

1 **Early Pliocene climatic optimum, cooling and early glaciation deduced**
2 **by terrestrial and marine environmental changes in SW Spain**

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30

31 **Abstract**

32 The Pliocene is a key period in Earth's climate evolution, as it records the transition from
33 warm and stable conditions to the colder and more variable glaciated climate of the
34 Pleistocene. Simultaneously, climate became more seasonal in the Mediterranean area,
35 and Mediterranean-type seasonal precipitation rhythm with summer drought established.
36 These climatic changes presumably had significant impacts on terrestrial environments.
37 However, the response of terrestrial environments to such climate changes is still not fully
38 understood due to the lack of detailed studies dealing with this period of time. In this
39 study, multiproxy analyses of continuous core sampling from La Matilla (SW Spain)
40 shows detailed and continuous record of pollen, sand content and abundance of benthic
41 foraminifer *Bolivina spathulata* to describe paleoenvironmental and paleoclimate trends
42 during the early Pliocene. This record shows warmest, most humid climate conditions
43 and highest riverine nutrient supply at ~ 4.35 Ma, coinciding with the Pliocene climatic
44 optimum and high global sea level. A climate cooling and aridity trend occurred
45 subsequently and a significant glaciation occurred at ~ 4.1-4.0 Ma, during a period known
46 by very little terrestrial evidence of glaciation. Our multiproxy data thus indicate that
47 terrestrial and marine environments were significantly variable during the early Pliocene
48 and that major glaciation-like cooling occurred before the intensification of northern

49 hemisphere glaciation at the beginning of the Pleistocene (~2.7 Ma). This major climate
50 cooling and aridity maxima between 4.1-4.0 Ma is independently validated by a coeval
51 sea-level drop (third order Za_2 sequence boundary). This sea level drawdown is supported
52 by enhanced coarse sedimentation and minima in riverine nutrient supply, showing paired
53 vegetation and sea-level changes and thus a strong land-ocean relationship. This study
54 also shows that long-term climatic trends were interrupted by orbital-scale cyclic climatic
55 variability, with eccentricity, obliquity and precession acting as the main triggers
56 controlling climate and environmental change in the area.

57

58 **1. Introduction**

59

60 The early Pliocene (Zanclean stage; between 5.3 and 3.6 Ma) is a very interesting
61 period because it encompasses the so-called Pliocene climatic optimum (PCO) from 4.4
62 to 4 Ma, probably the warmest interval in this epoch with global average temperature ~
63 4 °C higher than today (Brierley and Fedorov, 2010; Fedorov et al., 2013). Carbon
64 dioxide reconstructions show higher-than-present values around 410 μatm (Bartoli et al.,
65 2011) and a global sea-level about 25 m higher than present (Miller et al., 2005).
66 Therefore, a great effort has been put into obtaining palaeoclimate records for the
67 Pliocene, as it is recognized as the most recent example of prolonged global warmth in a
68 higher-than-today CO_2 context in the geological past (Fedorov et al., 2013) and a very
69 good analog for future climate change (Robinson et al., 2008).

70 Marine isotopic records suggest that a climate cooling took place from the warmer
71 and more stable early Pliocene to the colder and more variable Pleistocene (Lisiecki and
72 Raymo, 2005). This gradual cooling was probably due to a decrease in atmospheric
73 carbon dioxide of about 100 parts per million (Bartoli et al., 2011). Even though the

74 Pliocene is thought to be a warmer period than today, a recent review by De Schepper et
75 al. (2014) shows evidences of significant glaciation events in both northern and southern
76 Hemispheres during this epoch. A progressive aridification in the Mediterranean area also
77 happened during the Pliocene (Fauquette et al., 1998; Popescu et al., 2010; Jiménez-
78 Moreno et al., 2013a), as well as the establishment of the Mediterranean-type seasonal
79 precipitation rhythm (summer drought) at ~ 3.4 Ma (Suc, 1984; Suc and Popescu, 2005;
80 Jiménez-Moreno et al., 2010). All these changes greatly affected past terrestrial
81 environments in the Mediterranean area and vegetation experienced a decrease and
82 disappearance of many thermophilous and hygrophilous species and the increase in
83 xerophytes and Mediterranean adapted taxa (Suc, 1984; Popescu et al., 2010). Very few
84 studies provide with information about how terrestrial western Mediterranean
85 environments reacted to such long- and short-term climatic changes (Suc, 1984; Bertini,
86 2001; Combourieu-Nebout et al., 2004; Jiménez-Moreno et al., 2010; 2013a). Therefore,
87 detailed pollen studies are needed to improve our knowledge about vegetation changes
88 and the main forcings triggering cyclical vegetation changes during the early Pliocene in
89 the Mediterranean area (i.e., Gauthier and Muñoz, 2009).

90 In the present study, we show a detailed and continuous record of pollen,
91 percentage of sand and abundance of the benthic foraminifer *Bolivina spathulata* from a
92 marine sedimentary record from the Guadalquivir Basin (SW Spain). This was done with
93 the main goal of describing long-term paleoenvironmental and paleoclimate trends during
94 the early Pliocene climatic optimum in the study area. This record shows that besides
95 long-term trends, climate was also characterized by cyclical variability (i.e., orbital
96 changes) that forced both terrestrial (e.g., vegetation changes of forested vs. open
97 vegetation) and marine (sedimentation, organic matter fluxes, sea-level) environmental
98 changes. The possible triggers of the observed orbital-scale variability are also discussed.

