

172

173 *2.4. Clay mineral sources*

174 In order to understand the variations of the clay mineralogy in sediments from the
175 Alboran Sea, the clay mineral assemblages of main source areas were reconstructed using
176 previously published and unpublished data in the frame of the general fluvial, oceanic and
177 atmospheric patterns (Fig. 3). The clay mineralogy of various Mediterranean marine sites has
178 been studied in several marine cores (e.g. Chamley, 1989; Foucault and Mélières, 2000). On
179 average sediments from the western Mediterranean are dominantly composed of 50% illite
180 and 25% kaolinite, with lower amount of smectite (15%) and chlorite (10%) whereas fibrous
181 clays (palygorskite) are present as trace amounts.

182 Illite generally represents the relative contribution of physical weathering to
183 sedimentation, because this mineral is resistant to degradation and to transport (Chamley,
184 1989). In the northern Mediterranean (Fig. 3a) the Rhone River and the Po River receiving
185 their detrital material from the Alps are particularly rich in illite associated with some
186 chlorite. As a result, illite dominates the clay mineral association of sediments from the Gulf
187 of Lion (80%) and from the Adriatic Sea (60%) (Tomadin, 2000). Illite is also a major
188 component (35%) of the Ionian Sea sediments (Chamley, 1989) and of the Ebro sedimentary
189 system (35%) (Alonso and Maldonado, 1990). On the North African continent, the relative
190 abundance of illite displays a north–south gradient: illite constitutes 60% of the clay mineral
191 assemblage in northern Algeria, 50% in central Sahara and less than 30% in the Sahelian zone
192 (Paquet et al., 1984). As a result, dust-blown (Fig. 3b) particles originating from Western
193 Sahara are richer in illite (60%) than the particles (30%) issued from central and southern
194 Sahara (Avila et al., 1997).

195 Kaolinite mainly forms through hydrolysis processes and is typical of highly
196 weathered environment (e.g. Chamley, 1989) such as well-drained lateritic soils
197 characterizing equatorial regions (e.g. Chamley, 1989). Kaolinite (Fig. 3) is thus rare (10%)
198 and reworked from ancient formations in the Rhone and Nile river sediments and even absent
199 in the Po river (e.g. Chamley, 1989), whereas it is much more abundant (30%) in the Ebro
200 river which drains kaolinite rich deposits (Alonso and Maldonado, 1990). In North Africa the
201 distribution of kaolinite depends on the latitude (Paquet et al., 1984): trace amounts in the
202 northern and westernmost part of North Africa, more common in central and South Sahara
203 and abundant in Sahelian and equatorial regions (Pastouret et al., 1978; Caquineau et al.,
204 1998). Moreover kaolinite (Fig. 3b) is more abundant in dust originating from eastern Sahara
205 compare to western Sahara (Guerzoni et al., 1999).

206 In a general way, smectite is not abundant in the western part of the Mediterranean
207 (Fig. 3a) as a result of the increasing distance from the Nile River, which is the main
208 contributor of smectite in the Mediterranean. The Po and Rhone Rivers do not transport more
209 than 20% of smectite but small Italian coastal and Pyrenean rivers may, respectively,
210 contribute to the supply of smectite in the Tyrrhenian Sea and in the Gulf of Lion (e.g.
211 Chamley, 1989; Foucault and Mélières, 2000). Smectite is rare in the northern Sahara whereas
212 it is abundant in southern Sahara and Sahel. In these areas, smectite may represent 70% of the
213 clay mineral fraction and is associated with kaolinite issued from ancient lateritic profiles
214 (Sarnthein et al., 1982; Paquet et al., 1984; Chamley, 1989). In agreement with this latitudinal
215 distribution, dust originating (Fig. 3b) from western Sahara and Moroccan Atlas are depleted
216 in smectite compared to dust originating from central Algeria and Sahelian sources (Avila et
217 al., 1997).

218 Although chlorite is often associated with illite, it is far less resistant to weathering
219 and transport. Chlorite thus mainly reflects the composition of nearby source area (Chamley,
220 1989). In the northwestern part of the Mediterranean basin, the main source of chlorite is the
221 Ebro sedimentary system (35%) (Alonso and Maldonado, 1990) whereas the respective
222 contribution of the Rhone and the Po river is of minor importance (e.g. Chamley, 1989).

223 Palygorskite is characteristic of the sub-arid belt of the northern hemisphere (Singer
224 and Galan, 1984; Chamley et al., 1989) where its formation is favored by chemically
225 restricted conditions (Singer and Galan, 1984). For instance, evaporation and chemical
226 concentration provide the formation of palygorskite (Fig. 3a) on poorly drained carbonated
227 rocks in the anti-Atlas (El Mouden et al., 2005). But elongated fibers of palygorskite are

228 usually destroyed during fluvial transport (Chamley, 1989; Snoussi et al., 1990). As a result
229 there are some discrepancies (Fig. 3a) between the composition of the source area and of the
230 mineralogical assemblages recorded in the downstream alluvial sediment (El Mouden et al.,
231 2005). Palygorskite from recent marine deposits off Africa is commonly considered to be
232 dust-blown particles reworked from Neogene North African deposits (e.g. Chamley, 1989).
233 Palygorskite can be distributed through eolian processes over long-range distance as far as
234 Scotland and has been used to trace the Saharan origin of dust (Coudé-Gaussen et al., 1982;
235 Molinaroli, 1996). At present-day, Sahara winds are reported to carry sporadically noticeable
236 amounts of palygorskite over the whole Mediterranean basin (Coudé-Gaussen and Blanc,
237 1985). For example, some Tunisian loess's are composed of 45% of palygorskite (Grousset et
238 al., 1992). Robert et al. (1984) identified up to 25% of African-derived palygorskite
239 associated to kaolinite in sediments from a high-altitude lake in Corsica (Fig. 3b).
240 Palygorskite represents 10–15% of the clay mineral fraction in northern Algeria (Paquet et al.,
241 1984), 10–25% on the central Algeria and less than 10% in the southern Sahara (Paquet et al.,
242 1984). Similarly, dust from central Algeria and western Sahara (10%) and Morocco Atlas
243 (17%) contain lower amounts of palygorskite than dust deposited (Fig. 3b) in northern
244 Morocco (up to 75%) (Avila et al., 1997).

245

246 **3. Material and methods**

247 *3.1. Stratigraphy*

248 ODP Site 976 (36°12N, 41°8W, 1108m depth) is located in the Alboran Sea, close to
249 the Atlantic–Mediterranean gateway (Fig. 1). Chronology is first based on 17 AMS14C ages
250 (Combourieu Nebout et al., 2002), and then on a correlation between the oxygen isotopes
251 record of site 976 and core MD95-2042 (Cacho et al., 2000) and secondly on correlation
252 between the pollen temperate records of site 976 and $\delta^{18}\text{O}$ of ice from the NorthGRIP ice core
253 (NorthGRIP members, 2004). This age scale does not enable us to estimate precisely the
254 vegetation response time compared with the ice-core record, occurring within a few decades
255 to centuries (Masson-Delmotte et al., 2005). Here, we present the uppermost 25m that span a
256 time interval corresponding to the last 50,000 yr.

257

258 *3.2. Clay mineralogy*

259 All samples were first decalcified with 0.2N hydrochloric acid. The excess acid was
260 removed by H₂O washing and repeated centrifugations. The clay-sized fraction (<2mm) was
261 isolated by settling, and oriented on glass slides (oriented mounts). Three X-ray diffraction
262 (XRD) determinations were performed: (a) untreated sample; (b) glycolated sample (after
263 saturation for 12 h in ethylene glycol); (c) sample heated at 49°C for 2 h. The analyses were
264 run on a Philips PW 1710 X-ray diffractometer between 2.49 and 32.51°2theta. Each clay
265 mineral is then characterized by its layer plus interlayer interval as revealed by XRD analysis.
266 Smectite is characterized by a peak at 14Å on the untreated sample test, which expands to
267 17Å after saturation in ethylene glycol and retracts to 10Å after heating. Illite presents a basal
268 peak at 10Å on the three tests (natural, glycolated and heated). Chlorite is characterized by
269 peaks at 14, 7, 4.72 and 3.53Å on the three tests. Kaolinite is characterized by peaks at 7 and
270 3.57Å on the untreated sample and after saturation in ethylene glycol. Both peaks disappear or
271 are strongly reduced after heating. Palygorskite presents a basal peak at 10.34Å accompanied
272 by a weaker peak at 6.44Å, on both untreated and glycolated tests. The 10.34Å peak collapses
273 at 10Å after heating (Brindley and Brown, 1980). The presence of palygorskite has been
274 confirmed by MET observations of the palygorskite-rich samples. Semi-quantitative
275 estimation of clay mineral abundances, based on the pseudo-Voigt deconvolution for the
276 doublets illite–palygorskite (10–10.34Å) and kaolinite–chlorite (3.57–3.53Å), was performed
277 using the software MacDiff developed by Petschick (2000).

278

279 3.3. Pollen analyses and quantitative climate reconstruction

280 Micropaleontological analyses were performed on the size fraction <125µm, and more
281 than 300 specimens were counted per sample. Pollen methodology follows a classic protocol
282 already developed by Combourieu Nebout et al. (2002). More than a hundred pollen,
283 excluding *Pinus* were counted per sample for paleoenvironmental interpretation.
284 Paleoenvironmental interpretation of the downcore pollen assemblage fluctuations is based on
285 the assumption that the primary pollen contribution to Alboran Sea sediments comes from
286 western Mediterranean borderlands. Modern environments range from a thermo-
287 Mediterranean belt with *Olea*, *Pistacia* and some steppe or semi-desert representatives
288 (*Artemisia*, *Ephedra*), to a meso-Mediterranean belt, represented by a sclerophyllous oak
289 forest to a humid-temperate oak forest (mainly *Quercus* associated with *Ericaceae*), to a
290 supra-Mediterranean belt, with a cold-temperate coniferous forest (*Pinus*, *Abies*, *Cedrus*) at
291 the higher altitudes (Ozenda, 1975; Rivas-Martinez, 1982).

292 Around 120 pollen taxa were identified ranging from semi-desert to mountain
293 deciduous and coniferous forest. Their interpretation follows the modern climatic-plant
294 relationships in Eurasia and northern Africa (e.g. Peyron et al., 1998). Here we present the
295 variations of pollen percentages of two main associations: (1) the temperate association
296 composed of European-Siberian trees such as *Quercus*, *Fagus*, *CarPinus*, *Corylus*, *Alnus*,
297 *Betula*, *Tilia* and *Ulmus* associated with *Ericaceae*, reflecting the warmer and moist climate
298 characteristics of interstadials, and (2) the steppe to semi-desert association, composed of
299 *Artemisia* and *Ephedra*, which marks the dry and cold climatic conditions of the stadials. The
300 analog technique has been applied to the ODP 976 fossil pollen assemblages to provide
301 quantitative estimates of temperatures and precipitation during the last 50,000 yr BP (Guiot,
302 1990). First developed for continental pollen sequences, the MAT has been tested with
303 success to marine pollen cores from the Mediterranean region (Desprat et al., 2005). In this
304 method, similarity between fossil and modern pollen assemblages is evaluated by a chord
305 distance calculated as a μm of differences between log-transformed percentages of the taxa.
306 Such method does not imply a direct analogy between modern and fossil assemblages,
307 although the quality of the results depends on the size and diversification of the modern data
308 set (Peyron et al., 1998). Here, this technique is based on a modern pollen database including
309 1510 modern pollen spectra mainly located in the Mediterranean basin (especially Spain and
310 Morocco), Europe and Eurasia (Peyron et al., 1998). Since *Pinus* is overrepresented in marine
311 sediments, this pollen type has been removed from the marine pollen counting as well as from
312 the continental pollen database. The 10 modern spectra which have the smallest chord
313 distance are considered as the best modern analogs of the given pollen spectrum, and used for
314 the reconstruction. The climatic parameters of the 10 best modern analogs are averaged by a
315 weighting inverse to the chord distance. Here, the climatic parameters reconstructed are the
316 mean temperature of the coldest month ($^{\circ}\text{C}$) and annual precipitation (mm/yr). The error is
317 computed as lower and upper limits of positive and negative deviation of extreme analogs
318 compared to the mean value.

319

320 **4. Results**

321 *4.1. Clay minerals*

322 The average composition of the clay mineral fraction ($<2\ \mu\text{m}$) of the uppermost part of
323 the ODP site 976 (0–25m composite depth), which records the last 50,000 yr, is composed of
324 33% illite, 31% smectite, 16% kaolinite, 15% chlorite and 5% palygorskite. All clay minerals

325 show several oscillations during the last glacial period whereas their abundances are less
326 variable during the Holocene (Fig. 4). This apparent weak variability may result from
327 significantly lower sampling resolution within the Holocene (one sample per 500 yr)
328 compared with the last glacial stage (one sample per 300 yr). These results are in good
329 agreement with previous mineralogical studies in the Alboran sea (e.g. Chamley, 1989;
330 Martínez-Ruiz et al., 1999).