100 **2. Geological setting**

101

102 The study area is the western sector of the Guadalquivir Basin in SW Spain (Fig.
103 1A). This ENE-WSW-elongated foreland basin is limited to the north by the passive
104 Iberian Massif and to the south by the active Betic Cordillera (Braga et al., 2002;
105 González-Delgado et al., 2004). The Guadalquivir Basin has been linked to the isostatic
106 subsidence produced by the loading of the Betic units on the south Iberian margin during
107 the Neogene. By the earliest Tortonian, the Guadalquivir Basin was the Atlantic side of
108 the North Betic Strait, connecting the Atlantic Ocean and the Mediterranean Sea (Martín
109 et al., 2014; Braga et al., 2010). Afterwards, its paleogeography became an open and wide
110 Atlantic bay (Martín et al., 2009), mostly in absence of fault tectonics (Fernández et al.,
111 1998; Garcia-Castellanos et al., 2002), although subject to slow geodynamic vertical
112 motions related to the mantle dynamics under the Betic cordillera (Garcia-Castellanos et
113 al., 2002; Garcia-Castellanos & Villaseñor, 2011; Pérez-Asensio et al., 2018). During the
114 Pliocene, the coastline steadily migrated westwards (Sierro et al., 1996) due to the axial
115 sediment input together with the flexural isostatic response of the Betic-Guadalquivir-
116 Hercynian massif system. Flexural basculation towards the south, in combination with
117 the main sediment source being in the Betic cordillera, determined an axial (along-strike)
118 fluvial drainage running along the northern boundary of the sedimentary basin (Garcia-
119 Castellanos, 2002) as the Guadalquivir River does today. Sediments filling the
120 Guadalquivir Basin are organized in several marine and continental units ranging from
121 the Tortonian to the Holocene and the olistostromic deposits from the Betic Cordillera
122 (Riaza and Martínez del Olmo, 1996; Sierro et al., 1990, 1996; González-Delgado et al.,

123 2004; Salvany et al., 2011; Larrasoña et al., 2014; Aguirre et al., 2015; Rodríguez-
124 Ramírez et al., 2016).

125 Neogene sediments from the study area have been ascribed to eight marine and
126 continental lithostratigraphic units (Civis et al., 1987; Salvany et al., 2011) (Fig. 1). The
127 lowermost unit over the Iberian Massif basement is the Niebla formation (late Tortonian),
128 which is composed of coastal carbonate-siliciclastic deposits (Civis et al., 1987; Baceta
129 and Pendón, 1999). The second unit is the Gibraleón Formation (latest Tortonian-early
130 Pliocene) and includes greenish-bluish clays with glauconitic silts at its base (Civis et al.,
131 1987; Flores, 1987; Sierro et al., 1993; Pérez-Asensio et al., 2018). A Transitional Unit
132 (late Messinian-early Pliocene) comprising transitional facies with alternating silts and
133 sands is found over the Gibraleón Formation in central areas of the basin (De Torres,
134 1975; Mayoral and González, 1986–1987; Muñiz and Mayoral, 1996; Pérez-Asensio et
135 al., 2018). The third unit, the Huelva Formation (early Pliocene), consists of silts and
136 sands with a glauconitic layer at the base (Civis et al., 1987). The fourth unit is the sandy
137 Bonares Formation (early Pliocene) (Mayoral and Pendón, 1986-87). Four continental
138 units have been described above the marine units (Salvany et al., 2011). The Almonte
139 Formation (Upper Pliocene-Lower Pleistocene) is the first continental unit, and is
140 comprised of gravels and sands from proximal-alluvial deposits. Proximal sediments
141 from this unit are the so-called High Alluvial Level (Pendón and Rodríguez-Vidal, 1986–
142 1987; Salvany et al., 2011). The second continental unit is the Lebrija Formation (late
143 Pliocene-late Pleistocene), which includes sands, gravels and clays from distal-alluvial
144 deposits. The two last continental units (latest Pleistocene-Holocene) are the continental
145 Abalarío Formation and the continental-estuarine Marismas Formation. They consist of
146 eolian sands and alluvial-estuarine clays, respectively.

147

148 **3. Material and methods**

149 The 276-m-long La Matilla (LM) core was drilled in the vicinity of Mazagón
150 (Huelva) in the western Guadalquivir Basin (37°10'26.77''N, 6°43'27.14''W; 47 m
151 altitude; Fig. 1). The LM core, currently curated at the Geological and Mining Institute
152 of Spain (IGME) core repository, was drilled by IGME in 2006 using a rotary drilling rig
153 with continuous core sampling. The core description, including lithostratigraphy, facies
154 analysis and assignation of different units to the different formations outcropping in the
155 lower Guadalquivir Basin area, was previously done in Pérez-Asensio et al. (2018).

156 The LM core chronology was developed from a combination of biostratigraphy
157 and magnetostratigraphy (for a detailed explanation, see Pérez-Asensio et al., 2018; Fig.
158 2). Following the age model produced by these authors, the LM core contains a
159 continuous early Pliocene sedimentary record comprised between 4.50 and 3.95 Ma
160 (Pérez-Asensio et al., 2018; Fig. 2). The basinward migration of depositional facies in the
161 Guadalquivir Basin explains why stratigraphic formations classically attributed to the
162 Late Miocene in land sections (e.g., Gibráleón Formation) have an early Pliocene age at
163 the location of LM core (Pérez-Asensio et al., 2018). Age estimates for the studied
164 samples from the La Matilla core were assigned by assuming linear accumulation rates
165 between the age tie points provided by the paleomagnetic boundaries (the tops of chrons
166 C3n.2n, C3n.1r, and C3n.1n). For the lowermost part of the core (N1 polarity interval),
167 the sedimentation rate of the R1 polarity interval (42.9 cm/ka) was extrapolated
168 downward (Fig. 2). In the upper part of the core (R2 and an interval of uncertain polarity),
169 the sedimentation rate of the R2 polarity interval (49.9 cm/ka) was extrapolated upward
170 (Fig. 2). This resulted in an age of 3.95 Ma for the end of marine sedimentation (Fig. 2).

171 The percentage of sand content in the different facies along the 3 studied marine
172 units (Fig. 2) was calculated every 3 m (83 samples) dividing the weight of the sand
173 fraction (>63 μm) by the total sample weight (50 g) and multiplying by 100.