331 Illite represents 28–40% of the total clay mineral fraction. The illite record is
332 characterized by high frequency oscillations of moderate amplitude throughout the core,
333 slightly lower during the Holocene (Fig. 4a). The illite content is maximum around 27 and
334 22.5 ka (H2) whereas it is minimum around 35 ka, 30 ka (H3), 23.5, 20.5, 18, 13.5, 10 and 7
335 ka.

336 The percentages of smectite range between 19% and 42%. The average smectite
337 content decreases slightly between 50 and 22 ka. High-frequency variations are added to this
338 general decreasing trend (Fig. 4b). The relative abundance of smectite is especially low
339 around 38, 32.5, 26 and 20/22 ka (H2), and reaches minimum values around 15 ka (H1).
340 Smectite is abundant around 39, 27.5, 18 and 12 ka reaching maximum values around 36 ka.

341 The kaolinite record varies between 11% and 24%. The average content of kaolinite
342 increases from last glacial (<15%) to the Holocene (<20%). There is no consistent evolution
343 either during the North Atlantic cold events: an increase of kaolinite is associated with H1
344 whereas kaolinite is low during H2–H4 (Fig. 4c).

345 The abundance of chlorite varies between 10% and 22% throughout the core. The
346 chlorite content is higher between 22 and 12 ka than over the rest of the core. High-frequency
347 oscillations overwhelm a slightly increasing trend between 50 and 22 ka. Minimum
348 percentages of chlorite are associated with the HE and with the Younger Dryas (Fig. 4d).

349 Palygorskite composes 3–11% of the clay mineral fraction. The record is characterized
350 by the presence of several significant peaks, out of the standard deviation range (Fig. 4e).
351 Most of these peaks are associated with cold climatic events, YD and HE (Fig. 4e). H1 and
352 H4 are especially enriched in palygorskite. Except these peaks the record is quite smooth and
353 show very little variations. We can notice a reduce amount of palygorskite during the
354 Holocene.

355

356 **4.2. Pollen**

357 Palynological records from ODP Site 976 document the classic climatic trend in the
358 Mediterranean region from the glacial times to the Holocene (e.g. Reille and Lowe, 1993;
359 Watts et al., 1996; Allen et al., 1999; Combourieu Nebout et al., 2002; Sánchez-Goñi et al.,
360 2002; Roucoux et al., 2005; Tzedakis, 2005). Variability of pollen assemblages reflects
361 repetitive alternations between temperate forest (mainly *Quercus*), very similar to today's
362 vegetation in the mountains of the western Mediterranean, and semi-desert vegetation as
363 observed today in North African and South- Eastern Europe (Walter et al., 1975) (Fig. 5).

364 Elevated abundance of temperate pollen taxa occur during warm interstadials,
365 indicating warm and humid climates on continents adjacent to the Alboran sea. Cold stadials
366 correlate with increased *Artemisia* pollen relative abundance that is indicative of enhanced
367 continental aridity (Fig. 5) (Combourieu Nebout et al., 2002). Periods of maximum cooling in
368 the North Atlantic, the HE H1 to H5, are reflected at Site 976 by coeval maxima of semi
369 desert- rich *Artemisia* and minima of *Quercus* forest. Such associations are characteristic of
370 cold steppe to cold desert (Tarasov et al., 1998) and suggest that the western Mediterranean
371 borderlands experienced cold climates and enhanced severe aridity (Combourieu Nebout et
372 al., 2002). These changes in vegetation correlate with modifications in marine environments
373 as revealed by coeval modifications of foraminiferal and dinocysts assemblages that mark
374 cooling of the sea surface temperatures (Combourieu Nebout et al., 2002; Sánchez-Goñi et al.,
375 2002). These episodes were immediately followed by increases of temperate pollen
376 assemblage that document rapid warming and fast increasing humidity in the area.

377 These results are in agreement with the evidence of higher intensity of wind systems
378 over the northern hemisphere during cold intervals (stadials and HE) revealed by the dust
379 content in Greenland ice cores and other results on continents adjacent to the Alboran sea
380 (Mayewski et al., 1997; Sánchez-Goñi et al., 2002; Moreno et al., 2005).

381 Climatic parameters reconstructed from pollen analyses reveal repetitive oscillations
382 of mean annual precipitation and mean temperature of the coldest month. During the HE, the
383 pollen-based climatic estimates indicates a decrease of at least 200–400mm in mean annual
384 precipitation and of 5–15°C in mean temperature of the coldest month. The decrease in
385 precipitation is consistent with the elevated abundance of semi-desert taxa. By contrast the
386 reconstructed temperature may appear surprisingly low considering the dominance of
387 *Artemisia* pollen. At present day, the local species *Artemisia herba-alba* is usually associated
388 with MTCO of 0–4°C. More generally, *Artemisia* is today a major component of steppe ad
389 desert environments. Nevertheless, as pollen grains do not permit the determination at species

390 level, it remains difficult to separate hot and warm steppe or desert in the database because of
391 similar associations. This may induce an accentuation of cold temperatures in our samples,
392 but our results remain generally in accordance with other data in marine and continental
393 records (Allen et al., 1999; Sánchez-Goñi et al., 2002). The database is periodically amended
394 in order to solve this problem and better discriminate these two biomes.

395 When compared to pollen data the variations of some clay minerals appear to vary
396 together with those of temperate, altitudinal and semi-desert groups (Fig. 5). The variations of
397 palygorskite are positively correlated to semi-arid pollen abundances. As a result,
398 palygorskite and precipitation records exhibit a negative correlation index (-0.41). Although
399 their correlation index is low ($r = 0.34$) chlorite and altitudinal vegetation are somehow linked
400 to each other. By contrast, the kaolinite record appears to be inversely correlated to semi-arid
401 vegetation ($r = -0.40$) and to the oxygen isotopic ratio ($r = -0.40$). Illite and smectite do not
402 show any significant correlation with pollen data. Principal Component Analysis of this data
403 set indicates a dominant factor (>80%) retracing the variations of pollen, palygorskite and
404 $\delta^{18}\text{O}$ of ice from the NorthGRIP ice core whereas the second factor (<10%) corresponds to
405 the smectite record.

406

407 **5. Discussion**

408 *5.1. Clay mineral supply*

409 All clay minerals records show oscillations during the last glacial, but the increase of
410 palygorskite specifically characterizes the North Atlantic cold events whereas the proportions
411 of illite, kaolinite and smectite do not show consistent variations during these climatic events.

412 The illite and chlorite primarily discharged by the Rhone River can be further
413 transported from the Gulf of Lion to the Alboran Sea by the oceanic gyre (Millot, 1999). This
414 current is characterized by important seasonal variations (Alb erola and Millot, 2003). It is
415 more active during winter than in summer when stratification prevents any convective activity
416 (Durrieu de Madron et al., 1999). The chemical composition and morphology of both illite
417 and chlorite indicate proximal sources from, respectively, Betic Cordilleras and Nevado-
418 Filaboride complexes (Mart inez-Ruiz et al., 1999). Similarly morphological analyses of
419 smectite suggest a soil-derived provenance (Mart inez-Ruiz et al., 2003). By contrast, the
420 occurrence of elongated fibers of palygorskite within sediments is characteristic of a wind-

421 driven transport. Indeed, there are several evidences that rivers only represent a minor
422 contribution compared to atmosphere at the basin scale (Elbaz-Poulichet et al., 2001),

423 These results indicate that illite, chlorite and smectite are partly transported via rivers
424 toward the Alboran Sea but may also be supplied through eolian processes together with
425 palygorskite. Clay minerals, except palygorskite, are likely to be transported to the Alboran
426 Sea through oceanic, riverine or eolian processes. As a result their variations are less
427 informative than palygorskite ones in terms of global atmospheric configurations.
428 Nevertheless the increase of some of these clay minerals (i.e. illite during H2, kaolinite during
429 H1) or their decrease (i.e. smectite during H3, kaolinite during H2) suggests that regional
430 specific configurations are likely to modify the clay mineral association.

431

432 *5.2. Provenance of palygorskite*

433 The presence of palygorskite (Fig. 4e) and the increase in semi-desert taxa (Fig. 5a
434 and b) characterizing sediments deposited during the cold intervals confirm that arid
435 conditions prevailed on the continent during the North Atlantic cold climatic events (Cacho et
436 al. 2000; Combourieu Nebout et al., 2002; Moreno et al., 2002; Sánchez-Goñi et al., 2002).

437 Because palygorskite is typical of arid and semi-arid climate, it mainly records the
438 North African contribution to sedimentation. Palygorskite is also reported in several
439 formations over the Iberian Peninsula. Although such proximal supply from the Iberian
440 Peninsula has to be taken in account, it is not a major contributor to Alboran deep-sea
441 sedimentation since (1) palygorskite is easily destroyed while transported by rivers and (2)
442 only trace amounts of palygorskite have been detected in proximal sediments. Western
443 Morocco, northern Algeria, central Algeria and southern Sahara (Paquet et al., 1984; El
444 Mouden et al., 2005), as well as reworked Neogene North African deposits (e.g. Chamley,
445 1989), are potential palygorskite source areas.

446 In order to pinpoint its origin, the palygorskite content was compared with the illite-to-
447 kaolinite (I/K) ratio (Fig. 6) which remains unchanged after long-term transport (Caquineau et
448 al., 1998). This comparison gives a rough estimation of the respective contribution of eolian
449 vs. riverine supplies. The I/K ratio (Fig. 6) is also a relevant fingerprint of the regional origin
450 of Saharan dust (Caquineau et al., 1998): dust from North and West Sahara is enriched in
451 illite (I/K =2) whereas kaolinite (I/K =0.1) becomes dominant when the dust has a Sahelian
452 origin (Paquet et al., 1984). South and central Sahara are characterized by intermediate values

453 (I/K =0.4) (Caquineau et al., 1998). This latitudinal evolution is consistent with the
454 mineralogy of Atlantic sediments and dust collected over the Atlantic Ocean (e.g. Chamley,
455 1989). The content in kaolinite of dust also varies with the longitude. The I/K ratio decreases
456 from the northwestern Africa (I/K =2–1.1 in northern Algeria) to northeastern Africa (I/K
457 =0.5–0.7) (e.g. Guerzoni and Chester, 1996; Caquineau et al., 1998). In the studied samples
458 the I/K ratio ranges from 1.35 to 3 with an average value of 2.1, and does not significantly
459 change during the old events (Fig. 6). Our data indicate that the eolian contribution should be
460 important in the Alboran Sea since the I/K ratio of proximal riverine supply is rather low (I/ K
461 =1.38) (Alonso and Maldonado, 1990). When compared with data from Caquineau et al.
462 (1998) this ratio suggests sources from the North and West Sahara (I/ K =1.3–2.6) and rules
463 out any contribution from Sahel (I/ Ko0.25) or South and central Sahara (I/K =0.4–0.7).
464 During the North Atlantic cold events, the I/K remains stable while the palygorskite content
465 increases. This result indicates larger contribution of an eolian source characterized by a high
466 palygorskite content and I/K ratio around 2, such as western Morocco (El Mouden et al.,
467 2005). Furthermore, the presence of *Argania* pollen, typical of southern Morocco, associated
468 with the palygorskite within the HE, HE1 and HE4, supports the southern origin of dust. The
469 presence of *Argania* pollen suggests low precipitation (200–400 mm) and positive
470 temperatures. This result is not contradictory with the reconstructed MTCO because this
471 pollen was not used in the MAT modeling and because the occurrence of *Argania* is here
472 interpreted as an evidence of intense eolian transport from southern areas during these HE.
473 *Argania* pollen were probably transported together with palygorskite from southern areas
474 which were not so cold but arid. The sediments from the ODP 976 seem to result from the
475 mixing between riverine supply (possibly the Ebro River) and eolian contributions from
476 North and West Sahara (Fig. 6).

477

478 5.3. *Palygorskite transport—atmospheric configuration*

479 As palygorskite represents the eolian contribution to deep-sea sedimentation, its
480 abundance suggests that the continental aridity was associated with specific atmospheric
481 configurations favoring dust transport from the source area to the Alboran sea. The different
482 atmospheric scenario leading to palygorskite-rich dust transport issued from Sahara toward
483 Europe are described by specific air-masses trajectories. Several studies (e.g. Avila et al.,
484 1997; Rodríguez et al., 2001), based on decennial observations, attempt to reconstruct the
485 main trajectories of dust outbreaks reaching Europe and their associated atmospheric

486 configurations (Fig. 7). These dust events are clearly controlled by the intensity of the
487 westerly winds regime over Europe. The migration of both anticyclone and depression cells
488 over the tropical Atlantic, the Mediterranean, the European and North African continents
489 seasonally modulates these situations. According to the potential sources of palygorskite and
490 to the regional wind system, the potential atmospheric configuration resulting in enhanced
491 palygorskite supply during the North Atlantic cold events can then be discussed (Fig. 7).