174 Samples (2 cm^3) for palynological analyses were taken roughly every 5 m
175 throughout the core, with a total of 52 samples analyzed. The palynomorph extraction
176 method followed a modified Faegri and Iversen (1989) methodology. Counting was
177 performed at x400 and x1000 magnifications to a minimum pollen sum of 300 terrestrial
178 pollen grains. Fossil pollen was compared with present-day relatives using published keys
179 (e.g., Beug, 1961) and a modern pollen reference collection at the University of Granada
180 (Spain). The raw counts were transformed to pollen percentages based on the terrestrial
181 sum excluding *Pinus* - usually overrepresented in marine environments because of the
182 advantage of bisaccate pollen for long-distance transport (Heusser, 1988; Jiménez-
183 Moreno et al., 2005). The pollen zonation of the detailed pollen diagram was
184 accomplished using CONISS (Grimm, 1987; Fig. 3). Arboreal Pollen (AP) abundance
185 was calculated based on the total pollen sum with and without *Pinus*. Furthermore, pollen
186 taxa were grouped, according to present-day ecological bases, into thermophilous
187 (subtropical) trees. The thermophilous tree group includes Arecaeae, Taxodioideae,
188 Rutaceae, Euphorbiaceae, *Cissus*, *Prosopis*, *Engelhardia* and Sapotaceae. An AP/arid
189 ratio was calculated in order to discriminate between warm/humid (i.e.,
190 interglacial/interstadial phases) and cold/arid (i.e., glacial/stadial phases). As arid taxa,
191 we included *Artemisia*, *Ephedra*, *Lygeum* and Asteraceae total (Cichorioideae and
192 Asteroideae). Dinoflagellate cysts (dinocysts) occur with the pollen in the studied
193 samples but at very low occurrences, which precluded their statistical study.

194 Principal Components Analysis (PCA) using PAST version 3.24 (Hammer et al.,
195 2001) was run on the most abundant pollen taxa time series (Fig. 4). This was done to

196 find hypothetical variables (components; i.e., environmental or climate parameters)
197 accounting for as much as possible of the variance in the pollen data. A PCA correlation
198 scatter diagram is shown in Fig. 4. This diagram shows to what degree the different taxa
199 correlate with the principal component 1 (PC1) and 2 (PC2). PC1 data time series is
200 represented in Figures 4B and 5.

201 A cyclostratigraphic analysis was performed on the *Quercus* and AP raw pollen
202 percentages and PC1 pollen time series from the LM sedimentary sequence (Fig. 6). We
203 used the software PAST (Hammer et al., 2001) with the program REDFIT (Schulz and
204 Mudelsee, 2002) with the objective of characterizing the different periodicities present in
205 the unevenly spaced raw pollen data.

206 A total of 83 samples of 50 g were analyzed for benthic foraminifera. At least 300
207 benthic foraminifera from the size fraction $>125 \mu\text{m}$ were counted and identified. The
208 relative abundances (%) of the benthic foraminifer *Bolivina spathulata* (Fig. 7) were
209 obtained from transforming the raw counts of this species into percentages. Higher
210 abundances of this shallow infaunal species were used as proxy for higher organic matter
211 fluxes linked to riverine discharge (Duchemin et al., 2008; Schmiedl et al., 2010; Pérez-
212 Asensio et al., 2014).

213

214 **4. Results**

215

216 *4.1. Sand content*

217 Sand content of the marine units of the LM sediment core shows an overall increasing
218 trend towards the top of the core and varies from 0.2 (255 m; 4.44 Ma) to 93.4 % (48 m;
219 4.01 Ma) (Fig. 2). Very low sand % values (lower than 10%) characterize the core bottom,
220 from 275 (4.49 Ma) to 150 m (4.21 Ma). Sand % increases in three cyclical increasing-

221 decreasing cycles since then, with peaks of 14, 20 and 33% at 147 (4.21 Ma), 132 (4.18
222 Ma) and 114 m (4.14 Ma), respectively. Minimum values (<5%) are reached again
223 between 102-96 m (4.12-4.10 Ma). An increase in sand % is observed later on, with a
224 maximum of 68% at 81 m (4.07 Ma). Sand values decreased after this peak, and another
225 minimum of ~20% is recorded at 78-75 m (4.07-4.06 Ma). A substantial increase is
226 observed then with a peak of ~80% recorded at 60 m (4.03 Ma). A relative minimum of
227 58% is recorded at 57 m (4.02 Ma). Another increase-decrease cyclical oscillation is
228 observed between 57 and 39 m (4.02-3.99 Ma), with a maximum in sand of 93% recorded
229 at 48 m (4.01 Ma) and another drop in the sand values at 39 m (3.99 Ma). An increase in
230 sand % with values around 70% characterize the record between 36-33 m (3.987-3.985
231 Ma).

232

233 *4.2. Pollen analysis*

234 Seventy-three different pollen taxa have been identified in the LM sedimentary record
235 pollen spectra. The record shows diverse pollen taxa. However, many of the identified
236 taxa occur in percentages lower than 1% and have not been plotted in Figure 3. These
237 rare species include thermophilous (subtropical) plants such as *Arecaceae*, *Taxodioideae*,
238 *Rutaceae*, *Euphorbiaceae*, *Cissus*, *Prosopis*, *Engelhardia* and *Sapotaceae*. Temperate tree
239 species are also diversified, but many of them occur in very low percentages (i.e., *Acer*,
240 *Castanea-Castanopsis* type, *Rhus*, *Pterocarya*, *Carya*, *Juglans*, *Corylus*, *Liquidambar*,
241 *Distylium*, *Lonicera*, *Hedera* and *Ulmus*), except for *Quercus* (see below).

242 Overall, the LM core pollen record shows high abundances of non-arboreal pollen
243 (NAP) (i.e., herbs and grasses), with average abundances around 75%. NAP pollen is
244 dominated by *Asteraceae Cichorioideae*, *Asteraceae Asteroideae*, *Poaceae* and
245 *Amaranthaceae*, and in smaller abundances, *Plantago*, *Apiaceae*, *Cistaceae*, *Ephedra*,

246 *Artemisia* and Liliaceae. With respect to the AP, taxa are dominated by *Pinus* varying
247 around average values of 26%. Less abundant trees are mostly dominated by evergreen
248 and deciduous *Quercus*, *Olea*, Cupressaceae, *Cedrus* and *Cathaya*. Aquatics such as
249 Cyperaceae also occur in this record but in low average abundances around 1%. We used
250 variations in pollen species to objectively zone the pollen data using the program CONISS
251 (Grimm, 1987), producing three pollen zones for the LM record (Fig. 3). The pollen
252 results in these zones are described below:

253 Pollen zone LM-1 (267 – 250 m, 4.47 – 4.43 Ma) is characterized by high NAP
254 percentage, with high abundance of Asteraceae Cichorioideae of around 40%, Poaceae
255 around 22% and Asteraceae Asteroideae around 10%.

256 Pollen zone LM-2 (250 – 105 m, 4.43 – 4.12 Ma) features a significant decrease in
257 NAP and the highest percentages of AP, which shows many cyclical oscillations and
258 several peaks above 45%. This zone is then characterized by the highest occurrences in
259 *Quercus* total (evergreen and deciduous) of 23% at the beginning of this zone at 216 m
260 (~4.35 Ma). *Pinus* and *Quercus* total stay relatively abundant but show a decreasing trend
261 throughout this zone. *Olea*, *Cathaya* and *Cedrus* occur in this zone with discrete
262 occurrences.

263 Pollen zone LM-3 (105 – 30 m, 4.12 – 3.97 Ma) is characterized by the decrease in
264 AP (notably in *Pinus* and *Quercus* but also in *Cathaya* and *Cedrus*) and the highest values
265 of NAP of the LM record, with two maxima centered at ~100 and 50 m (4.1 and 4.0 Ma).
266 *Olea* and Cupressaceae also increased and show maxima in this zone, featuring an
267 increasing trend interrupted by two cyclical oscillations.

268 PCA analysis on a selection of most abundant pollen taxa from the LM record shows
269 two main groups of distinctive taxa (Fig. 4A). PC1+ group, characterized by positive
270 correlation to PC1, is made up of the most abundant tree taxa such as *Pinus*, *Quercus*

271 (both evergreen and deciduous), *Cathaya*, *Cedrus* and the halophytic herb
272 Amaranthaceae. PC1- group is characterized by negative correlation to PC1 and is
273 dominated by non-arboreal species, such as Asteraceae Cichorioideae, Asteraceae
274 Asteroideae, Poaceae, *Ephedra*, and Mediterranean-adapted tree species *Olea* and
275 Cupressaceae. PCA analysis indicates that PC1 (probably a combination of temperature
276 and precipitation, see below) is strong, explaining the 44.12% of the variance. Pollen data
277 and CONISS cluster analysis agree with the PC1 (correlation of PC1 with AP: $r=0.92$;
278 $p<0.01$; PC1 with *Quercus* total $r=0.48$; $p<0.01$) and pollen zones LM-1 and LM-3 are
279 characterized by low abundances in the PC1+ pollen group and zone LM-2 is
280 characterized by the highest values in the PC1+ (Fig. 4B).

281

282 4.3. Periodicity of pollen changes

283 Pollen data show a very clear cyclical pattern in the relative abundance of many taxa
284 such as *Quercus* (Fig. 3). The PC1 is also characterized by cyclical oscillations, which
285 covary with those observed in the raw *Quercus*, AP, thermophilous and AP/arid ratios
286 (Figs. 4B, 5; see discussion below). Spectral analysis on the *Quercus* and AP pollen data
287 and PC1 shows statistically significant (above the 80 and 90% confidence level) spectral
288 peaks with periodicities between 80 - 67, 51 - 44, 37, 30 and 22-21 ka (Fig. 6).

289

290 4.4. Benthic foraminifer *Bolivina spathulata*

291 Relative abundance (%) of *Bolivina spathulata* changes considerably throughout the
292 studied sediment core and varies from 0 to 50% (Fig. 7). The bottom part of the record
293 between 273 – 240 m (4.49 – 4.41 Ma) is characterized by low values around 10%. An
294 increase is observed then, reaching the maximum value of the record (~48%) at 213 m
295 (4.35 Ma). A decreasing trend is observed since then, interrupted by cyclical variability,

296 reaching several minima and the occasional absence of this species between 100 and the
297 top of the record (since 4.12 Ma).

298

299 **5. Discussion**

300

301 *5.1. Vegetation, benthic foraminifera and sedimentation as paleoenvironmental and* 302 *paleoclimate proxies*

303 Pollen analysis on Miocene and Pliocene marine sedimentary sequences from the
304 Iberian Peninsula area have shown the highly sensitive response of pollen records to
305 climate change, recording vegetation changes related to long-term and short-term orbital-
306 scale climate variability (Jiménez-Moreno et al., 2007; 2010; 2013b). These previous
307 studies show that the abundance of thermophilous forest species such as subtropical and
308 temperate taxa can be used to track temperature changes through time. Hygrophilous
309 species can also be used as proxies for precipitation, although sometimes it is difficult to
310 separate the temperature vs. precipitation signals, for certain species require both high
311 temperature and precipitation (or the opposite) to thrive. In this study we also used
312 present-day thermophilous (i.e., subtropical) and temperate adapted species as proxies for
313 temperature (Fig. 5). In this respect, *Quercus* (both evergreen and deciduous species)
314 abundance has been shown to be an excellent proxy recording warm-humid vs. cold-arid
315 (e.g., interglacials vs. glacials) paleoclimate phases in the southern Iberian Peninsula
316 (Combourieu-Nebout et al 2002; Jiménez-Moreno et al., 2013b; Camuera et al., 2018,
317 2019). AP abundance can be used as a proxy for precipitation, for forested species require
318 more water availability to grow than NAP taxa (Faegri and Iversen, 1987; Herzschuh,
319 2007). Here we added the arid indicators (*Artemisia*, *Ephedra* and Asteraceae total) to the
320 forested humid/non-forested arid equation, calculating an AP/arid ratio as a better proxy