492 During summer the thermal convective activity over central and southern Sahara
493 desert lifts dust particles to high atmosphere (Prospero, 1981a, b). This Saharan air mass
494 flows westward at high-altitude. A part of this air mass is further redistributed over long-
495 range distance toward the Mediterranean (pathway 4) by the northern branch of the SAL
496 (Prospero, 1981a, b). This scenario would favor an increased contribution of dust originating
497 from the Lake Chad area. But even if the Bodélé depression is considered to be one of the
498 main dust sources at present-day, there is so far no clear evidence of palygorskite occurrence
499 in dust originating from this area. But few mineralogical studies have attempted to identify
500 fibrous clays so far. The average level of the Lake Chad has dropped during the late Holocene
501 while dustiness increases continuously. These conditions are likely to favor an enhanced
502 production and export of palygorskite toward the Mediterranean if considering Lake Chad as
503 a potential source area. According to our data, there is no significant increase in palygorskite
504 input in the Alboran Sea during the Holocene. The clay mineral fraction composition remains
505 stable over the Holocene. This observation suggests that the Bodélé depression and Lake
506 Chad were probably not the main sources of dust during the North Atlantic cold climatic
507 events.

508 In the lower trades, below the SAL (850 hPa, 1500 m) the northward transport of
509 desert dust (Fig. 2b) is also seasonally modulated (Bergametti et al., 1989a; Chiapello et al.,
510 1995; Guerzoni et al., 1997; Moulin et al., 1997; Rodríguez et al., 2001). During summer the
511 remoteness of the Azores high and the displacement of the North African anticyclone over
512 Algeria favor the incursion of a depression trench between these two anticyclones gyres
513 (Coudé- Gaussen, 1982; Bergametti et al., 1989a; Moulin et al., 1997; Rodríguez et al., 2001;
514 Torres-Padrón et al., 2002). Dust particles originating from western and central part of the
515 Sahara (Guerzoni et al., 1997) are transported toward the western and central part of the
516 Mediterranean (Figs. 2c and 7, pathway 3) (Moulin et al., 1997). The atmospheric back-
517 trajectories associated with such events indicate that the main dust emission is located in the
518 western part of Morocco, where important source of palygorskite have been identified (Avila

519 et al., 1997; El Mouden et al., 2005). The increase of palygorskite associated with the North
520 Atlantic cold events could then be tentatively attributed to dominant summer atmospheric
521 configurations. Such meridian circulation of air masses occurs when the westerly regime is
522 weak or disrupted (Coudé-Gaussen, 1982). It would then imply that the North Atlantic cold
523 climatic events are associated with a reduction or a northward shift of the westerlies over
524 Europe. Our results confirm the previous studies in the Alboran sea sediments suggesting a
525 link between the North Atlantic cold events (stadials and HE) and the westerly regime over
526 Europe (Cacho et al., 2000; Combourieu Nebout et al., 2002; Moreno et al., 2002; Sánchez-
527 Goñi et al., 2002)

528 In winter (Figs. 2b and 7) African dust outbreaks mainly reach Europe through
529 meridian circulation across the Mediterranean (Coudé-Gaussen, 1982). A NS depression
530 trench (Fig. 7) is created between the Azores high (pathway 1) and the high-pressure located
531 over central Mediterranean or over North Africa (Rodríguez et al., 2001; Torres- Padrón et al.,
532 2002). Saharan air masses move northward along the western edge of the high-pressure cell
533 (Coudé- Gaussen, 1982; Rodríguez et al., 2001). The trajectory of such meridian transport is
534 constrained both by the position and the high-pressure cell and the Atlas Mountains (Fig. 7),
535 mainly providing dust and pollen to the northwestern and central Mediterranean. A recent
536 study of southern Europe sedimentary records suggest that this pattern is responsible for the
537 presence of Cedrus pollen originating from northwest Africa and flowering in winter (Magri
538 and Parra, 2002). But the reconstructed trajectories indicate that dust particles were not able to
539 reach the Alboran Sea. This eastern pattern is not likely to influence significantly the
540 sedimentation in the Alboran Sea.

541 Inter-season Saharan dust outbreaks represent less than 30% of the total dust emission
542 (Guerzoni et al., 1997; Rodríguez et al., 2001). Spring and early summer dust events represent
543 20% of total annual events (Rodríguez et al., 2001). They are linked to the position of
544 cyclones which favors the air masses crossing the Mediterranean between Tunisia and Egypt
545 toward eastern and central Mediterranean basins (Moulin et al., 1997). Such wind trajectories
546 would not be able to transport fine-dust particles toward the Alboran Sea. At the end of
547 summer the dust main routes are shifted westward because most cyclones originate from the
548 Balearic region. The dust outbreaks have a general NE trajectory toward Corsica and Italy
549 (Bergametti et al., 1989c) (Fig. 7, pathway 1b). Nevertheless the presence of the Atlas
550 mountain (Fig. 7) shift to the East the main direction of dominant winds, preventing any
551 significant contribution to the Alboran Sea sedimentation.

552 Saharan intrusions occurring during fall represent less than 10% of the total annual
553 events (Rodríguez et al., 2001). These events are generally induced by the simultaneous
554 occurrence of a depression off the southwest Iberian Peninsula and of a high-pressure cell
555 over Algeria (Fig. 7, pathway 2) (Rodríguez et al., 2001). The dominant direction of
556 associated winds is likely to transport Saharan dust to the Iberian Peninsula and to the
557 Alboran Sea. Moreover, the dust produced by this synoptic situation probably originates from
558 one of the potential source area of palygorskite (Paquet et al., 1984). But the rare occurrence
559 of such events and their low contribution to the annual dust export suggest they are not the
560 main mechanism leading to palygorskite input in the Alboran Sea. But synoptic situations
561 were different during the last glacial. The enhanced supply associated with the North Atlantic
562 cold events may then indicate that the modern meteorological situation leading to fall Saharan
563 intrusions was much more frequent than today.

564 In summary, according to the provenance of palygorskite and to the atmospheric back-
565 trajectories, the pathways 2 and 3 are the most probable patterns followed by western
566 Moroccan dust-blown particles which characterize the North Atlantic cold events.

567

568 *5.4. Paleoclimatic implications*

569 Glacial periods are characterized by dust fluxes 1.5 to 6 times higher than today
570 especially in tropical oceans (Kolla et al., 1979; Chamley et al., 1989; Ruddiman, 1997;
571 Hoogakker et al., 2004). This enhanced supply was attributed to an aridification of the
572 continents (Kolla et al., 1979; Rea, 1994) and/or to strengthening of the winds (Ruddiman,
573 1997). During glacial intervals, cold and dry conditions develop over the Mediterranean as a
574 result of colder sea surface temperatures associated with the stability of the northern high-
575 pressure cell and with an increased seasonality of precipitations (Prentice et al., 1992; Pérez-
576 Folgado et al., 2003). There is a strong relationship between rainfall and dust storm
577 occurrence (Middleton, 1985). Low precipitations limit the expansion of vegetation, favoring
578 the erosion of unconsolidated fine-grained soil particles (Middleton, 1985; Balsam et al.,
579 1995). As a consequence the aridification is thought to become one of the main factor
580 controlling the production of dust during glacial periods (Kolla et al., 1979; Middleton, 1985;
581 Rea, 1994). But other studies evidenced the influence of wind intensity on the enhanced
582 glacial dust fluxes. Previous studies mainly based on pollen and sediment analyses suggest
583 the intensification of winds, favoring the northward transport of dust across the Mediterranean
584 during the last glacial period. This enhanced eolian input from North Africa was evidenced in

585 lacustrine sediments from central Italy (Narcisi, 2000) and in terrestrial deposits from a
586 Mediterranean island (Lampedusa) located between Tunisia and Sicily (Giraudi, 2004). The
587 presence of *Cedrus* pollen, a modern marker of northwest African provenance, in several sites
588 from southern Europe, also supports this hypothesis (Magri and Parra, 2002). Several studies
589 argued that winter transport over the Atlantic ocean should be enhanced during glacial
590 because the most intense present-day dust events originating from the southern Sahelian
591 region typically occur during winter (Chiapello et al., 1997; Ratmeyer et al., 1999; Hoogakker
592 et al., 2004; Washington and Todd, 2005). But major dust outbreaks originating from West
593 and North Sahara also occur during summer (Moulin et al., 1997; Rodríguez et al., 2001;
594 Ginoux et al., 2004). This mechanism should be considered to explain the increased dust
595 fluxes during glacial (Balsam et al., 1995). Grousset et al. (1998) then suggested that both
596 aridity and wind strength should be involved to explain the high glacial dust input. In the
597 frame of the recent studies in the Alboran Sea, our results allow to highlight the importance of
598 eolian processes during the North Atlantic cold events.

599 In West Mediterranean, cold events as HE and Dansgaard/Oeschger stadials are
600 evidenced by the increase of deep oceanic convection and by the development of arid and
601 cold conditions on the surrounding continents. Locally these cold events seem to be related to
602 changes in atmospheric circulation and intensification of westerly winds (Rohling et al., 1998;
603 Sánchez-Goñi et al., 2002). The increase of steppic plants in Alboran sea sediments associated
604 with low paleoprecipitation estimations indicates that HE were dry and cold (Combourieu
605 Nebout et al., 2002; Sánchez-Goñi et al., 2002). Such a decrease has already been observed in
606 other records in Alboran Sea and off Portugal for HE 3 to 5 (Sánchez-Goñi et al., 2002) and
607 in continental series in Lago Grande di Monticchio, Italy (Allen et al., 1999). It remains
608 slightly higher than the sea surface temperature changes (5–10°C) obtained from alkenones in
609 the Alboran Sea (Cacho et al., 2000) and the temperature of the coldest month deduced from
610 the Monticchio record for the studied period (Allen et al., 1999). As already mentioned in
611 Section 4.2, the small discrepancies between the MTCO at site ODP 976 (Alboran sea) and in
612 Monticchio record may result both from the use of different methods of reconstruction and
613 database. High eolian fluxes based on grain-size measurements, resulting from increased
614 aridity and wind strength, were also evidenced in the Alboran Sea sediments during H3, H4
615 and H5 (Moreno et al., 2002). Our data also suggest that aridity was enhanced during the
616 North Atlantic cold events, as revealed by steppic vegetation, precipitation estimation and
617 clay minerals (Fig. 5). The presence of palygorskite indicates that peri-Mediterranean areas

618 were dry with sparse vegetation cover, allowing the erosion of unconsolidated soils. As
619 palygorskite is wind transported, its increase suggests a significant wind strengthening over
620 northern North Africa and allows the reconstruction of the dominant synoptic conditions over
621 the Mediterranean during the North Atlantic cold events. The meridian transport of
622 palygorskite to the Alboran Sea during the North Atlantic cold events implies not only that
623 strong high-pressure cells develop over the tropical Atlantic (Azores High) and over the North
624 African continent (North African High) but also that the westerlies, probably shifted
625 northward, would not prevent the incursion of the Saharan masses toward Europe.

626

627 *5.5. Relation with the NAO*

628 According to the identification of the main clay sources and to atmospheric back
629 trajectories, the increase of palygorskite during the North Atlantic cold events indicates the
630 stability of two high-pressure cells, the Azores high over the tropical Atlantic Ocean and the
631 North African anticyclone over Algeria. During the North Atlantic cold climatic events, these
632 two high-pressure systems were associated with the existence of a depression over western
633 Europe. The meridian transport of the palygorskite implies that the westerly regime was
634 weak, disrupted or displaced northward. Such synoptic situations are very similar with
635 positive phases of the so-called NAO (Hurrell, 1995). Moulin et al. (1997) evidenced the role
636 of the NAO in controlling the desert dust transport. The NAO is responsible for much of the
637 climate variability observed in the Mediterranean region (Fig. 8) at present-day and possibly
638 during the last glacial (Cacho et al., 2000; Combourieu Nebout et al., 2002; Moreno et al.,
639 2002; Sánchez-Goñi et al., 2002). During positive phase of the NAO, the high-pressure
640 gradient between the strong Azores anticyclone and the Icelandic depression results in a
641 northward shift and an increase strength of the westerlies (Hurrell, 1995). When the NAO is
642 high, dry conditions develop over southern Europe and North Africa (Pittalwala and Hameed,
643 1991) and the northeast trade winds intensity increases, leading to the enhanced westward
644 transport of desert dust (Moulin et al., 1997). As a result, severe decennial time-scale
645 droughts in Sahel are correlated to low surface temperature in the North Atlantic Ocean
646 (Moulin et al., 1997). Conversely, when the NAO is negative, the pressure gradient between
647 the Azores high and the Iceland low decreases (Hurrell, 1995). The westerlies are shifted to
648 the South providing precipitations over the Mediterranean and the North African continent.
649 Negative phases of the NAO thus prevent dust uptake and transport (Moulin et al., 1997).
650 Several studies in the West Mediterranean and in the Alboran Sea highlight the influence of

651 northwesterly and Saharan winds in the low sea surface temperatures, in high continental
652 aridity, and in the enhanced dust transport associated with the HE and D/ O stadials.