321 for precipitation. The observed covariation between the PC1 with the above mentioned
322 proxies for temperature and precipitation also indicate that increases in PC1 are related
323 to warm/humid periods (Fig. 5). We are unsure about how to interpret the climatic
324 inference of the herb Amarathaceae in this pollen record. Statistically it seems to be
325 associated with the tree-dominated PC1+ group, however, in zone LM-02 it also shows a
326 timid and progressive increasing trend, covarying at that time with the aridity proxies so
327 it looks like it might be a mixed signal.

328 *Bolivina spathulata* abundance can be used as a proxy for organic matter fluxes
329 related with high freshwater riverine input (Duchemin et al., 2008; Schmiedl et al., 2010).
330 This species can tolerate low-oxygen conditions and prefer environments with supply of
331 terrestrial degraded organic matter related to river runoff (Barmawidjaja et al., 1992;
332 Stefanelli, 2004; Duchemin et al., 2008; Schmiedl et al., 2010) (Fig. 7). Previous studies
333 showed high abundance of *B. spathulata* during interglacial-like periods, characterized
334 by high riverine discharge bringing nutrients into the ocean (Pérez-Asensio et al., 2014).

335 Lithological changes (i.e., sand content) of the LM sedimentary core can be used as a
336 proxy for relative sea-level oscillations controlling the proximity to coast of the studied
337 site and thus the amount of coarse detritic input from the continent (Fig. 7).

338

339 5.2. Climate change recorded in the LM core during the early Pliocene

340

341 High abundances of NAP in the pollen spectra from LM indicate overall open
342 vegetation environments and arid conditions during the early Pliocene in the studied area.
343 The occurrence of herbaceous subdesertic taxa such as *Lygeum*, supports this
344 interpretation. Occurrences of subtropical species also point to a warm subtropical
345 climate. Climate was warmer than today, which is indicated by the higher occurrence of

346 thermophilous taxa currently living in warmer areas of North Africa (Suc et al., 1995).
347 This agrees with previous studies from the area for the early Pliocene, which show similar
348 vegetation and climate estimations of mean annual temperatures around 21°C and mean
349 annual precipitation of ~400-600 mm (Andalucía G1 site; Jiménez-Moreno et al., 2010).
350 A mosaic of different plant associations inherited from the Miocene and organized in
351 altitudinal belts characterized the vegetation at that time. Subtropical evergreen-
352 deciduous species lived at low elevations, an open mixed deciduous forest (mainly made
353 up of conifers like *Pinus*, and several deciduous trees such as *Quercus*), occurred at higher
354 altitude, and conifers such as *Cathaya* and *Cedrus* grew at higher elevations on the
355 surrounding mountains.

356 Significant long-term changes in climate are observed during the early Pliocene
357 between 4.5 and 3.9 Ma in the SW Guadalquivir Basin region. This is deduced by changes
358 in the terrestrial vegetation that parallel marine benthic fauna and sedimentary variations
359 in the LM core (Fig. 7). The beginning of the studied record (including LM-1 pollen zone)
360 at around 4.45 Ma begins with overall cold and arid climate conditions. Relatively low
361 organic matter fluxes (low *B. spathulata* abundances) is also recorded at that time,
362 indicating low riverine runoff, which further support aridity at that time. This
363 interpretation agrees with climate inferences obtained from previous palynological
364 studies showing a cooling event at ~4.5 Ma, in the marine pollen record from the
365 Andalucía G1 site (Suc et al., 1995), located offshore of S Iberia and 300 km SE of LM,
366 and in the marine pollen record from the Garraf 1 site in NE Iberian Peninsula (Suc and
367 Cravatte, 1982). Globally, this time period corresponds with relatively low sea level, right
368 after the Za1 minimum sea-level sequence boundary (Handerbol et al., 1998), which
369 would agree with cold conditions during a period of eccentricity minima (Laskar et al.,
370 2004; Fig. 8).

371 Rapid warming and enhanced humid conditions occurred after ~4.37 Ma, and
372 warmest and wettest conditions in the vicinity of the LM record were reached at around
373 4.35 Ma. (Figs. 7 and 8). This is deduced by the highest occurrences in *Quercus* total,
374 thermophilous and AP/arid ratios of the LM record (Fig. 5). Conifers requiring relatively
375 high humidity such as *Cedrus* and *Cathaya* reached their maxima around that time (Fig.
376 3), supporting highest humidity. Highest *B. spathulata* abundances are also recorded at
377 4.35 Ma in the LM record (Fig. 7), indicating highest fluvial runoff supplying continental
378 degraded organic matter. Warmest conditions at that time are supported by low global ice
379 volume deduced by global isotopic composition of benthic foraminifera (perhaps the CN3
380 isotopic event; Lisiecki and Raymo, 2005), and high insolation and eccentricity,
381 coinciding with the early Pliocene climatic optimum and high global sea level (Fig. 8).
382 Warmest conditions at this time are also recorded regionally in other pollen records from
383 the Mediterranean area such as the marine sedimentary sequences of Cap d'Adge 1 and
384 Pichegu (Suc et al., 2018).