653 The modification of the northwesterly regime was compared to the present-day NAO
654 (Cacho et al., 2000; Combourieu Nebout et al., 2002; Moreno et al., 2002, 2005; Sánchez-
655 Goñi et al., 2002), but oscillating with a lower frequency than the decennial one (Hurrell,
656 1995). High NAO index and increased intensity of the northwesterlies were also invoked to
657 explain the active deep-water convection which occurs in the Mediterranean during HE and
658 stadials (Rohling et al., 1998; Cacho et al., 2000). Furthermore, modeling data indicate high
659 correlation between the winter NAO index and the dust emission from the Bodélé region–
660 Lake Chad area. But this model does not take in account the impact of vegetation reduction
661 on the erodability of soils. Moreover, since no palygorskite was reported so far in dust-blown
662 particles from the Bodélé region, this area cannot be considered as the main dust contributor
663 toward the Alboran sea during the North Atlantic cold events. Our results suggest that
664 palygorskite-rich events are favored by specific atmospheric configurations. A depression
665 corridor is created between the Azores high and the North African anticyclone, leading to the
666 transport of dust particles from western Morocco to the Alboran Sea. Such meridian transfer
667 is efficient only if westerlies are weak, disrupted or displaced northward. But recent studies
668 suggest that the northwesterlies were intense during D/O stadials (Rohling et al., 1998; Cacho
669 et al., 2000; Moreno et al., 2002; Sánchez-Goñi et al., 2002). Our data indicate that
670 northwesterlies should be shifted to the North during the North Atlantic cold events in order
671 to allow the intrusion of Saharan air masses toward Europe. This interpretation is not
672 contradictory with previous studies suggesting intensification of the westerly winds, but may
673 explain the singular feature of the amplified aridity signal characterizing the HE compared to
674 other D/O stadials by shifting the westerly winds toward a more northerly position
675 (Combourieu Nebout et al., 2002; Sánchez-Goñi et al., 2002).

676

677 **6. Conclusions**

678 The Alboran core ODP 976 provides a combined mineralogical and palynological data
679 set that illustrates connection between climatic and atmospheric system on West
680 Mediterranean throughout the last glacial cycle. Our results provide new insights on the
681 atmospheric configuration in the Alboran Sea during last glacial, especially during the North
682 Atlantic cold events.

683 The increase of palygorskite—a typical wind-blown clay mineral—during these cold
684 episodes suggests the intensification of dust events across the Mediterranean during the North
685 Atlantic cold events. The peculiar mineralogical composition of the clay-size fraction
686 evidences western Morocco as a potential source of dust during the North Atlantic cold
687 events. This hypothesis is supported by the abundance of semi-desert taxa and the presence of
688 *Argania* pollen associated with palygorskite. Coeval palygorskite supply and development of
689 the semi-arid vegetation during the North Atlantic cold events suggest severe droughts on
690 peri-Mediterranean areas, as evidenced by estimated annual precipitations. The enhanced
691 Saharan dust export toward the Alboran Sea during the North Atlantic cold events also
692 implies a strengthening of dominant winds. According to the different air mass trajectories
693 resulting from various atmospheric configurations, summer-type dust events are the best
694 candidate to explain the important transport of fine-particles from western Morocco to the
695 Alboran Sea. According to atmospheric models, such a meridian transport (1) results from the
696 development of strong and stable anticyclonic conditions over the tropical Atlantic and North
697 Africa, similar to today's summer meteorological configuration and (2) implies a northward
698 position of the westerly winds during the North Atlantic cold events.

699 The reconstructed synoptic situation over the West Mediterranean during the North
700 Atlantic cold events was compared with meteorological configurations characterizing the
701 NAO. This observation reveals that the prevailing weather regime over North Africa and
702 western Europe during the North Atlantic cold events was very similar to the one described
703 for positive phases of the NAO, suggesting a systematic shift towards a positive NAO
704 situation.

705 Further geochemical analyses will help to estimate the contribution of the Moroccan
706 source versus other sources such as the Bodélé region during the North Atlantic cold events.
707 Moreover high-resolution mineralogical and palynological studies of sediments deposited
708 during the Marine Isotopic Stage 5 and the Holocene in the Alboran sea will give essential
709 informations on the links between North Atlantic climate and Mediterranean weather regimes.

710

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720 **References**

721 Albérola, C., Millot, C., 2003. Circulation in the French Mediterranean coastal zone near
722 Marseille: influence of the wind and of the northern current. *Continental Shelf Research* 23,
723 587–610.

724 Allen, J.R.M., Brandt, U., Brauer, A., Hubberten, H.-W., Huntley, B., Keller, J., Kraml, M.,
725 Mackensen, A., Mingram, J., Negendank, J.F.W., Nowaczyk, N.R., Oberhänsli, H., Watts,
726 W.A., Wulf, S., Zolitschka, B., 1999. Rapid environmental changes in southern Europe
727 during the last glacial period. *Nature* 400, 740–743.

728 Alonso, B., Maldonado, A., 1990. Late Quaternary sedimentation patterns of the Ebro
729 turbidite systems (northwestern Mediterranean): two styles of deep-sea deposition. *Marine*
730 *Geology* 95, 353–377.

731 Avila, A., Queralt-Mitjans, I., Alarcón, M., 1997. Mineralogical composition of African dust
732 delivered by red rains over northeastern Spain. *Journal of Geophysical Research* 102 (18),
733 21,977–21,996.

734 Balsam, W.L., Otto-Bliesner, B.L., Deaton, B.C., 1995. Modern and last glacial maximum
735 eolian sedimentation patterns in the Atlantic Ocean interpreted from sediment iron oxide
736 content. *Paleoceanography* 10, 493–507.

737 Bergametti, G., Dutot, A.L., Buat-Menard, P., Losno, R., Remoudaki, E., 1989a. Seasonal
738 variability of the elemental composition of atmospheric aerosol particles over the
739 northwestern Mediterranean. *Tellus* 41 (B), 353–361.

740 Bergametti, G., Gomes, L., Coudé-Gaussen, G., Rognon, P., Le Coustumer, M.N., 1989b.
741 African dust observed over Canary islands: source-regions identification and transport pattern
742 for some summer situations. *Journal of Geophysical Research* 94, 14855–14864.

743 Bergametti, G., Gomes, L., Remoudaki, E., Desbois, M., Martin, D., Buat-Menard, P., 1989c.
744 Present transport and deposition patterns of African dusts to the North-Western
745 Mediterranean. In: Leinen, M., Sarnthein, M. (Eds.), *Paleoclimatology and Paleometeorology:*

746 Modern and Past Patterns of Global Atmospheric Transport. Serie C/ Mathematical and
747 Physical Sciences. Kluwer Academic, Dordrecht, pp. 227–251.

748 Béthoux, J.P., 1980. Mean water flux across sections in the Mediterranean sea, evaluated on
749 the basis of water and salt budgets and of observed salinities. *Oceanologica Acta*. 3, 79–88.

750 Brindley, G.W., Brown, G., 1980. *Crystal Structures of Clay Minerals and their X-ray*
751 *Identification*. Mineralogical Society, London.

752 Brooks, N., Legrand, M., 2000. Dust variability over northern Africa and rainfall in the Sahel.
753 In: McLaren, S.J., Kniveton, D. (Eds.), *Linking Climate Change to Land surface Change*.
754 Kluwer Academic, Dordrecht, pp. 1–25.

755 Cacho, I., Grimalt, J.O., Sierro, F.J., Shackleton, N., Canals, M., 2000. Evidence for enhanced
756 Mediterranean thermohaline circulation during climatic coolings. *Earth and Planetary Science*
757 *Letters* 183, 417–429.

758 Caquineau, S., Gaudichet, A., Gomes, L., Magonthier, M.-C., Chatenet, B., 1998. Saharan
759 dust: clay ratio as a relevant tracer to assess the origin of soil-derived aerosols. *Geophysical*
760 *Research Letters* 25, 983–986.

761 Chamley, H., 1989. *Clay Sedimentology*. Springer, Berlin.

762 Chamley, H., Debrabant, P., Robert, C., Mascle, G., Rehault, J.P. Aprahamian, J., 1989.
763 Mineralogical and geochemical investigations on latest Miocene deposits in the Tyrrhenian
764 sea (ODP Leg 107). In: Kastens, K., Mascle, J., et al., (Eds.), *Ocean Drilling Program,*
765 *Proceedings 107B*. US Government Printing Office, pp. 1501–1513.

766 Chiapello, I., Bergametti, G., Gomes, L., Chatenet, B., Dulac, F., Pimenta, J., Santo Soares,
767 E., 1995. An additional low layer transport of Sahelian and Saharan dust transport over the
768 north-eastern tropical Atlantic. *Geophysical Research Letters* 22, 3191–3194.

769 Chiapello, I., Bergametti, G., Chatenet, B., Bousquet, P., Dulac, F., Santos Suarez, E., 1997.
770 Origins of African dust transported over the north-eastern tropical Atlantic. *Journal of*
771 *Geophysical Research* 102 (D12), 13701–13709.

772 Combourieu Nebout, N., Turon, J.L., Zahn, R., Capotondi, L., Londeix, L., Pahnke, K., 2002.
773 Enhanced aridity and atmospheric high-pressure stability over the western Mediterranean
774 during the North Atlantic cold events of the past 50 ky. *Geology* 30 (10), 863–866.

- 775 Coudé-Gaussen, 1982. Les poussières éoliennes sahariennes. Mise au point. *Revue de*
776 *Géomorphologie Dynamique* 31, 49–69.
- 777 Coudé-Gaussen and Blanc, M 1985. Présence de grains éolisés de palygorskite dans les
778 poussières actuelles et les sédiments d'origine désertique. *Bulletin de la Société Géologique de*
779 *France* 8 (1), 571–579.
- 780 Coudé-Gaussen, G., Hillaire-Marcel, C., Rognon, P., 1982. Origine et évolution pédologique
781 des fractions carbonatées dans les loess des Matmata (Sud-Tunisien) d'après leurs teneurs en
782 13C et 18O. *Comptes Rendus de l'Académie des Sciences de Paris* 295, 939–942.
- 783 Coudé-Gaussen, G., Rognon, P., Bergametti, G., Gomes, L., Strauss, B., Le Coustumer, M.N.,
784 1987. Saharan dust on Fuerteventura island (Canaries): chemical and mineralogical
785 characteristics, air mass trajectories, and probable sources. *Journal of Geophysical Research*
786 92, 9753–9771.
- 787 Desprat, S., Sánchez-Goñi, M.F., Turon, J.-L., McManus, J., Loutre, M.F., Duprat, J.,
788 Malaizé, B., Peyron, O., Peyrouquet, J.-P., 2005. Is vegetation responsible for glacial
789 inception during periods of muted insolation changes? *Quaternary Science Reviews* 24 (12–
790 13), 1361–1375.
- 791 Durrieu de Madron, X., Radakovitch, O., Heussner, S., Loÿe-Pilot, M.- D., Monaco, A., 1999.
792 Role of the climatological and current variability on shelf-slope exchanges of particulate
793 matter: evidence from the Rhône continental margin (NW Mediterranean). *Deep-Sea*
794 *Research I* 46, 1513–1538.
- 795 El Mouden, A., Bouchaou, L., Snoussi, M., 2005. Constraints on alluvial clay mineral
796 assemblages in semiarid regions. The Souss Wadi Basin (Morocco, Northwestern Africa).
797 *Geologica Acta* 3 (1), 3–13.
- 798 Elbaz-Poulichet, F., Guieu, C., Morley, N.H., 2001. A reassessment of trace metal budgets in
799 the western Mediterranean sea. *Marine Pollution Bulletin* 42 (8), 623–627.
- 800 Foucault, A., Mélières, F., 2000. Palaeoclimatic cyclicity in central mediterranean Pliocene
801 sediments: the mineralogical signal. *Palaeogeography, Palaeoclimatology, Palaeoecology*
802 158, 311–323.
- 803 Gascó, C., Antón, M.P., Pozuelo, M., Meral, J., González, A.M., Papucci, C., Delfanti, R.,
804 2002. Distributions of Pu, Am and Cs in margin sediments from the western Mediterranean
805 (Spanish coast). *Journal of Environmental Radioactivity* 59, 75–89.

806 Ginoux, P., Prospero, J.M., Torres, O., Chin, M., 2004. Long-term simulation of global dust
807 distribution with the GOCART model: correlation with North Atlantic Oscillation.
808 *Environmental Modelling and Software* 19, 113–128.

809 Giraudi, C., 2004. The upper Pleistocene to Holocene sediments on the Mediterranean island
810 of Lampedusa (Italy). *Journal of Quaternary Science* 19, 537–545.