385 Overall, warm and humid conditions prevailed after this warmest maximum during
386 pollen zone LM-02 until 4.13 Ma. However, a progressive climate cooling and aridity
387 trend interrupted by cyclic climatic variability also characterized the LM record (Fig. 8).
388 This is deduced by the progressive decrease in abundance of *Quercus*, thermophilous,
389 high AP/arid ratios and PC1 (Fig. 5). Riverine nutrient supply deduced from the LM
390 record covaried with the vegetation also featuring a significant decreasing trend at that
391 time (Fig. 7). This indicates a progressive decrease in riverine runoff with a decaying
392 supply in degraded organic matter from the continent into the marine environment, which
393 agrees with the increasing trend in aridity. This environmental change observed in the
394 LM record could be related with the cooling trend and increase in global ice volume
395 deduced by the increase in the global isotopic $\delta^{18}\text{O}$ stack record (Lisiecki and Raymo,

396 2005), perhaps related with a decrease in eccentricity and its modulating effect in summer
397 insolation (Laskar et al., 2004) (Fig. 8). A progressive increase in sand content occurred
398 in the LM record between 4.21 and 4.14 Ma (Fig. 7). This could be due to a sea-level
399 glacio-eustatic lowering due to the progressive cooling, generating enhanced influence of
400 coarse terrestrial sedimentation due to closeness to coast. West-southwestward
401 progradation of terrigenous depositional systems along the axial part of the Guadalquivir
402 Basin and also from North-east (passive border), filling up the basin, would account for
403 the important increase in coarser detritics and sedimentary rates in a context of sea-level
404 lowering in this area, as deduced by previous studies (Sierro et al., 1996; Pérez-Asensio
405 et al., 2018; Jiménez-Moreno et al., 2013b). This gradual filling could have been
406 accelerated in a context of eustatic sea level lowering with the subsequent decrease in
407 accommodation space in the Guadalquivir basin.

408 This cooling trend ended with significant glaciation-like cold and arid events that
409 affected the terrestrial environments in the study area at ~ 4.1 and 4.0 Ma (LM-03 pollen
410 zone) (Fig. 8). Coldest/driest conditions at this time are deduced by lowest *Quercus*,
411 AP/arid and PC1 values (Fig. 5). Similar very low percentages (<5%) in *Quercus* forest
412 were reached during the last two glaciations (ca. 20 and 140 ka) in the southern Iberian
413 Peninsula (Camuera et al., 2019), supporting our climatic interpretations. Related with
414 this major climate cooling and aridity maxima, was enhanced coarse sedimentation and
415 minima in organic matter fluxes to the seafloor due to low riverine discharge, showing
416 paired vegetation and sea-level changes and a strong land-ocean relationship (Fig. 7).
417 Coldest/driest conditions of the LM record could be related to significant glaciation
418 events recorded in the marine isotopic records of benthic $\delta^{18}\text{O}$ Gi24-20 (Lisiecki and
419 Raymo, 2005) and minima in eccentricity (Fig. 8). The glacio-eustatic sea-level drop
420 associated with this especially cold glacial period was recorded globally as a third order

421 (Za2) sequence boundary (Fig. 8; Handebol et al., 1998), affecting our study site with a
422 significant regression, increasing its proximity to the coast and enhancing coarse
423 sedimentation (Fig. 7). The evidences of glacial-like conditions between 4.1-4.0 Ma in
424 the LM area are supported by a recent review about climate variability during the Pliocene
425 by De Schepper et al. (2014), who show evidences of a significant glaciation event in
426 both northern and southern Hemispheres at around 4.0 Ma. This glacial-like climatic
427 event occurred during the early Pliocene climatic optimum, a period known by very little
428 terrestrial evidence of glaciation, and indicates that major glaciation-like cooling occurred
429 before the intensification of northern hemisphere glaciation at the beginning of the
430 Pleistocene (~2.7 Ma; Lisiecki and Raymo, 2005). This cooling trend and associated
431 glacio-eustatic sea-level lowering might have contributed to the final continentalization
432 of the study area that occurred at about 30 m core depth in the LM sediment core (Almonte
433 and Abalario Fm.; Fig. 1). A previously mentioned cause that could have triggered
434 enhanced cooling and glaciation at this time in the Northern Hemisphere is the
435 constriction of the Indonesian Seaway between 4-3 Ma, generating a weakening of the
436 Atlantic Meridional Overturning Circulation, which regulates climate in the area (Karas
437 et al., 2017).

438 An increase in climate seasonality (i.e., summer drought) seems to have affected the
439 terrestrial environments in the study area since 4.12 Ma and related with the above
440 mentioned significant glacial event. This is deduced by the increasing trend in *Olea*, a
441 typical Mediterranean and summer-drought-adapted sclerophyllous taxon, from 4.12 Ma
442 towards the top of the LM record at 3.97 Ma (Fig. 7). Previous studies noticed a major
443 reduction in subtropical taxa and an increase in sclerophyllous vegetation during the late
444 Pliocene at around 3.4-3.2 Ma, which they interpreted as the effect on the vegetation of
445 the onset of the Mediterranean-type seasonal precipitation rhythm in the Mediterranean

446 area (Suc, 1984; Suc and Popescu, 2005). Our pollen data from the LM record indicate
447 that this change towards a more seasonal Mediterranean-like climate could have started
448 earlier, at around 4 Ma ago. However, more data from additional sites in the area are
449 necessary to confirm this, as the *Olea* pollen change is small (from 0 to 4%; Fig. 7).
450 Anyway, the climate change to a colder, drier and more seasonal climate at this time had
451 considerable effects on Pliocene environments and vegetation, reducing tropical species
452 worldwide, and triggering the disappearance of forests and the spread of more open and
453 xeric landscapes (see regional syntheses in Jiménez-Moreno et al., 2010; Biltekin et al.,
454 2015; Fauquette et al., 2018).

455

456

457 *5.3. Climate variability during the early Pliocene*

458

459 Previous paleoclimatic studies concluded that initial assumption of persistent global
460 warmth and stable Pliocene climate conditions were not substantiated (Prescott et al.,
461 2014), and temperatures were as variable as those during the late Pleistocene (Lawrence
462 et al., 2009). In this study, we show that long-term scale trends in climate in the early
463 Pliocene LM record are interrupted by shorter-orbital-scale cyclical climatic changes,
464 deduced by the alternation between thermophilous-temperate forest (i.e., AP) and herbs
465 (i.e., NAP), most-likely representing warm/humid-cold/arid climatic cycles, respectively
466 (see explanation above). Different scale cyclicities can be observed visually in the pollen
467 abundances (Fig. 5) and statistically through spectral analysis of the *Quercus*, AP and
468 PC1 data time-series (Fig. 6). Two main and statistically significant vegetation and
469 climate cyclicities can be noticed in the three studied proxies, with periodicities around
470 51-37 and 22-21 ka, which could be related with obliquity (~41 ka) and precession (~21

471 ka) orbital cycles, respectively (Laskar et al., 2004). We are unsure about the significance
472 of the later 22-21 ka cycle, since the average sample resolution in the study record is 9.4
473 ka, perhaps insufficient to statistically support this cycle. However, the occurrence of this
474 cycle is supported by previous studies suggesting that precession induced climatic
475 oscillations in rainfall in this area generated cyclical variations in the input of freshwater
476 and sedimentation into the Guadalquivir Basin and Gulf of Cadiz during the early
477 Pliocene (Ledesma, 2000; Sierro et al., 2000). Two other obtained statistically significant
478 cyclicities are ~80-67 and 30 ka, which are more difficult to interpret but could be related
479 to a mixed signal of different orbital-scale cycles (eccentricity, obliquity and precession;
480 Berger, 1977). Lisiecki and Raymo (2005) also obtained a similar spectral peak at 29 ka
481 on the last 860 ka of the LR04 benthic $\delta^{18}\text{O}$ stack, which they interpreted as a nonlinear
482 climate response. We are unassertive about why the 100-ka eccentricity cycle is not
483 showing up in the spectral analyses, as visually it seems to be characterizing the main
484 variability of the environmental and vegetation changes (see *Quercus* data filtered to 100-
485 ka and correlations to short-term eccentricity in Fig. 8). Long-term eccentricity (~400 ka)
486 cycles are not obtained in the spectral analysis either as the record is too short to register
487 several of these cycles but seems to be the one controlling long-term environmental and
488 climatic evolution in this area (long-term minima in *Quercus* or AP/arid ratios in pollen
489 zones LM-01 and LM-03, at 4.5-4.4 and 4.1-4.0 Ma; Fig. 8). The 400-ka cycle has
490 previously been reported to be one of the main controls of cyclical marine sedimentation
491 in the Guadalquivir and Gulf of Cadiz area (Ledesma, 2000; Sierro et al. 2000). The sea-
492 level drop recorded at ~4.0 Ma, coinciding with the 3rd order sequence boundary Za2
493 (Hardenbol et al., 1998), is simultaneous with an eccentricity minimum related to the
494 long-term eccentricity cycle and thus is interpreted here to have a glacio-eustatic origin.
495 This orbital-scale variability seems to be reciprocated in the proxy for continental organic

496 matter fluxes to the seafloor (*B. spathulata* abundance), showing minima during cold
497 events (Fig. 7) and pointing to simultaneous variations and fast responses in the terrestrial
498 and marine environments due to same orbital-scale climate oscillations. Overall, the
499 presence of orbital changes in the studied LM record support the age model of Pérez-
500 Asensio et al. (2018) even for its uppermost part, were magnetobiostratigraphic tie points
501 could not be retrieved due to a change in paleoenvironmental conditions and a loss in
502 paleomagnetic quality.

503 This study reveals the strong influence of the eccentricity and obliquity orbital-
504 scale climatic changes on the environment in the study area. Long- and short-term
505 eccentricity are one of the most significant orbital-scale cycles controlling climate and
506 environmental changes recorded in late Miocene and Pliocene sedimentary sequences
507 (Braga and Martin, 1996; Shackleton and Crowhurst, 1997; Ledesma, 2000; Vidal et al.,
508 2002; Pérez-Asensio et al., 2012, 2013; Jiménez-Moreno et al., 2013a, b; van den Berg
509 et al., 2015, 2018). In the mid-latitude Mediterranean area, cyclical changes in the
510 vegetation are mostly forced by precession (Kloosterboer-van Hove, 2006; Tzedakis,
511 2007). Nevertheless, obliquity seems to have also played an important role in shaping the
512 vegetation during the Pliocene and Pleistocene period (Popescu, 2001; Popescu et al.,
513 2010; Suc et al., 2010; Joannin et al., 2007, 2008; Jiménez-Moreno et al., 2013a; this
514 study). This indicates a high-latitude impact on the climate from the Mediterranean area
515 through variations in seasonal contrast, mainly controlling temperature changes (Tuenter
516 et al., 2003; Suc et al., 2010).

517

518 **Conclusions**

519

520 The detailed multiproxy study on an early Pliocene marine sedimentary record
521 from SW Spain shows:

522 1. Warmest and wettest conditions during the 4.5-3.9 Ma period occurred in this
523 area at ~4.35 Ma. Highest organic matter fluxes to the seafloor related to
524 riverine discharges are also recorded at this time, supporting high fluvial
525 runoff supplying continental degraded organic matter. This agrees with
526 warmest conditions shown by low global ice volume deduced by global
527 isotopic composition of benthic foraminifera, and high insolation and
528 eccentricity, coinciding with the early Pliocene climatic optimum and high
529 global sea level.

530 2. Vegetation and riverine nutrient supply proxies show a subsequent cooling
531 and drying trend after the warmest maximum until ~4.13 Ma. This
532 environmental change could be related with the cooling trend and increase in
533 global ice volume, perhaps caused by a decrease in eccentricity and its
534 modulating effect on summer insolation. A progressive increase in sand
535 content in the LM record between 4.21 and 4.14 Ma could also indicate a
536 glacio-eustatic lowering of the sea-level. West-southwestward progradation
537 of terrigenous depositional systems along the axial part of the Guadalquivir
538 Basin and important detrital inputs from the Iberian Massif prograding
539 towards the center, filling up the basin, would account for the important
540 increase in coarser detritics in a context of sea-level lowering in this area.