811 Grousset, F.E., Rognon, P., Coudé-Gaussen, G., Pédemay, P., 1992. Origins of peri-Saharan
812 dust deposits traced by their Nd and Sr isotopic composition. *Palaeogeography,*
813 *Palaeoclimatology, Palaeoecology*

814 Grousset, F.E., Parra, M., Bory, A., Martinez, P., Bertrand, P., Shimmiel, G., Ellam, R.M.,
815 1998. Saharan wind regimes traced by the Sr–Nd isotopic composition of subtropical Atlantic
816 sediments: last glacial maximum vs. today. *Quaternary Science Reviews* 17, 385–409.

817 Guerzoni, S., Chester, R., 1996. *The Impact of Desert Dust Across the Mediterranean*. Kluwer
818 Academic, Dordrecht.

819 Guerzoni, S., Molinaroli, E., Chester, R., 1997. Saharan dust inputs to the western
820 Mediterranean sea: depositional patterns, geochemistry and sedimentological implications.
821 *Deep-Sea Research II* 44 (3–4), 631–654.

822 Guerzoni, S., Chester, R., Dulac, F., Herut, B., Loÿe-Pilot, M.-D., Measures, C., Migon, C.,
823 Molinaroli, E., Moulin, C., Rossini, P., Saydam, C., Soudine, A., Ziveri, P., 1999. The role of
824 atmospheric deposition in the biogeochemistry of the Mediterranean sea. *Progress in*
825 *Oceanography* 44, 147–190.

826 Guiot, J., 1990. Methodology of the last climatic cycle reconstruction in France from pollen
827 data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 80, 49–69.

828 Hoogakker, B.A.A., Rothwell, R.G., Rohling, E.J., Paterne, M., Stow, D.A.V., Herrle, J.O.,
829 Clayton, T., 2004. Variations in terrigenous dilution in western Mediterranean sea pelagic
830 sediments in response to climate change during the last glacial cycle. *Marine Geology* 211,
831 21–43.

832 Hurrell, J.W., 1995. Decadal trend in the North Atlantic Oscillation: regional temperatures
833 and precipitations. *Science* 269, 676–679.

834 Johnsen, S., Clausen, H.B., Dansgaard, W., Fuhrer, K., Gundestrup, M., Hammer, C.U.,
835 Iversen, P., Jouzel, J., Stauffer, B., Steffensen, J.P., 1992. Irregular glacial interstadials
836 recorded in a new Greenland ice core. *Nature* 359, 311–313.

837 Kolla, V., Biscaye, P.E., Hanley, A.F., 1979. Distribution of quartz in late Quaternary
838 Atlantic sediments in relation to climate. *Quaternary Research* 11, 261–277.

839 Loye-Pilot, M.-D., Martin, J.-M., Morelli, J., 1986. Influence of Saharan dust on the rainfall
840 acidity and atmospheric input to the Mediterranean. *Nature* 321, 427–428.

841 Luck, J.M., Ben Othman, D., 2002. Trace element and Pb isotope variability during rainy
842 events in the NW Mediterranean: constraints on anthropogenic and natural sources. *Chemical*
843 *Geology* 182, 443–460.

844 Magri, D., Parra, I., 2002. Late Quaternary western Mediterranean pollen records and African
845 winds. *Earth and Planetary Science Letters* 200, 401–408.

846 Martínez-Ruiz, F., Comas, M.C., Alonso, B., 1999. Mineral associations and geochemical
847 indicators in upper Miocene to Pleistocene sediments in the Alboran basin (ODP leg 161,
848 Sites 976 and 977). In: Zahn, R., Comas, M.C., Klaus, A. (Eds.), *Proceedings of the Ocean*
849 *Drilling Program, Scientific Results*. College Station, TX, pp. 21–36.

850 Martínez-Ruiz, F., Paytan, A., Kastner, M., González-Donoso, J.M., Linares, D., Bernasconi,
851 S.M., Jimenez-Espejo, F.J., 2003. A comparative study of the geochemical and mineralogical
852 characteristics of the S1 sapropel in the western and eastern Mediterranean. *Palaeogeography,*
853 *Palaeoclimatology, Palaeoecology* 190, 23–37.

854 Masson-Delmotte, V., Landais, A., Combourieu-Nebout, N., von Grafenstein, U., Jouzel, J.,
855 Caillon, N., Chappellaz, J., Dahl-Jensen, D., Johnsen, S., Stenni, B., 2005. Rapid climate
856 variability during warm and cold periods in polar regions and Europe. *C.R. Geosciences*
857 337, 935–946.

858 Matthewson, A.P., Shimmield, G., Kroon, D., Fallick, A.E., 1995. A 300 kyr high-resolution
859 aridity record of the north African continent. *Paleoceanography* 10, 677–692.

860 Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B.,
861 Prentice, M., 1997. Major features and forcing of high latitude northern hemisphere
862 atmospheric circulation using a 110,000- year-long glaciochemical series. *Journal of*
863 *Geophysical Research* 102, 23,366–26,345.

864 Middleton, N.J., 1985. Effect of drought on dust production in the Sahel. *Nature* 316, 431–
865 434.

866 Milliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans.
867 *Journal of Geology* 91, 1–21.

868 Millot, C., 1999. Circulation in the western Mediterranean Sea. *Journal of Marine Systems*
869 20, 423–442.

870 Molinaroli, E., 1996. Mineralogical characterization of Saharan dust with a view to its final
871 destination in Mediterranean sediments. In: Guerzoni, S., Chester, R. (Eds.), *The Impact of*
872 *Desert Dust across the Mediterranean*. Kluwer Academic, Dordrecht, pp. 153–162.

873 Moreno, A., Cacho, I., Canals, M., Prins, M.A., Sánchez-Goñi, M.F., Grimalt, J.O., Weltje,
874 G.J., 2002. Saharan dust transport and high latitude glacial climatic variability: the Alboran
875 sea record. *Quaternary Research* 58, 318–328.

876 Moreno, A., Cacho, I., Canals, M., Grimalt, J.O., Sánchez-Goñi, M.F., Shackleton, N., Sierro,
877 F.J., 2005. Links between marine and atmospheric processes oscillating on a millennial time-
878 scale. A multiproxy study of the last 50,000 yr from the Alboran sea. *Quaternary Science*
879 *Reviews* 24, 1623–1636.

880 Moulin, C., Lambert, C.E., Dulac, F., Dayan, U., 1997. Control of atmospheric export of dust
881 from north Africa by the north Atlantic Oscillation. *Nature* 387, 691–694.

882 Narcisi, B., 2000. Late Quaternary eolian deposition in central Italy. *Quaternary Research* 54,
883 246–252.

884 NorthGRIP members, 2004. High resolution climate record of the northern hemisphere back
885 to the last interglacial period. *Nature* 431, 147–151.

886 Ozenda, P., 1975. Sur les étages de végétation dans les montagnes du bassin Méditerranéen.
887 *Documents de Cartographie Ecologique* 16, 1–32.

888 Paquet, H., Coudé-Gaussen, G., Rognon, P., 1984. Etude minéralogique de poussières
889 sahariennes le long d'un itinéraire entre 19° et 35° de latitude nord. *Revue de Géologie*
890 *Dynamique et de Géographie Physique* 25, 257–265.

891 Pastouret, L., Chamley, H., Delibrias, G., Duplessy, J.C., Thiede, J., 1978. Late Quaternary
892 climatic changes in western tropical Africa deduced from deep-sea sedimentation of the Niger
893 delta. *Oceanologica Acta* 1 (2), 217–232.

894 Pérez-Folgado, M., Sierro, F.J., Flores, J.A., Cacho, I., Grimalt, J.O.,

895 Zahn, R., Shackleton, N., 2003. Western Mediterranean planktonic foraminifera events and
896 millennial climatic variability during the last 70 kyr. *Marine Micropaleontology* 48, 49–70.

897 Petschick, 2000. MacDiff Freeware.

898 Peyron, O., Guiot, J., Cheddadi, R., Tarasov, P., Reille, M., de Beaulieu, J.-L., Bottema, S.,
899 Andrieu, V., 1998. Climatic reconstruction in Europe for 18,000 yr BP from pollen data.
900 *Quaternary Research* 49, 183–196.

901 Pittalwala, I., Hameed, I., 1991. Simulation of the North Atlantic Oscillation in a general
902 circulation model. *Geophysical Research Letters* 18, 841–844.

903 Prentice, I.C., Cramer, W., Harrison, S.P., Leemans, R., Monserud, R.A., Solomon, A.M.,
904 1992. A global biome model based on plant physiology and dominance, soil properties and
905 climate. *Journal of Biogeography* 19 (2), 117–134.

906 Prospero, 1981b. Arid regions as sources of minerals aerosols in the marine atmosphere.
907 *Geological Society of America, Special paper* 186, 71–86.

908 Prospero, 1981b. Eolian transport to the world ocean. In: Emiliani, C. (Ed.), *The Sea VII the*
909 *Oceanic Lithosphere*. Wiley, New York, pp. 871–874.

910 Prospero, J.M., Glacuum, R.A., Nees, R.T., 1981. Atmospheric transport of soil dust from
911 Africa to South America. *Nature* 289, 570–572.

912 Pye, K., 1987. *Aeolian Dust and Dust Deposits*. Academic Press, San Diego, USA.

913 Ratmeyer, V., Fischer, G., Wefer, G., 1999. Lithogenic particle fluxes and grain-size
914 distributions in the deep ocean off northwest Africa: implications for seasonal changes of
915 aeolian dust input and downward transport. *Deep-Sea Research I* 46, 1289–1337.

916 Rea, D.K., 1994. The paleoclimatic record provided by eolian deposition in the deep ocean:
917 the geologic history of wind. *Reviews of Geophysics* 32, 159–195.

918 Rea, D.K., Leinen, M., Jacenek, T.R., 1985. Geologic approach to the long-term history of
919 atmospheric circulation. *Science* 227, 721–725.

920 Reille, M., Lowe, J.J., 1993. A re-evaluation of the vegetation history of the Eastern Pyrénées
921 (France) from the end of the glacial to the present. *Quaternary Science Reviews* 12, 47–77.

922 Rivas-Martinez, S., 1982. Etages bioclimatiques, secteurs chronologiques et séries de
923 végétation de l'Espagne méditerranéenne. *Ecologia*
924 *Mediterranea* 8, 275–288.

- 925 Robert, C., Gauthier, A., Chamley, H., 1984. Origine autochtone et allochtone des argiles
926 récentes de haute altitude en Corse. *Géologie de la Méditerranée* XI, 243–253.
- 927 Rodríguez, S., Querol, X., Alastuey, A., Kallos, G., Kakaliagou, O., 2001. Saharan dust
928 contributions to PM10 and TSP levels in Southern and Eastern Spain. *Atmospheric*
929 *Environment* 35, 2433–2447.
- 930 Rognon, P., Coudé-Gaussen, G., Revel, M., Grousset, F.E., Pédemay, P., 1996. Holocene
931 Saharan dust deposition on the Cape Verde islands: sedimentological and Nd–Sr isotopic
932 arguments. *Sedimentology* 43, 359–366.
- 933 Rohling, E.J., Hayes, A., de Rijk, S., Kroon, D., Zachariasse, J.W., 1998. Abrupt cold spells
934 in the NW Mediterranean. *Paleoceanography* 13, 316–322.
- 935 Roucoux, K.H., de Abreu, L., Shackleton, N.J., Tzedakis, P.C., 2005. The response of NW
936 Iberian vegetation to North Atlantic climate oscillations during the last 65 kyr. *Quaternary*
937 *Science Review* 24, 1637–1653.
- 938 Ruddiman, W.F., 1997. Tropical Atlantic terrigenous fluxes since 25,000 yr. *Marine Geology*
939 136, 18–207.
- 940 Ruddiman, W.F., Sarnthein, M., Backman, J., Baldauf, J.G., Curry, W., Dupont, L.M.,
941 Janecek, T., Pokras, E.M., Raymo, M., Stabell, B., Stein, R., Tiedemann, R., 1989. Late
942 Miocene to Pleistocene evolution of climate in Africa and the low-latitude Atlantic: overview
943 of leg 108 results. In: Ruddiman, W.F., Sarnthein, M., et al., (Eds.), *Proceedings of the Ocean*
944 *Drilling Program, Scientific Results*, pp. 463–484.
- 945 Sánchez-Goñi, M.F., Cacho, I., Turon, J.L., Guiot, J., Sierro, F.J., Peypouquet, J.-P., Grimalt,
946 J.O., Shackleton, N., 2002. Synchronicity between marine and terrestrial responses to
947 millennial scale climatic variability during the last glacial period in the Mediterranean region.
948 *Climate dynamics* 19, 95–105.
- 949 Sarnthein, M., Thiede, J., Pflaumann, U., Erlenkeuser, H., Fütterer, D., Koopmann, B., Lange,
950 H., Seibold, E., 1982. Atmospheric and oceanic circulation patterns off Northwest Africa
951 during the past 25 million years. In: Rad, U., Hinz, K., Sarnthein, M., Seibold, E. (Eds.),
952 *Geology of the Northwest African Continental Margin*. Springer, Berlin, pp. 545–604.
- 953 Schütz, L., 1980. Long-range transport of desert dust with special emphasis on the Sahara.
954 *Annual of the New York Academy of Science* 338, 515–532.