541 3. This cooling trend ended with significant glaciation-like cold and arid events
542 affecting the study area between ~4.1 and 4.0 Ma. Related with this major
543 climate cooling and aridity maxima was enhanced coarse sedimentation and
544 minima in riverine nutrient supply to the ocean, showing paired vegetation

545 and sea-level changes and a strong land-ocean relationship. Coldest/driest
546 conditions of the LM record could be related to significant glaciation events
547 (Gi24-20) recorded in the marine isotopic records and minima in eccentricity.
548 The glacio-eustatic sea-level drop associated with this glaciation affected our
549 study site with a significant regression, increasing its proximity to the coast
550 and enhancing coarse sedimentation and was recorded globally as a third order
551 (Za2) sequence boundary.

552 4. Our study shows that terrestrial and marine environments were forced by long-
553 and short-term eccentricity, obliquity and perhaps precession orbital cycles,
554 shaping vegetation, fluvial organic matter fluxes to the seafloor and
555 sedimentary changes in SW Iberia.

556
557

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870 **Figure captions**

871

872 Figure 1. (A) Simplified geological map of the study area and location of La Matilla (LM)
873 sedimentary core. The regional cross section in B is also indicated. (B) A NW-SE cross
874 section of the lower Guadalquivir Basin showing the main lithostratigraphic units and the
875 LM core location. Modified from Pérez-Asensio et al. (2018).

876

877 Figure 2. The LM core lithology, sand content, variations in inclination of the
878 characteristic remanent magnetization (ChRM) based on quality types 1 and 2 data and
879 the associated pattern of polarity intervals identified, and location of biostratigraphic
880 events recognized by planktonic foraminifera (modified from Pérez-Asensio et al., 2018).
881 On the bottom right is the age-depth model and sedimentary rates (cm/k.y.) for the LM
882 record (modified after Pérez-Asensio et al., 2018). Gray shadings and dashed lines
883 indicate the interpreted correlation to the GTS2012 time scale (Hilgen et al., 2012). FO—
884 first occurrence (lowest occurrence); LO—last occurrence (highest occurrence); LcO—
885 last common occurrence (highest common occurrence); G.—*Globorotalia*.

886

887 Figure 3. Detailed pollen diagram of the early Pliocene LM core in depth (m) and age
888 (Ma). Only species with percentages higher than 1% are shown. Arboreal pollen (AP)
889 percentages are also plotted. Green and yellow indicate the trees and herbs, respectively.
890 Shading in some pollen species is the exaggeration of their abundance x5. Aquatic
891 Cyperaceae is in blue. On the right is a cluster analysis (Grimm, 1987) of the pollen results
892 and pollen zones, Climatic inferences (with color shading, red indicating warm/humid,
893 blue cold/dry) are shown in the pollen zones.

894

895 Figure 4. Principal Component Analysis (PCA) from the LM pollen data. (A) PCA scatter
896 diagram with the most significant (abundant) pollen taxa. PCA (PC1+ and PC1-) groups
897 are shown. The analysis was carried out using PAST (Hammer et al., 2001). (B) Obtained
898 PC1 plot and AP (%) from LM record. Note the visual covariation with each other. Pollen
899 zones are shown on the right with climatic inferences (with color shading, red indicating
900 warm/humid, blue cold/dry).

901

902 Figure 5. Comparison of the pollen paleoclimatic proxies obtained from the early
903 Pliocene LM record. From bottom to top: percentages of thermophilous taxa, percentages
904 of *Quercus*, AP/arid ratios, and PC1. The pollen zones and climatic inferences (with color
905 shading, red indicating warm/humid, blue cold/dry) are shown. Note the covariation of
906 all proxies shown by dashed lines.

907

908 Figure 6. Spectral analysis of the most significant climatic pollen proxies from the early
909 Pliocene LM record: *Quercus*, AP and PC1. Confidence levels are shown in orange (80%
910 confidence level) and green (90% confidence level). Significant periodicities (above the
911 80 and 90% confidence level) are shown with numbers (all in ka). The spectral analysis

912 was done using the software PAST (Hammer et al., 2001). In pink shading are frequencies
913 of orbital-scale eccentricity, obliquity and precession cycles.

914

915 Figure 7. Comparison of paleoclimatic, riverine nutrient supply and sedimentation
916 (proximity to coast) proxies for the 4.5-3.9 Ma interval from LM record. From bottom to
917 top are abundances (%) of: *Bolivina spathulata*, *Quercus*, *Olea* and sand content. Blue
918 shading indicates cold/dry periods. Note the covariation of the proxies shown by dashed
919 lines. Blue dashed line highlight the significant cooling/drying at ~4.12 Ma (see text for
920 explanation).

921

922 Figure 8. Comparison of paleoclimatic pollen proxies from the LM record with global
923 paleoclimatic records of the early Pliocene 4.5-3.9 Ma interval. From bottom to top: raw
924 *Quercus* abundance (%) and filtered 100-ka component of the *Quercus* abundance from
925 LM, PC1 from LM, LR04 benthic $\delta^{18}\text{O}$ record showing major isotopic events (Lisiecki
926 and Raymo, 2005), orbital eccentricity (Laskar et al., 2004), summer insolation at 65°N
927 (Laskar et al., 2004) and global sea-level cycles of Hardenbol et al. (1998) with sequence
928 boundaries Za1 and Za2. Blue shading indicates cold/dry periods. Dashed lines point to
929 correlations between the LM record and global paleoclimatic and glacio-eustatic records:
930 in blue are events corresponding to long-term eccentricity minima, in black are events
931 corresponding to 100-ka eccentricity cycles and in orange are correlations to obliquity
932 cycles (see text for explanation).

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