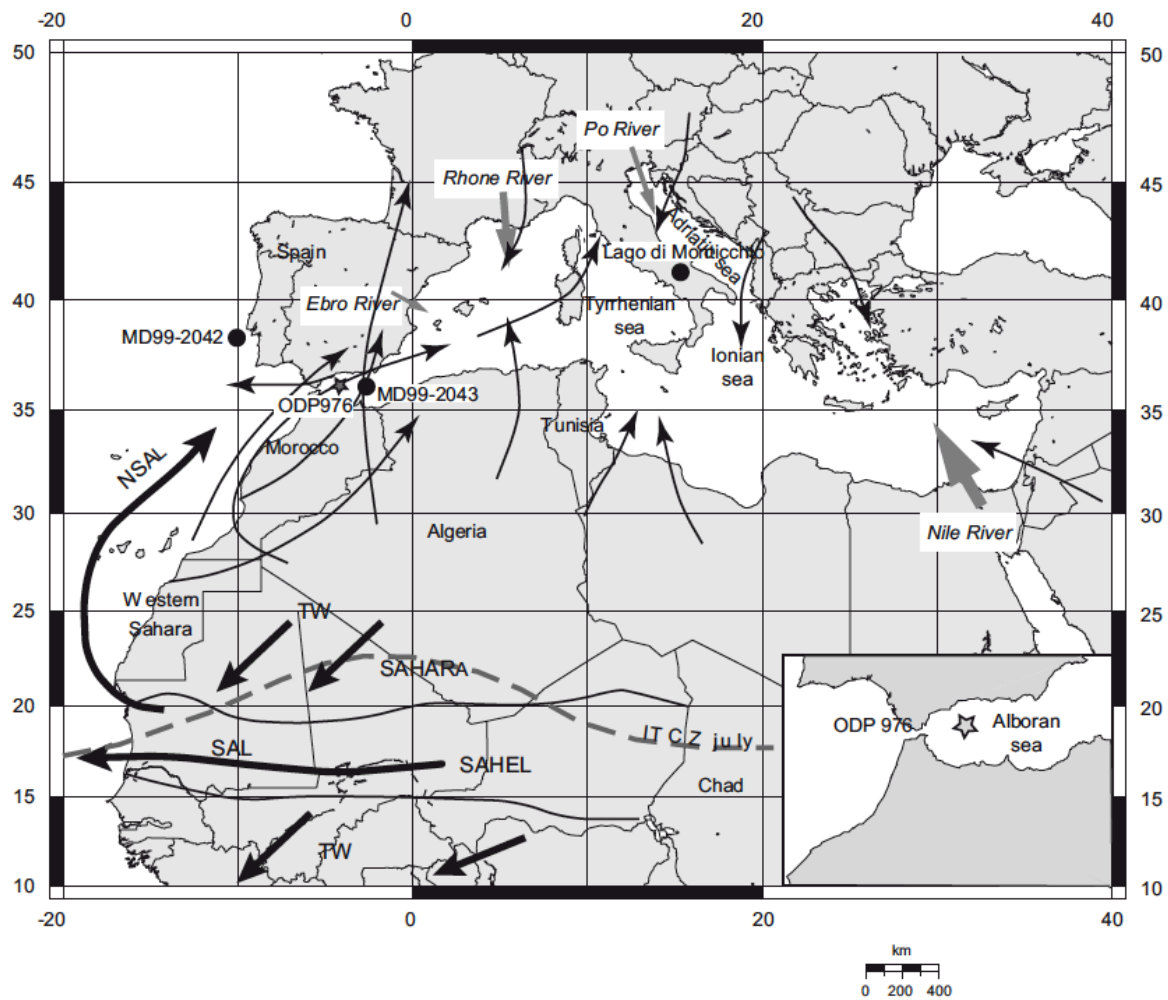
- 955 Singer, A., Galan, E., 1984. Palygorskite–Sepiolite. Occurrences, Genesis and Uses.
956 Developments in Sedimentology. Elsevier, Amsterdam.
- 957 Snoussi, M., Jouanneau, J.M., Latouche, C., 1990. Flux de matières issues des bassins
958 versants de zones semi-arides (bassin du Sebou et du Souss, Maroc). Importance dans le bilan
959 global des apports d’origine continentale parvenant à l’océan mondial. *Journal of African*
960 *Earth Sciences* 11 (1–2), 43–54.
- 961 Stanley, D.J., Warne, A.G., Davis, H.R., Bernasconi, S.M., Chen, Z., 1992. Nile delta.
962 *National Geographic Research Exploration* 8 (1), 22–51.
- 963 Tarasov, P.E., Cheddadi, R., Guiot, J., Bottema, S., Peyron, O., Belmonte, J., Ruiz-Sanchez,
964 V., Saasi, F., Brewer, S., 1998. A method to determine warm and cool steppe biomes from
965 pollen data: application to the Mediterranean and Kazakhstan regions. *Journal of Quaternary*
966 *Science* 13, 335–344.
- 967 Tomadin, L., 2000. Sedimentary fluxes and different dispersion mechanisms of the clay
968 sediments in the Adriatic basin. *Rendiconti Scienze Fisiche e Naturali Accademia Lincei* 9
969 (11), 161–174.
- 970 Tomadin, L., Lenaz, R., 1989. Eolian dust over the Mediterranean and their contribution to
971 the present sedimentation. In: Leinen, M., Sarnthein, M. (Eds.), *Paleoclimatology and*
972 *Paleometeorology: Modern and Past Patterns of Global Atmospheric Transport. Series C/*
973 *Mathematical and Physical Sciences*. Kluwer academic, Dordrecht, pp. 267–281.
- 974 Torres-Padrón, M.E., Gelado-Caballero, M.D., Collado-Sánchez, C., Siruela-Matos, V.F.,
975 Cardona-Castellano, P.J., Hernández-Brito, J.J., 2002. Variability of dust inputs to the
976 CANIGO zone. *Deep-Sea Research II* 49, 3455–3464.
- 977 Tzedakis, P.C., 2005. Towards an understanding of the response of southern European
978 vegetation to orbital and suborbital climate variability. *Quaternary Science Reviews* 24,
979 1585–1599.
- 980 Walter, W., Harnickell, E., Mueller-Dombois, D., 1975. *Climate-Diagram Maps*. Springer,
981 Berlin.
- 982 Washington, R., Todd, M.C., 2005. Atmospheric controls on mineral dust emission from the
983 BodéléDepression, Chad: the role of the low level jet. *Geophysical Research Letters* 32
984 (L17701).

985 Watts, W.A., Allen, J.R.M., Huntley, B., 1996. Vegetation history and palaeoclimate of the
986 last glacial period at Lago Grande di Monticchio, southern Italy. *Quaternary Science Reviews*
987 15, 133–153.

988

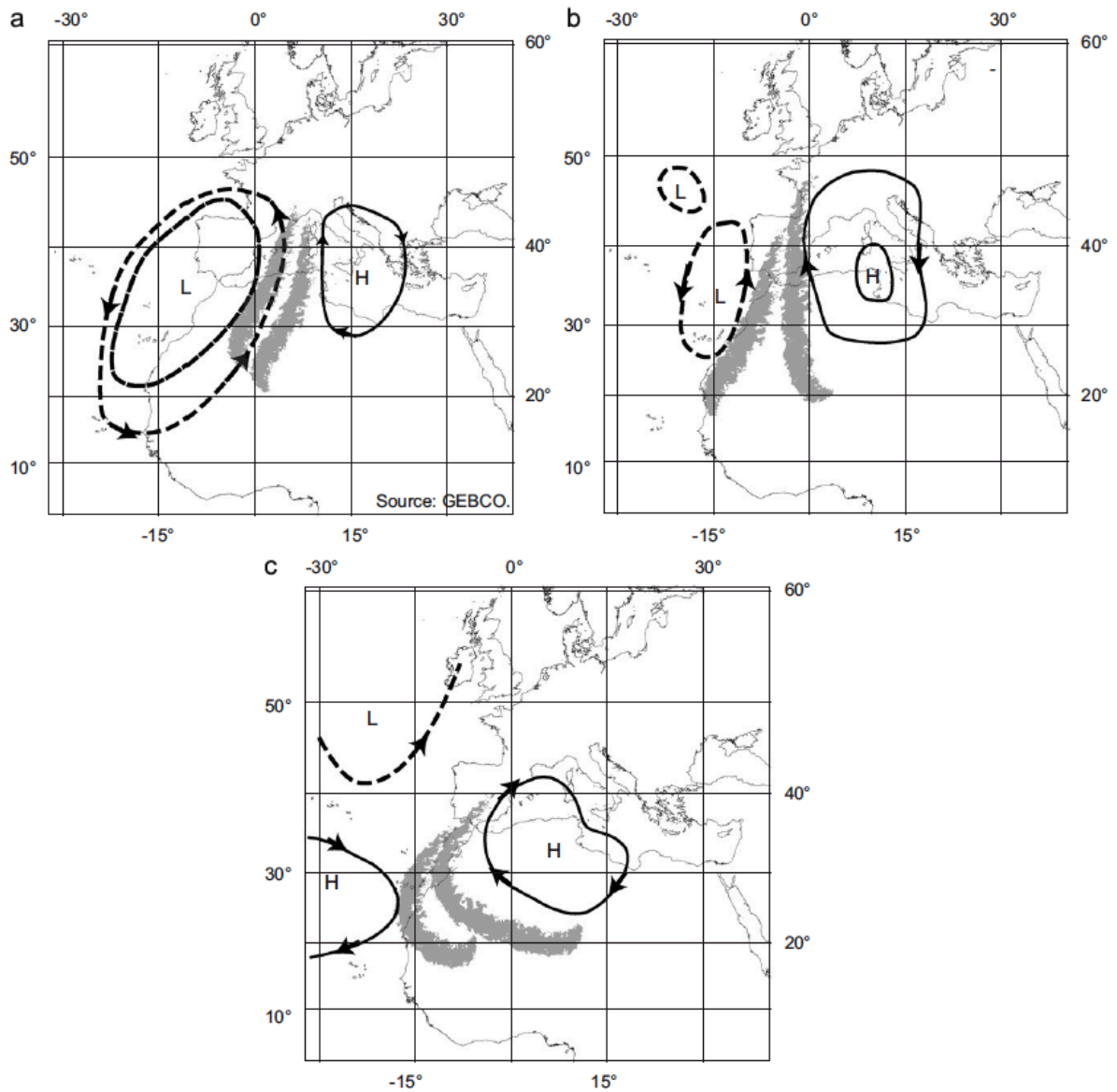
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990 **Figure captions**



991
 992 Fig. 1. Geographical settings. Main wind trajectories (black arrow) and rivers supply (gray
 993 arrow) in the Mediterranean area. The geographical boundary between Sahara and Sahel is
 994 reported. SAL: Saharan air layer, TW: northeast trade winds, NSAL: northern branch of the
 995 SAL, ITCZ July: position of the Inter-Tropical Convergence Zone in July.

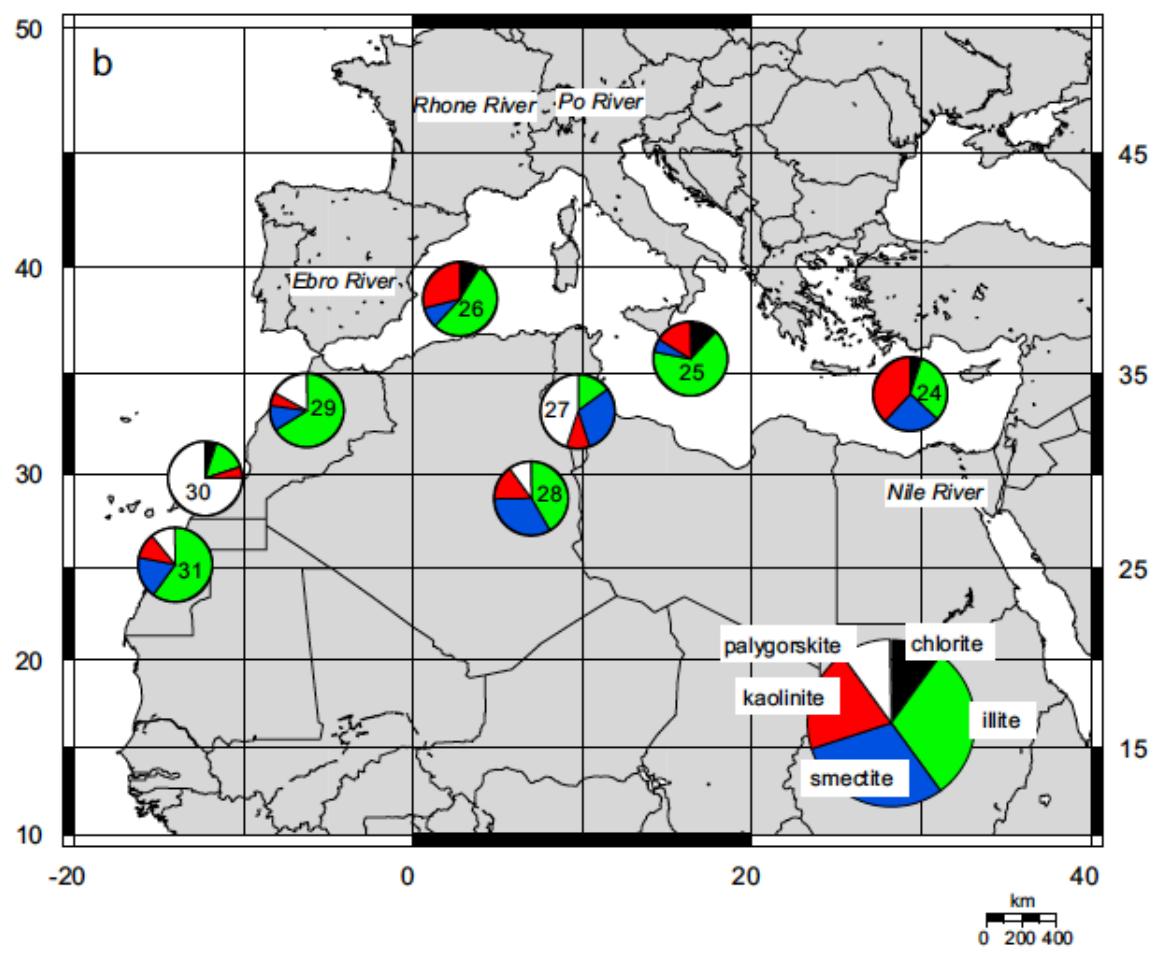
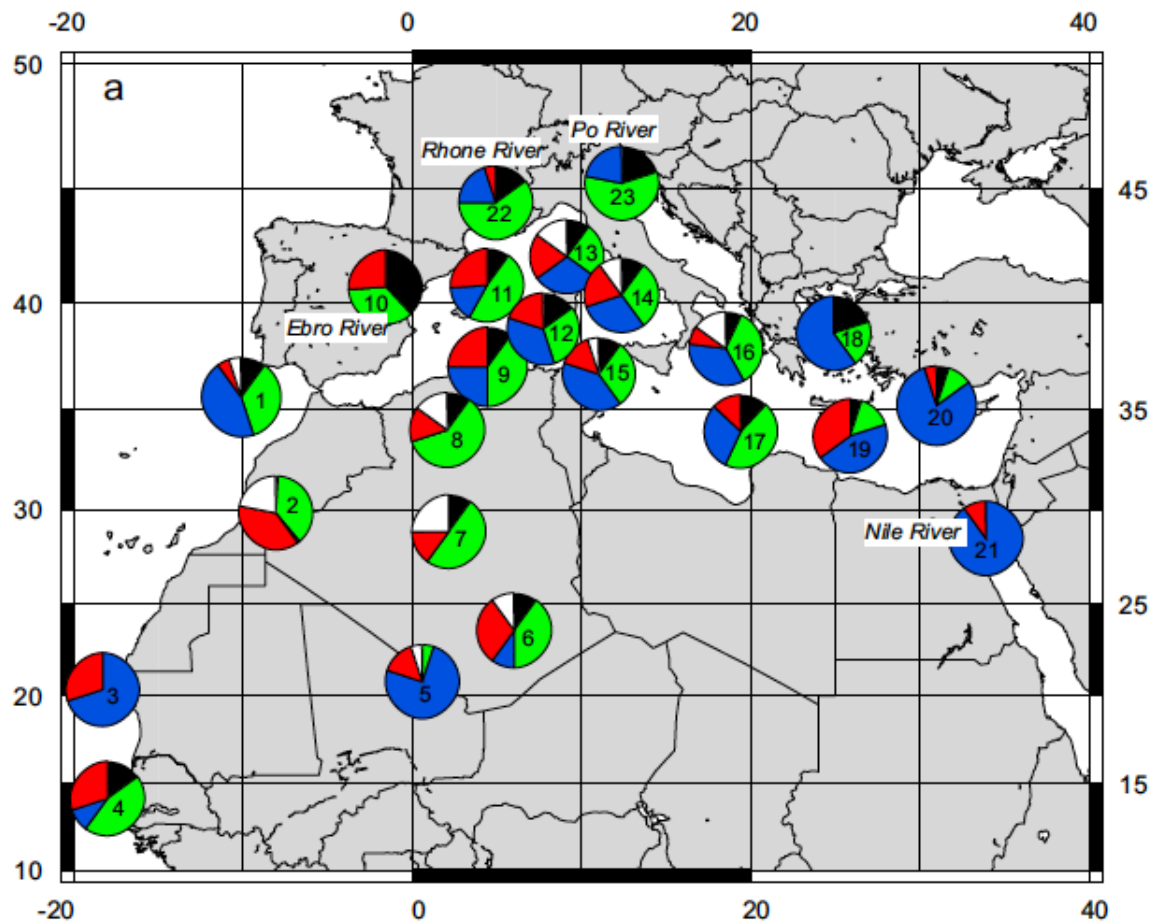
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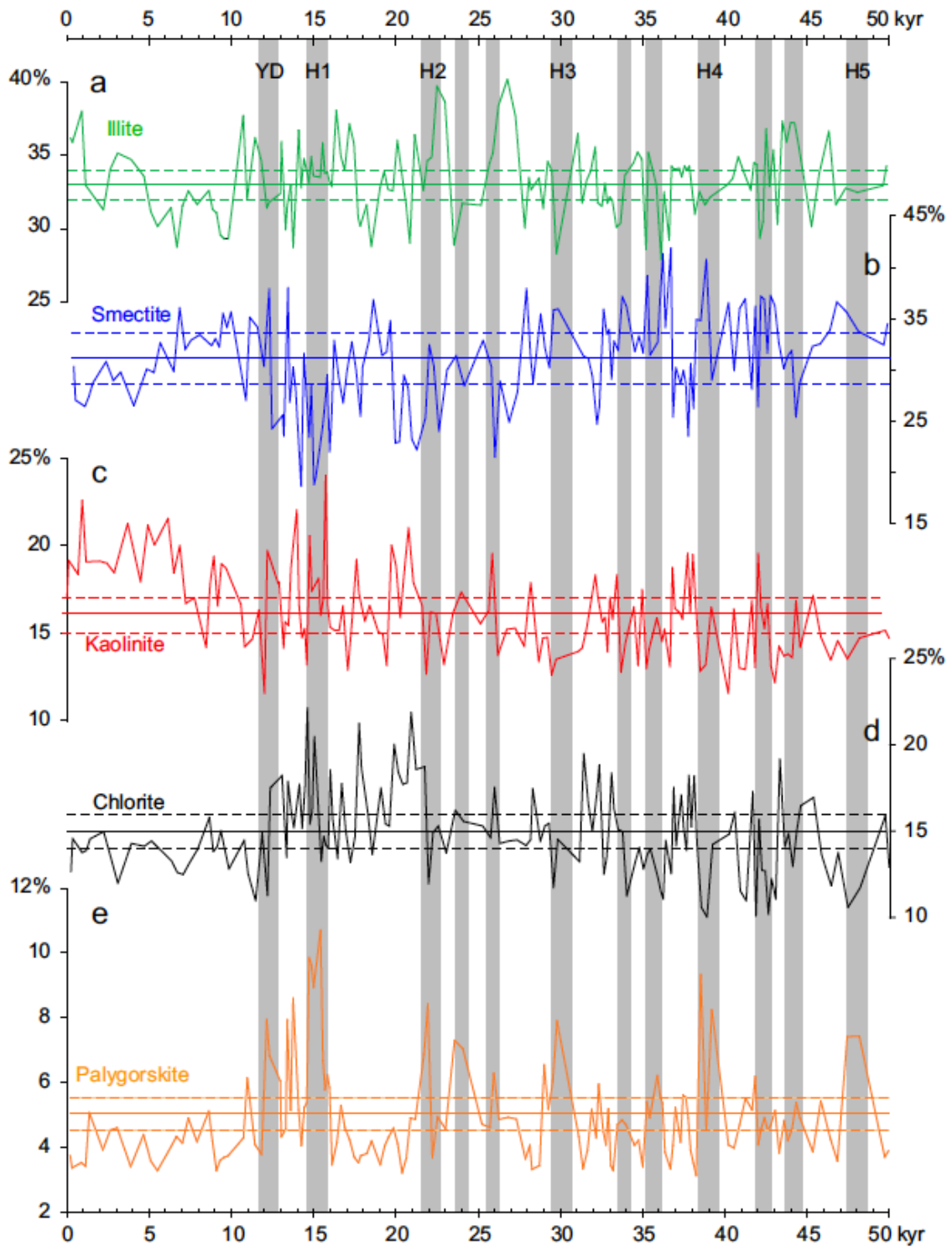
998 Fig. 2. Three main atmospheric configurations favouring the meridional transport of Saharan
 999 dust toward Europe during winter (a) strong low pressure (L) over the Iberian peninsula,
 1000 during fall (b) strong high pressure (H) over central Mediterranean combined with a low
 1001 pressure off Portugal, and during summer (c) strong low pressure over North Africa and
 1002 tropical Atlantic and low pressure over North Atlantic. Modified from (Coudé-Gaussen, 1982;
 1003 Rodríguez et al., 2001).

1004



1006 Fig. 3. Clay mineralogy of (a) peri-Mediterranean river particles and sediments (in %) and (b)
1007 dust and aerosols (Pastouret et al., 1978; Coudé-Gaussen, 1982; Paquet et al., 1984; Robert et
1008 al., 1984; Chamley, 1989; Alonso and Maldonado, 1990; Grousset et al., 1992; Avila et al.,
1009 1997; Guerzoni et al., 1999; El Mouden et al., 2005). 1: Gibraltar, 2: Morocco; 3: Cape blanc,
1010 4: Cape Verde, 5: Tanezrouft, 6: Tamanrasset, 7: In Salah, 8: northern Algeria, 9: Algerian
1011 shelf, 10: Ebro river, 11: western Mediterranean sediments, 12: Sardinia, 13: Corsica, 14:
1012 Tyrrhenian sea, 15: Malta, 16: Ionian sea, 17: central Mediterranean sediments, 18: eastern
1013 Mediterranean sediments, 19: Aegean sea, 20: Florence rise, 21: Nile river, 22: Rhone river,
1014 23: Po river, 24 eastern Mediterranean aerosols, 25: central Mediterranean aerosols, 26:
1015 western Mediterranean aerosols, 27: Tunisian loess, 28: dust from central Algeria, 29: dust
1016 from Moroccan Atlas, 30: Moroccan dust, 31: dust from central Sahara.

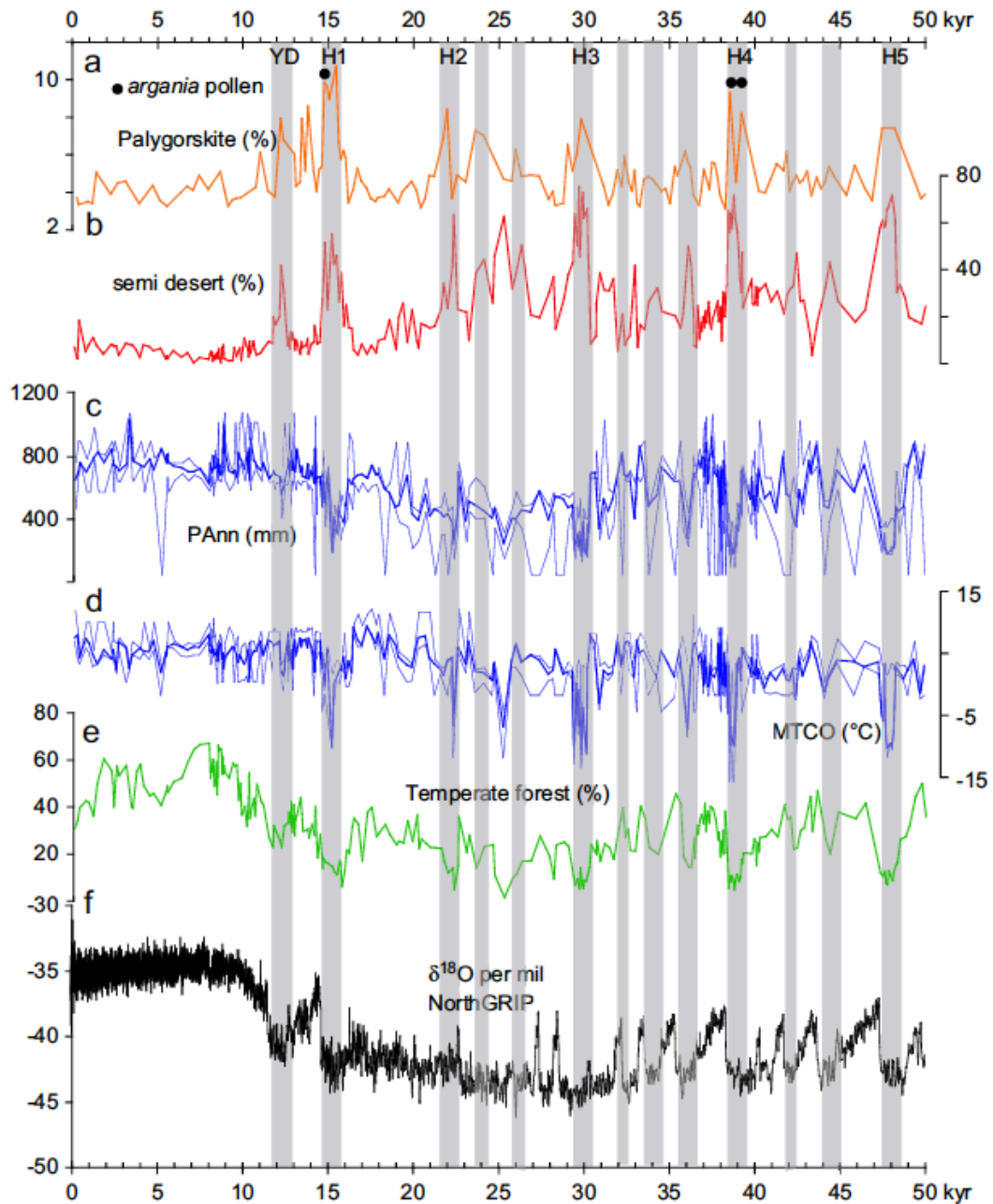
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1019 Fig. 4. Clay minerals variations (%) with time (ka): (a) illite, (b) smectite, (c) kaolinite, (d)
 1020 chlorite and (e) palygorskite. Time-slices corresponding to the Younger Dryas (YD) and to
 1021 Heinrich events 1 to 5 (H1 to H5) are delimited by gray rectangle.

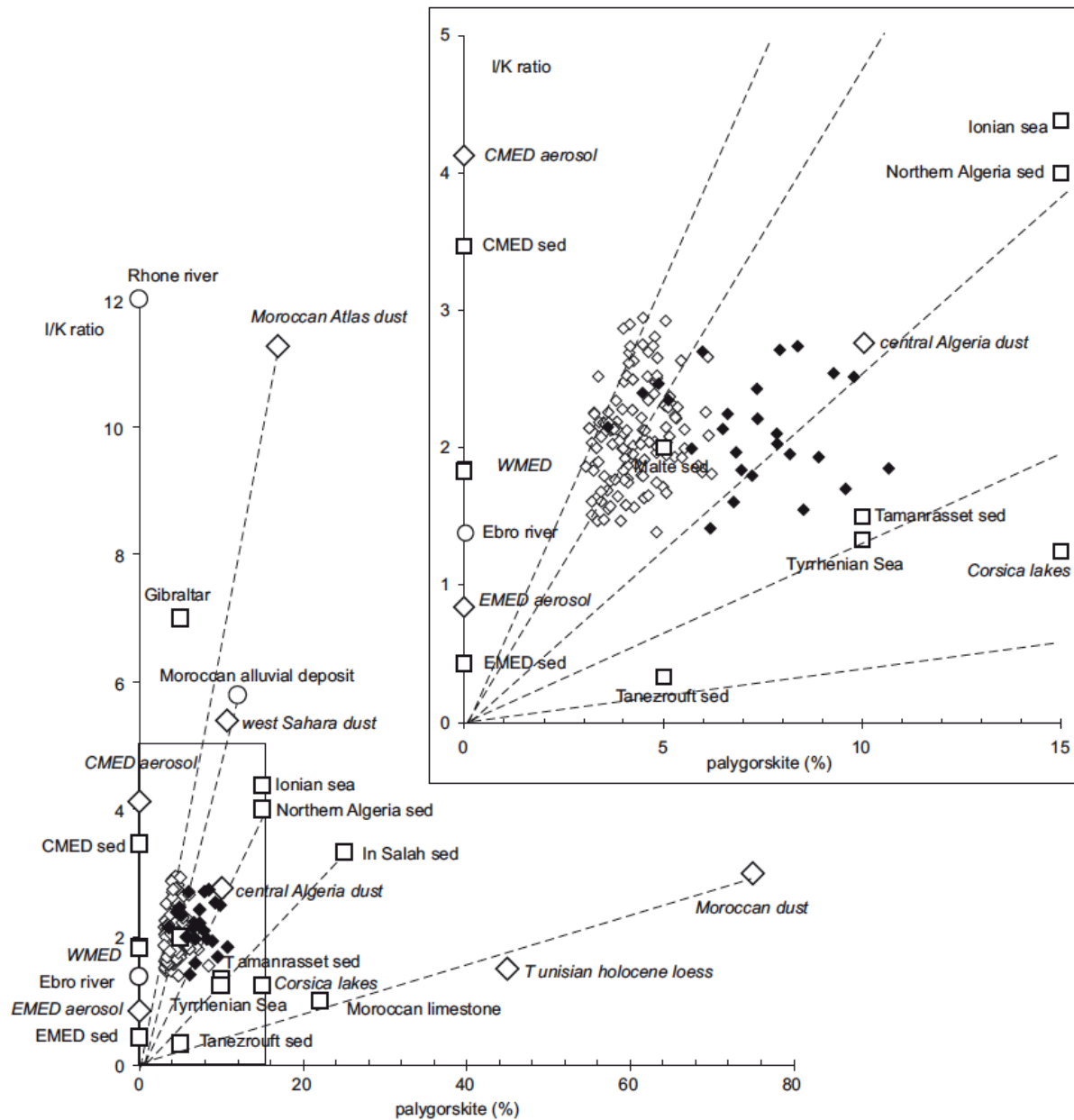
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1024 Fig. 5. (a) Palygorskite content (%), (b) semi-desert vegetation abundance (%), (c) annual
 1025 precipitation (PAnn in mm) and (d) mean temperature of the coldest month (MTCO) based on
 1026 the modern analog technique (see text for explanation) with sigma errors, (e) temperate pollen
 1027 (%) and (f) oxygen isotopic ratio at NorthGRIP (%). Time-slices corresponding to the
 1028 Younger Dryas (YD) and to Heinrich events 1 to 5 (H1 to H5) are delimited by gray
 1029 rectangle. A black circle marks the presence of *Argania* pollen.

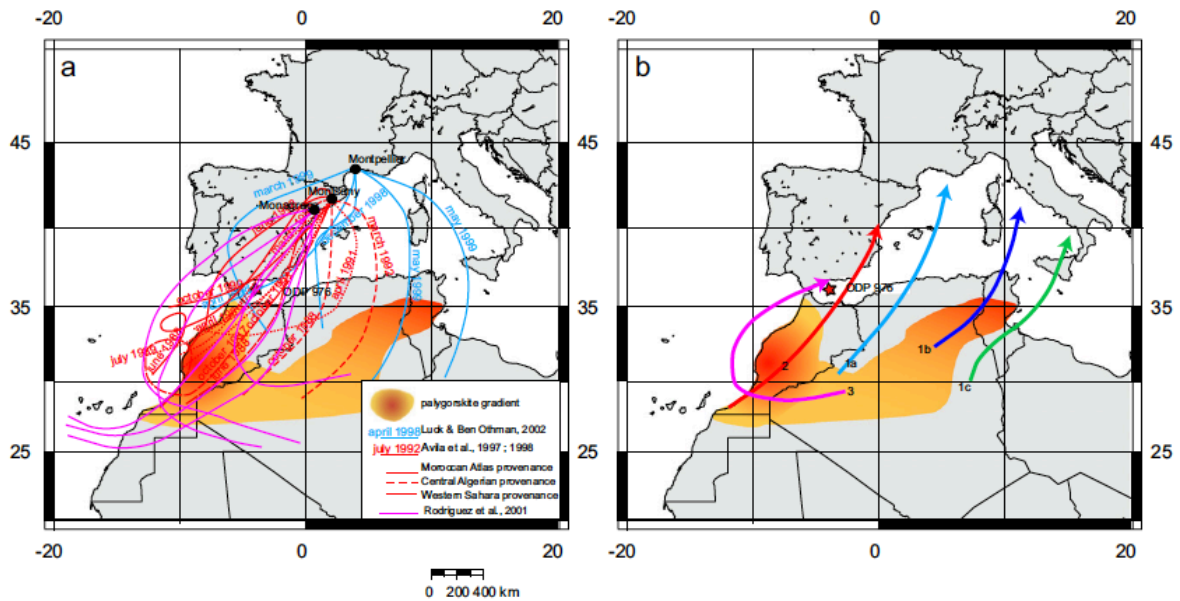
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1031

1032 Fig. 6. (a) Palygorskite content (%) versus illite-to-kaolinite ratio (I/K) of ODP 976 sediments
 1033 (diamonds) and of main end-members: rivers (circle), dust and aerosols (star), and sediments
 1034 (square). Black diamonds correspond to Younger Dryas and Heinrich events samples. Mixing
 1035 lines between end members are suggested (dotted lines), (b) enlarged view of (a). CMED:
 1036 central Mediterranean, EMED: eastern Mediterranean, WMED: western Mediterranean.

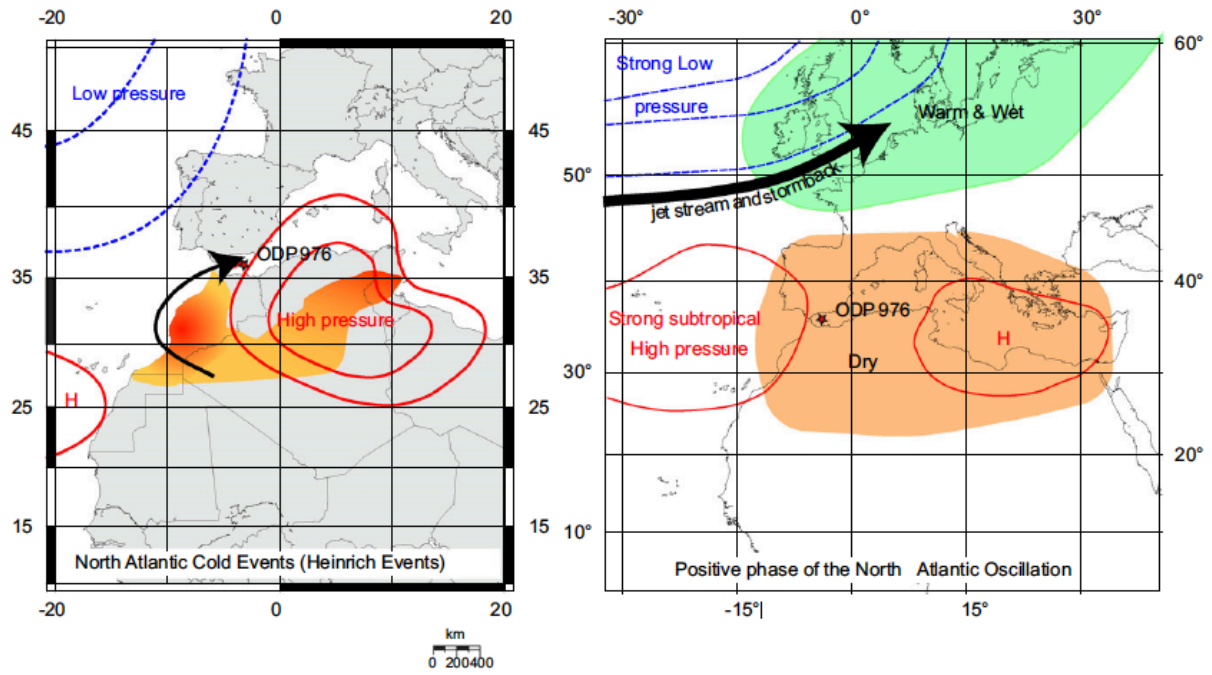
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1038

1039 Fig. 7. Main potential sources of palygorskite with gradient ranging from >25% (dark orange)
 1040 to 10% (light orange) and (a) main air masses trajectories for different dust events ending at
 1041 Montpellier, France (blue lines), Montseny station, Spain (red lines), and Monanegra station,
 1042 Spain (pink lines) with respect to their respective origin: thin dotted-line for Moroccan Atlas
 1043 provenance; medium dotted-line for central Algeria provenance and thick dotted-line for
 1044 western Sahara provenance (Avila et al., 1997; Rodríguez et al., 2001; Luck and Ben Othman,
 1045 2002), (b) main average dust trajectories reaching Europe.

1046



1047

1048 Fig. 8. Synoptic atmospheric configurations over the Mediterranean and the North Atlantic
 1049 Ocean (a) during the north Atlantic cold events and (b) associated with positive phase of the
 1050 North Atlantic Oscillation (Hurrell, 1995).